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Manuscript title: Wetting-Drying Response of an Unsaturated Pyroclastic Soil Vegetated with Long-Root Grass

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Abstract

This paper investigates the effect of a long-root grass on the hydraulic response of a partially saturated pyroclastic soil. The work is based on both long-term monitoring under atmospheric conditions and short-term wetting/drying tests, aimed to simulate rainfall/evapotranspiration during different seasons. A 1D physical model was created, namely two identical columns were filled with a pyroclastic silty-sand, and later equipped with tensiometers and soil moisture sensors at four depths. One column was vegetated, while the second was left bare as a control. Roots growth and foliage evolution were observed for one year. The monitoring of the hydraulic variables highlighted the capability of vegetation to modify the retention ability of the rooted soil. During the drying tests, the final soil suction within the rooted zone was higher than in the bare soil, especially during summer, when plant transpiration is very high. In the wetting tests, the presence of vegetation delayed the infiltration process, reducing the total amount of water infiltrating the soil, and consequently the chances for rainfall to cause a drop in soil suction. The paper quantifies the effects of long-rooted grass, here conceived as a nature-based solution viable in landslide prone areas.

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Notation

n	soil porosity
s	soil matric suction
S_r	saturation degree
u_a	pore air pressure
u_w	pore water pressure
VWC	Volumetric Water Content
Δ_s	daily suction increment
η	output electrical signal
η_a	lower boundary of η
η_{rel}	relative electrical signal
η_w	upper boundary of η

Introduction

The increasing awareness about the benefits of using nature-based solutions as mitigation measures against hydro-meteorological hazards (Ruangpan et al., 2019) such as shallow landslides (Kalsnes and Capobianco, 2019), is pushing researchers and practitioners to investigate the effects of vegetation on the main drivers of slope instability problems, even if many key issues have yet to be faced (Stokes et al., 2014). It is widely recognized that the presence of vegetation, such as plants, shrubs or trees, can affect the soil in different ways, from modifying the mechanical properties of shallow soil covers to changing the hydrological response to the main atmospheric factors such as rainfall and evaporation. How vegetation may change the soil hydrological response mostly relates to the variation of pore water pressure (u_w) into soil and Volumetric Water Content (*VWC*) within the rooted zone. It is worth reminding that in a partially saturated soil, *VWC* is lower than soil porosity (n) because some parts of the voids are filled with air. In this case, the pore water pressure (u_w) is negative, i.e. lower than the atmospheric pressure. In many engineering applications pore air pressure (u_a) is nil (equal to atmospheric pressure), and the difference (u_a- u_w) is called soil matric suction (s). The latter may change greatly in space and in time (Cascini and Sorbino, 2002).

Rainfall and evapotranspiration are the atmospheric factors that mostly influence suction and soil water content, and the presence of vegetation can act either as an absorber reducing the rainfall infiltration or as a pump-like material helping in extracting water from the soil through transpiration. During rainfall infiltration, the vegetation can influence both the surface runoff and the infiltration rate (Huat et al., 2006; Ng et al., 2013; Cuomo and Della Sala, 2013; Leung et al., 2015), with strong dependency on the plant species, the root type and whether the roots are young, mature or decaying. Controversial results have been found so far in relation to the effect of roots on soil water retention capacity. Some studies have shown either in field tests (Rahardjo et al., 2014; Leung et al., 2015a) or laboratory tests (Leung et al., 2015b; Jotisankasa and Sirirattanachat, 2017), that rainwater infiltration is delayed due to an increase in water retention capability of soils vegetated by alive roots. Such evidence has been attributed to the occupancy of the soil pore spaces by the roots, with a consequent reduction in soil water permeability (Sholl et al., 2014; Ng et al., 2016a, b). Opposite results were found for mature decaying roots (Barley 1954; Leung et al., 2018; Jotisankasa and Sirirattanachat, 2017), due to the formation of channel macro-pores formed by roots during their growth or during shrinkage upon decay in loose soils (Ghestem et al., 2011). In this case, increase in pore size and consequently in water permeability has been reported as explanation (Vergani and Graf., 2016; Leung et al., 2018). On the other hand, it has been widely demonstrated that the activity of roots during transpiration is reflected in a soil suction increment through water extraction (Ng et al., 2013a; Leung, 2014; Garg et al., 2015), which provides the main potential benefit to slope stability (Pollen-Bankhead and Simon, 2010). Therefore, soil retention capacity, which regulates the water exchanges between the soil and the external environment during wetting-drying cycles, can be heavily affected by the activity of roots. Quantifying the hydraulic response of rooted-soil is a key issue in order to assess slope stability. But roots are materials alive and their effect on soil varies over time. Surprisingly, the number of contributions on quantifying the effects of roots over time on soil water response is still limited especially in the geotechnical community. Only recently, few attempts have been done to study the root growth effects on the water retention capacities of completely decomposed granite soil vegetated with grass during early plant establishment (Leung et al., 2018) and with shrubs over a longer period (Ni et al., 2019).

This work presents the results of an experimental study aimed at quantifying the effect of grass roots on the hydraulic response of a pyroclastic silty-sand frequently involved in rainfall-induced shallow landslides. To take into account the age-dependent activity of roots, wetting-drying tests were performed during the plants growth and in different periods of the year for two consecutive years. In such time interval, variations in soil suction and soil volumetric water content were monitored and compared with those measured in the bare soil.

Materials and methods

Experimental set-up

Two twin plexiglass columns were constructed to perform both drying and wetting tests on vegetated soil (Capobianco et al., 2018). Each column was 2.0 m high to have a good representativeness of the thickness of pyroclastic covers that typically can be found along steep slopes. For instance, in many shallow soil covers around the Vesuvius volcano the upper soil layers are often in the order of 1-2 m (Cuomo et al., 2016). The inner and the outer diameters of the column were respectively equal to 0.192 m and 0.2 m, (Fig. 1), assuming that such dimensions prevented the lateral confinement of the fibrous root network and allowed the natural gravitropic growth along the vertical direction. The gravitropism (also known as geotropism) is a process that enables roots to reach water and nutrients, and firmly anchor

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plants in the ground.

In order to have a 1D vertical flow in the wetting and drying tests, the side boundaries were impermeable while a free drainage was allowed at the top and bottom of the column. The top boundary coincided with the ground surface exposed to the atmosphere, whereas the drainage at the bottom was provided by a series of 3 mm diameter holes covered by a geosynthetic mat with permeability similar to that of fine pyroclastic soils usually found in the deepest layers of the slopes (i.e., about 5×10^{-6} m/s, Sorbino and Foresta 2002; Cascini et al., 2009).

The column was filled up to a depth of 1.9 m, whereas the upper part (0.1 m) of the column was left empty for foliage protection and for irrigation during the plants growth (Fig. 1). The two columns were filled at the same time, but one was intended to accommodate the vegetation and the other was left bare to evaluate the differences in the hydraulic response. The sensors were installed at four depths, precisely at 0.3 m, 0.6 m, 1.2 m and 1.8 m from the top of the column.

The two columns, respectively called *V* for Vegetated and *NV* for Non-Vegetated, were laterally covered by means of an aluminum reflective panel, used for sunlight protection. The whole experimental set-up was built beside the Geotechnical Laboratory “Giuseppe Sorbino” of the University of Salerno (40°46’14.5’’ N, 14°47’21.4 E) under a rainout shelter.

The artificial rain system consisted essentially of a rain simulator and a water tank. The rain simulator was constructed with a main plastic pipe with an inner diameter of 3.0 mm forming a ring with 6 T-joints. Each T-joint was connected to a secondary plastic tube ending with a needle holed, from where the rain comes out. In total 6 holes were available to allow the water to be discharged as rainfall. The dimension of the holes can vary from almost nil to about 7 mm in diameter depending on the rainfall intensity value to simulate (Meyer, 1979). The diameter of the holes here selected, about 1 mm, was consistent with the rainfall intensity values to simulate. The rain simulator was connected to a water reservoir through a cable made of medical *PVC* (Polyvinyl Chloride) used for intra venous *(IV)* treatment applications and then was mounted on a circular support standing at a specified height above the soil surface. The *IV* cable consisted of a drip system linked to the tap of the water reservoir and a water flux regulator. A water 6 liters reservoir was placed on a shelf to maintain a constant hydraulic head difference relative to the rainfall simulator.

Devices and calibration

Four mini-tensiometers (T5 pressure transducer Tensiometer, UMS) were installed to measure the soil suction at the design depths, except for the depth of 1.2 m in the *NV* column due to the limited numbers of sensors available in the laboratory at that time. Prior of installation, the mini-tensiometers were saturated with de-aired water. Each mini-tensiometer had a sensor body incorporated with a piezoelectric pressure sensor that measures the soil water tension against atmospheric pressure in a range from -100 kPa (water pressure/level) to +85 kPa (suction/soil water tension) and with an accuracy of ±0.5 kPa. The acrylic glass shaft of each tensiometer was 0.1 m long and equipped with a high-grade porous ceramic tip with an Air Entry Value (*AEV*) of 200 kPa. When installed, each tensiometer was put into the hole for the entire length of the shaft so that the porous ceramic tip was placed exactly in correspondence of the baricentral vertical of the column. It is worth noting that the measurement range of suction is usually limited by water cavitation in the sensor when negative pore-water pressure approaches 80–90 kPa (Fredlund and Rahardjo, 1993). In this study, cavitation was already observed approaching 60-70 kPa.

VWC was indirectly measured with the method called Frequency Domain Reflectometry (*FDR*). The latter is a precise, automated and easy method for measuring soil water content by measuring the dielectric permittivity at a fixed frequency (80 MHz). The dielectric permittivity of water is much greater than that of air, soil minerals and organic matter. Thus, changes in water content can be detected by the sensor circuitry and correlated to the soil's moisture content. A sine-wave current is passed through a resistance made of two electrodes while the soil acts as dielectric medium. The dielectric properties of the soil are estimated on the basis of the tension measured between the two electrodes and the phase difference between the current and the tension. The electrodes may be of various shapes (laminar, ringed or cylindrical). Particularly, laminar FDR probes (SM100 - Waterscout) were selected for the measurement of *VWC* (%). They functioned in a range from 0% to 100% with an accuracy of ±3%, and they represented an economical and user-friendly solution.

Recently, FDR probes have been used for field monitoring of marine clay soils covered by riparian vegetation (Krzeminska et al., 2019). All the SM100 probes (FDR) used in this study were calibrated taking into account the peculiarities of the pyroclastic soils and the dimension of the sensors as well as their shape. The sensors were named respectively SM100_1, SM100_2, SM100_3 and SM100_4. A plastic cylinder with inner diameter of 59.5

mm and height of 85.0 mm was filled with soil at different volumetric water content. Each sensor was then introduced in the soil specimen by ensuring the perfect contact of the laminar plate to the soil for obtaining a reliable electrical signal in output. The first output of the measurement is usually an electrical signal (η), which is proportional to the dielectric permittivity and, with the relative calibration, can be converted into volumetric water content. The sensor was introduced firstly in a water reservoir to obtain the upper boundary of the signal (η_w) and then it was left in the air to obtain the lower boundary (η_a). Then, the reservoir was filled with soil, by using the moist tamping method (Ladd, 1977). This was done by fixing the target bulk density equal to that of the two soil columns, and by changing the percentage of soil water content. For each of the four sensors, 8 specimens were realized with different *VWC* for determining the relationship between η and the *VWC*. During the calibration, only the sensor SM100_1 gave different values compared to the others, and particularly the highest and the lowest values of η (Fig. 2a). Based on that, two calibration curves were considered: one for SM100_1 and another for the remaining sensors.

For a fair comparison, the concept of relative electrical signal (η_{rel}) was introduced, which varies from 0 to 1 and takes into account the limit values (η_w and η_a) of the output electrical signal. It reads as follows:

$$\eta_{rel} = \frac{\eta - \eta_a}{\eta_w - \eta_a} \quad (1)$$

Two fitting curves were considered (Fig.2b), each with 4 parameters, as follows:

$$VWC(\%) = a \cdot \left(\eta_{rel}\right)^{2.5} + b \cdot \left(\eta_{rel}\right)^{2} + c \cdot \left(\eta_{rel}\right)^{1.5} + d \quad (2)$$

where η_{rel} is the relative electrical signal and *a, b, c* and *d* are the calibration parameters, whose

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values are summarized in Table 1.

These calibration equations were used to obtain the *VWC* (%) for each measurement during the long-term monitoring and the short-term hydraulic tests.

The sensors were placed at the same depths of the mini-tensiometers. Furthermore, a thermal sensor (109, Campbell Scientific) was placed on the ground surface to continuously measure the temperature of the soil in direct contact with the atmosphere, in a range varying from -55 °C to +70°C with an accuracy of ±0.3 °C.

Selection and preparation of soil and vegetation

The experimental tests were performed on a pyroclastic soil originated from the explosive eruptions of the Somma-Vesuvius volcano (Cioni et al., 1999). Such soil covers steep limestone carbonate bedrocks over 3’000 square kilometres in the Campania region (Southern Italy). Field surveys outlined that the thickness and the stratigraphy of pyroclastic deposits are highly variable and depend mostly on: *i)* the exposure of the slopes towards Vesuvius in relation to the prevailing wind directions, *ii)* the type of deposition, i.e. primary air-fall or re-worked deposits (Cascini et al., 2000; Fiorillo et al., 2001; Mastrolorenzo et al., 2002; Guadagno and Revellino, 2005; De Vita et al., 2006a) and *iii)* geomorphology of slopes (Celico et al., 1986; Guadagno, 2000). However, Bilotta et al. (2005) classified the ashy soils in two main soil classes, based on detailed analysis of grain-size distribution, physical and mechanical properties of several samples collected along the Pizzo d’Alvano massif in recent years. According to the stratigraphical settings of most of the pyroclastic deposits (Revellino et al., 2004; Bilotta et al., 2005; Cascini et al., 2008), the coarser ashy soils generally belong to the superficial layers (1-2 m) and overlays finer soils with some inter–bedded thin layers of pumice.

The soil for the experimental campaign was collected from the pyroclastic deposits of the Pizzo d'Alvano massif (40°50'43.24"N, 14°36'36.57"E), in the source area of one of the several May 1998 debris flows, which caused loss of lives and huge damages to the towns located at its piedmont (Cascini et al., 2008). Precisely, the soil here investigated belongs to the coarse volcanic ashy soil, typical of the more superficial layers, with the contents of gravel, sand, silt and clay respectively of 8.1%, 60.2%, 30.6% and 1.1%. Such soil can be classified as sand with silt according to the Unified Soil Classification System USCS (ASTM, 2010). Detailed information about grain size distribution and index properties of the investigated soil are provided in Capobianco (2018). The two columns were filled (as mentioned before, up to a depth of 1.9 m) through the moist tamping method (Ladd, 1977) for successive layers of 5 cm, since a reasonable uniform dry density profile can be obtained, with a maximum deviation from the targeted value of about 2% (Ng et al., 2013). Under such uncertainty, we assume that the moist tamping method reduced the probability in having thin layers with different conductivity values. The soil was compacted to a target bulk density of 12.03 KN/m^3, corresponding to porosity of 53.5%, and with 10% of gravimetric water content. The porosity of 53.5% was chosen on purpose close to the lowest boundary of the porosity range found in situ for these materials (Bilotta et al., 2005), since in this way a possible reduction in volume due to the wetting was avoided. A parallel study on the effect of vegetation growth on the wetting-induced behaviour of pyroclastic soils under different initial porosities is discussed in

Capobianco et al. (2020).

The vegetation type here selected belongs to the *perennial graminae* grasses, having a gravitropic vegetative growth, which enables roots to reach water and nutrients and firmly anchor to the ground, and a fibrous root system capable to reach great depths (Cazzuffi et al., 2006). This species is able to grow in soils with different chemical properties and nutrients availability. In addition such vegetation can adapt to different geo-environmental contexts and seasons, and also in very dry conditions due to the capability of their roots to reach the deeper zones where water is available (i.e. water springs, deep aquifers). Such *graminae* grasses belong to the microthermal species, commonly known as "evergreen", because of both their resistance to medium humid climates and their two peaks of growth: the highest one during spring and another during fall. This species is indigenous, which means that it already exists in many geo-environmental contexts and helps the establishment of spontaneous vegetation; at the moment there is no proof that it can impact on the local biodiversity.

Climate conditions in Italy are favorable to this type of grasses, by ensuring a quite large amount of water due to rainfall and air humidity. Moreover, the well-known high fertility of pyroclastic soils, with nutrient rich path, can positively affect the growth of both roots and leaves eventually improving the reinforcement of vegetated soil, as formerly observed by Ng et al. (2018).

The grasses have been seeded in a small pot, germinated 1 month in a greenhouse with water supplied on a daily base, and then transplanted in the *V* column. Transplantation was at the end of January 2016. The initial mean root depth was 6.0 ±0.3 cm while the average height

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of foliage was approximately 8.0 ±0.2 cm. The column was watered automatically with one liter every 48 hours through an irrigation system commonly used for private gardens (T 1030 D, Gardena Water Timer electronic).

Long-term monitoring

Vegetation growth

The Root Depth (*RD*) was monthly measured through 4 graduated scales placed at each side of the transparent column. Particularly, the average value of the four longest roots observed from each side of the column was considered. The Height of Foliage (*HF*) was monthly calculated as the average value of the direct measurements of five different leaves randomly chosen. Figure 3a shows the measured *RD* and *HF* with time and Figure 3b the values of *RD* against those of *HF* for the monitoring period, i.e. 12 months from month "0" (January 2016), when the transplant of vegetation was done.

As expected, *HF* increased rapidly during the first months, from 8.0 ±0.2 cm in January 2016 up to 29.9 ±3.0 cm in the 4^{th} month (May), with a high rate of growth in the first vegetative season of the microthermal species. From June to September, *HF* increased at lower rate, from 36.3 ±6.2 cm up to 52.5 ±1.8 cm.

Starting from the 8^{th} month (September), a slower growth was observed up reaching *HF* equal to 55.7 ±2.4 cm at the 10^{th} month (November). From then *HF* remained quite the same until the end of the winter. On the other hand, *RD* increased exponentially from 6.0 ±0.3 cm up to 95.7 ±2.6 cm during the first spring vegetative season (from the 1^{st} to the 4^{th} month), consistently with the growth of the foliage, and showing the typical growth of microthermal species. After the first period, *RD* increased almost linearly during the summer season from 112.2 ±8.9 cm (in the 5th month) up to 181.1 ±4.4 cm (in the 8th month). In this study the second peak of growth, typically observed during fall season for microthermal species, was recorded between September and November although it was almost negligible compared to the first peak of growth. In fact, the root depth increased from 181.1 ±4.4 cm up to 185.6 ±2.0 cm during these months, reaching the bottom of the column. After that, the root growth was inhibited by winter climate conditions and for the limited height of the column, and no difference in root depth was recorded from the 10th to the 12th month (November - January 2017).

A positive linear correlation of *HF* and *RD* was observed during the first vegetative year (Capobianco et al., 2018). This means that the observation of the foliage allows inferring the expected root depth along the vertical direction, when 1-Dimensional condition exists. These results are consistent with agronomical considerations regarding the ratio between the hypogeum (roots) part and the part above the ground level (foliage), which is demonstrated to be higher than 3 in this experimental study. Root features such as root biomass and distribution of root diameters are reported in a parallel study conducted by Foresta et al. (2019) to investigate the effect of the roots of this grass on the shear strength of pyroclastic soils.

Suction and water content

The monitoring of soil suction (*s*) and volumetric water content (*VWC*) lasted from March 2016, when the grasses started to grow, until the end of July 2017, when the hydraulic tests on the rooted-soil were concluded. The sensors along the column were named respectively “A” (at

0.3 m depth from the top), “B” (0.6 m), “C” (1.2 m) and “D” (1.8 m). Figure 4 shows the daily *s*-*VWC* data over time acquired from monitoring of all the sensors in the vegetated column (Fig. 4a b), with also the indication of the long-duration drying tests (15 days) and short-duration wetting tests (few hours).

Both the measurements of soil suction and water content were depurated from unreliable values (i.e. *VWC*<0%) and the so-called "maintenance data" which were used for calibration of soil moisture sensors or saturation of mini-tensiometers. In fact, soil suction monitoring was occasionally interrupted for maintenance, when the mini-tensiometers were re-saturated because air bubbles had been observed in the plastic body. In addition, at the end of each drying test, all the mini-tensiometers were re-saturated again because most of them (in particular those placed in the superficial soil layers) have reached high suction values and thus have been desaturated. On the other hand, the *VWC* sensors occasionally detached from the soil (while they should be tightly connected to the soil), thus some measurements were lost, particularly in the first stage of the monitoring period.

It can be firstly observed that the soil suction clearly increased during the second year compared to the records of the first year, because vegetation had grown and its influence on soil suction had become more pronounced. With the roots already grown, the *VWC* fluctuated less than in the first 6 months (Fig.4b).

After the drying test conducted in July 2016 the irrigation frequency was changed to twice per day, because summer started and the vegetation required more water to survive. During this period the suction was relatively low, ranging from 0 to 10 kPa (Fig. 4a). Starting

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from October 2016 the irrigation frequency was reset again to on alternative days. Doing that, the suction changed a few probably for the low air temperature, while *VWC* increased a bit more probably because of the reduced root water uptake in the so called ‘dormant’ stage of the plants.

The suction variation was the highest at the low depths, and the maximum value was recorded at the row A because of the direct interaction between the superficial soil layers and the atmosphere. Such relevant variation was observed also for *VWC*, but at a lower amount.

During the drying tests, soil suction increased at all the depths and conversely a decrease in *VWC* occurred due to evaporation from soil and transpiration related to root water uptake.

Water retention capability

Figure 5 shows all the s-S_r (soil matric suction versus saturation degree) pairs along all the depths of the *NV* column. The Saturation degree was calculated as the ratio between the measured *VWC* and the design porosity of the column, which was found substantially the same of the rooted soil (Foresta et al., 2019). The curves were quite similar in shape except at row D for low suction. This was probably due to the weight of soil transferred at the deepest depths. A qualitative interpretation trend was also drawn for the bare soil, which is in good agreement with some fitting curves reported by Cuomo and Della Sala (2013), with the Van Genuchten parameters ranging from 0.11 to 0.5 kPa-1 for the inverse of the air entry value, and from 1.30 to 2.10 for the parameter taking into account of the steepness of the curve.

Figure 6 reports the suction measurements and the calculated Saturation degree (S_r) for all the depths of the vegetated (*V)* column. An attempt was made to divide the data into

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monthly groups with the aim to capture the evolution of the retention ability of the tested soil with time (and then with the roots growth). A clear modification of the shape of the retention curve was observed for the shallowest layer of the column (Fig. 6a) even if no more relevant changes in the data distribution were detected from February 2017. Conversely, for the deepest layer (Fig. 6d) not big differences in s-S_r were captured over time, and thus the acquired data were collected in group of months. It is possible to observe that for all the depths, the pairs s-S_r showed a tendency to flatten with the time. This means that for the same suction the saturation degree increased from one month to the next. One possible explanation of this findings is that the roots, during growth, can develop and occupy part of the voids, thus modifying the global porosity of the host soil. This leads to a vegetated soil, which is "virtually" denser than the bare soil (Graf et al., 2013). In addition, the roots are able to break one single void in multiple smaller voids thus modifying also the void size distribution of the entire soil matrix. This can lead to an increase of the matric suction according to the capillary law (Ng et al., 2016b). In this study, since not big changes of the porosity of the root-permeated soil were observed (Foresta et al., 2019), the tendency of flattening was more likely given by a change of the void size distribution experimented by the soil matrix during the roots growth. Moreover, the tendency to flatten of such curves seems to be delayed with the depth, in accordance with the roots growth.

For a better understanding, the reference curves of the vegetated soil were drawn for three periods of monitoring: at the beginning (Fig. 7a), middle vegetation growth period (Fig. 7b) and final period (Fig. 7c). These curves are compared to the s-S_r reference curve obtained for bare soil by referring to all the *s-VWC* data at all the depths of the *NV* column (Fig. 5).

At the beginning of the monitoring period, corresponding to the first 3 months of growth of the vegetation, the roots have reached 20 cm depth (Fig. 3) and thus the reference curves at all the depths in *V* column should be comparable to the curve of bare soil. However, this was true only for the row D, while the s-S_r curves for the rows A, B and C seemed to refer to a wetting path (Fig. 7a). This happened because during the first three months, when the roots were still very young and the temperatures were low, wetting-like paths were mostly registered at shallowest depths when irrigation was done every other day and roots adsorbed very quickly most of the water available without having a high transpiration activity. In the middle stage, corresponding to the month of July 2016 when the roots have reached almost 150 mm (Fig. 3), the s-S_r curves of vegetated soil were those of rows A and B (Fig. 7b). At the deepest depth (row D), roots were not grown yet, so no changes were measured. The tendency to flatten is visible especially for suction higher than 10 kPa, while after that value the roots probably increase the water uptake collected it into their “capillary tubes”.

At the end of the monitoring period (Fig. 7c) the reference curves of the vegetated column are all flattened and show higher values of S_r compared to the bare reference curve. In general for both *V* and *NV* soils, a multimodal shape of the retention curves is observable, according to previously findings for these specific pyroclastic soils (Ferlisi and Foresta, 2017). However, for high values of suction it seems that the *V* curves change again the steepness and become steeper than the reference curve.

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Short-term tests

Experimental programme

Cycles of drying and wetting were performed both for the *V* column and *NV* column to investigate the hydraulic behaviour under atmospheric stresses. All tests performed are summarized in Table 2.

Drying tests consisted in 15 days of evapotranspiration (*ET*) under atmospheric conditions in dry days, starting from a saturated condition along the whole column. The tests were repeated in the two vegetative years, and during both wet season (spring) and dry season (summer). In fact, it is well known that evapotranspiration is controlled by temperature and relative humidity of atmosphere as well as wind velocity, so their variation along the seasons can strongly affect the hydraulic response of soil. External atmospheric temperature and relative humidity were monitored at the meteorological station of the University of Salerno for the assessment of the evaporation fluxes during the drying tests.

The drying tests in wet season were performed in the month of April, for *V* column respectively in 2016 (V_D_A1) and 2017 (V_D_A2) and only in 2017 for the *NV* column (NV_D_A2) as control (Fig. 4). Similarly, the dry season tests for *V* column were conducted in July 2016 (V_D_Jul1) and July 2017 (V_D_Jul2), whereas only in July 2017 for *NV* column (NV_D_Jul2).

Infiltration tests were performed through a rainfall simulator described above, and they lasted less than drying tests, typically 48 hours. The rainfall intensity was selected between 1 and 4 mm/h, which are the most frequent rainfall intensities recorded from 2001 and 2011 in a

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similar test site of Campania region, where pyroclastic soil also covers calcareous bedrock (Comegna et al., 2016). The average rainfall intensity was equal to 2.4 mm/h, thus cumulative water infiltrated in 48 hours was 3.4 litres. For a fair comparison, soil suction was the variable investigated during the wetting tests, since it may undergo significant drop due to rainfall and with that leading to strong reduction of soil shear strength and eventually to slope failure (Anderson and Sitar 1995; Alonso et al. 1995). Two different wetting tests were conducted respectively in April and June of the 2nd year (Tab. 2), starting from different initial soil suction values (*s*) to simulate the initial conditions that can be found in situ respectively in wet and dry season (Sorbino and Nicotera, 2013; Cascini et al., 2014). Indeed, the first wetting test was performed with initial soil suction values around 12-15 kPa at shallowest layers, while the second wetting test was performed with initial soil suction values of 45-50 kPa at shallowest layers. Before the wetting tests, leaves exiting the column were cut in order to guarantee that rainfall applied was equal to net rainfall infiltrated, by avoiding that rain drops were intercepted by leaves and not infiltrate the soil.

Soil drying in wet season

Drying tests were performed in April, a period when rainstorms are frequent in Campania region and soils are close to saturation (Cascini et al., 2014). These tests were aimed to evaluate the effect of vegetation on the evapotranspiration processes in the soil when no rainfall occurs. The effect of roots growth on the *ET* process was taken into account by conducting the tests in both April 2016 and April 2017, under similar monthly averaged temperatures, i.e. 16.1 °C with a variation of ±2.9 °C around the mean value in 2016 and

14.1 °C with a variation of ±2.3°C around the mean value in 2017. Furthermore, the evolution of the Potential Evapotranspiration (*PET*) was calculated using the FAO Penman-Monteith Equation (Monteith, 1965) from the data of the nearby meteorological station. The *PET* calculated for the 15 days drying test was equal to 2.6 mm/day, consistent with the literature value available from a monitored slope about 50 km far away (Damiano et al., 2012). The actual evapotranspiration flux (*AET*) was estimated by adopting the empirical approach proposed by Baier and Robertson (1966), as progressive reduction of the *PET* through an empirical factor K_r. The latter is function of the measured *VWC* close to the surface, the field capacity water content here set to 0.485 (Rianna et al., 2014), and the permanent wilting point reasonably assumed equal to the soil residual water content. Figure 8 shows the daily averaged values of soil suction (*s)* and their fluctuation during the drying tests (Tab. 2), under the estimated potential and actual evapotranspiration fluxes. Furthermore the average daily increment of suction (Δs: kPa/d) was calculated at each depth and reported for each test. It can be observed that the soil suction increased more quickly in the surficial layers in both columns. Particularly, at the row A, Δs was respectively equal to 3.1 kPa/d and 3.5 kPa/d in the test V_D_A1 (1st year) and V_D_A2 (2nd year). These values were almost twice those recorded in the *NV* column (1.7 kPa/d), and they were also higher than those recorded on another type of grass species (Bermuda grass) in a similar study, where the grass did not have such a long root system and the rooted area investigated was smaller (Ng et al. 2013b). At the row B, the daily suction increment Δs in test NV_D_A2 was similar to that recorded in test V_D_A1 (Fig. 8a,b), while it slightly increased in the test V_D_A2 (Fig. 8c). This might be due to the still limited

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length of the roots in V_D_A1, which did not reached yet the depth of row B. As consequence, no water uptake occurred at that depth and thus the daily suction increment was similar, even smaller, of that recorded in the *NV* column. This suggests that in the first days of ET, the influence of vegetation on soil suction increment is mainly registered in the root zone, as observed also by Ng et al. (2016a). As it concerns the deepest rows (1.2 m to 1.8 m from the top of the column), the effect of roots was negligible being Δs quite the same in the tests V_D_A1 and V_D_A2 (Fig. 8b,c). Some difference in Δs was observed at the row D, passing from 0.1 kPa/d of NV column to 0.3 kPa/d of V_D_A1 test, up to 0.5 kPa/d of V_D_A2 test. In conclusion, bigger differences in soil suction increments can be observed at shallowest depths where both roots are more numerous and the soil is closer to the atmosphere for water exchange fluxes (Capobianco et al., 2018; Pagano et al., 2018). The small increase of daily suction ad deepest depths can be explained by the fact that the density of the roots tends to decrease with depth, as founded by the Authors investigating the same soil and same grass species (Foresta et al., 2019).

Soil drying in dry season

Drying tests in the dry season were performed in July 2016 and July 2017, with the roots respectively long 1.47 m and 1.85 m (Tab. 2), and monthly averaged temperature respectively equal to 24.9 °C with a variation of ±2.2 °C around the mean value and 25.0 °C with a variation of ±1.9°C around the mean value. For comparison, a drying test in *NV* column was also performed in July 2017. Indeed, the positive effect of plant evapotranspiration on induced soil suction in summer season is widely recognized, because of the high temperatures and the lack of rainfall events. During this period the vegetation is florid and plants need water for their vital functions. In Campania region the dry period goes from May to September (Cascini et al., 2014). Figure 9 shows the suction (*s*) daily measured during the 15 days drying period under the estimated potential and actual evapotranspiration fluxes, respectively in the tests labelled as NV_D_Jul2 test (Fig. 9a), V_D_Jul1 (Fig. 9b) and V_D_Jul2 (Fig. 9c).

At row A, Δs in the *V* column was definitely higher than that observed in the *NV* column, varying in a range from 8.7 kPa/d (Fig.9c) up to 22.8 kPa/d (Fig. 9b). Furthermore, in the test V_D_Jul1, both the tensiometers of row A and row B reached the cavitation after 5 days (Fig. 9b). This means that plant transpiration induced a total built-up of soil suction of about 70 kPa or higher, while in the *NV* column, suction increased up to 40 kPa as maximum (Fig. 9a).

Cavitation occurred also at row A in the test V_D_Jul2, with the last reliable suction value equal to 63 kPa and measured after 10 days (Fig. 9c). In general, the suction values recorded at the end of the drying tests in the *V* column were considerably higher in V_D_Jul1 compared to V_D_Jul2. This might be due to the different stage of growth between July 2016 and July 2017. In fact, in July 2016 the grass was in its first stage of growth and it required more water to grow and to face with high temperatures during the first dry season. Differently, in July 2017 grass was already 1.5 years old, thus required less water to survive as reflected in lower values of Δs (Fig. 9c). Furthermore, in April 2017 some leaves have been cut for infiltration tests and this influenced the evapotranspiration occurred in July 2017, because it is widely known that evapotranspiration depends on *Leaf Area Index, LAI* (Monteith, 1965). As direct consequence, *LAI* influences the suction increment (Ng et al., 2016a). However, the drying test results obtained in July 2017 can be selected as representative of the hydraulic response of vegetated soil in dry season.

Wetting tests in wet season

The measured soil suction along depth during the 48 hours wetting tests conducted in wet season respectively in *NV* column (NV_W1) and *V* column (V_W1) are shown in Figure 10. For both cases, the initial suction conditions at shallowest depth were typical of wet season, while suction values at deepest depths were higher. This was because the test was conducted after the *ET* test of April 2017, and thus after few days of irrigation the soil suction values at deepest depths were not reduced yet.

The initial soil suction at shallowest layers was between 12 and 15 kPa. From the beginning of the test up to 5 hours, a slight suction reduction was observable with the same rate for 0.3 m and 0.6 m depth in *NV* column (Fig. 10a), whereas for *V* column the soil suction values remained almost constant at both 0.3 m and 0.6m (Fig. 10b) because of the presence of vegetation, which delayed the rainfall infiltration. Furthermore, at 0.6 m depth the soil suction values started to increase since a delay in rainfall infiltration allowed continuing the evapotranspiration process due to root-water uptake.

After 5 hours, in both *NV* and *V* columns a drop in suction was observed, that was steeper for the *NV* column. This means that the suction reduction during time in *V* column was slower compared to that observed in *NV* column. The suction reached almost 2 kPa in *NV* after 12 hours, compared to *V* column, where this value was reached after the double of time (24 hours). However, after 30 hours of rainfall, the soil suction values in *NV* column appeared to increase again, and this was because a problem with the rainfall simulator was found out, since two of the needles holed were obstructed and no water was exiting. On the other hand, in *V* column, the presence of vegetation reduced the water flux from 0.3 m to 0.6 m until the duration of 10 hours, when a slow reduction of soil suction started also at 0.6 m. However, the rate of suction reduction was smaller than that observed for the *NV* column. In fact, after 30 hours, the suction value at 0.6 m reached 8 kPa in *V* column and 2 kPa in *NV* column.

The rainfall duration did not influence the deepest layers, which kept almost the same suction during the whole test, as reasonably simulated by Leung et al. (2018), for 2 days of wetting.

In Figure 11 the measured suction profiles every 3 hours are reported (Fig. 11a,b) respectively for *NV* and *V* column. The delay of water infiltration due to the presence of vegetation is visible from the suction profile after 6 hours, which was still at the same values of initial conditions (Fig. 11b), compared to that of *NV* column, which changed in correspondence of 0.3 and 0.6 m (Fig. 11a).These results are in agreement with Leung et al. (2015), who observed that no changes in soil suction occurred in soil vegetated with a similar grass after 2 hours of ponding.

After 9 hours and 12 hours, the suction profiles changed also for *V* column, nevertheless only a change in the inclination of the profile between 0.3 m and 0.6 m was observed. On the contrary, in *NV* column, both the inclination changed and the suction profile moved to the left, because all suction values have been reduced during infiltration process.

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Wetting tests in dry season

The measured soil suction along depth during the 48 hours wetting tests conducted in dry season respectively in NV column (NV_W2) and V column (V_W2) are showed in Figure 12. In this case the initial soil suction at shallowest layers was typical of dry season.

In both cases a 48 hours rainfall caused a drop in soil suction values at the shallowest layers up to 0.6 m of depth, at deepest layers suction remained almost constant, as already observed in the previous wetting test.

During first few hours the presence of vegetation led to a delay in rainfall infiltration at 0.3 m of depth. In fact, the soil suction values in *V* column started to decrease after 5 hours (Fig. 12b) compared with *NV* column, where soil suction values decreased with a low rate from the beginning of the test (Fig. 12a).

After 5 hours, a steep soil suction drop was measured indistinctly in both *V* and *NV* columns at shallowest depths. Indeed, suction values reached almost 5 kPa after 15 hours of rainfall in both columns. On the other hand, the drop in suction of the shallowest layer did not influence the variation of suction at 0.6 m depth of the vegetated column, which conversely passed from 36 kPa to 40 kPa because of root water uptake (Fig. 12b). This effect was enhanced also by the external climatic conditions, since the test was conducted in June. In *NV* column the soil suction started to decrease linearly from the beginning of the test also at 0.6 m of depth, so no delay of water fluxing along depth was observed. In this case, the effect of the presence of vegetation was observed at the deeper layer (0.6m) where, after 15 hours, the suction was still high in V column (40 kPa), compared to that registered in the NV column (25

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kPa).

As for the wetting test in the wet season, suction profiles every 3 hours are reported for both *NV* column (Fig. 13a) and *V* column (Fig. 13b).

In this case, suction profile after 6 hours is the same of the initial measured in *V* column (Fig. 13b), while in *NV* column it changed at shallowest depth because the suction was already reduced due to rainfall infiltration. After 9 hours also in *V* column the suction profile changed, as for 12 hours, even if it only change inclination between the two shallowest layers (Fig. 13b). On the other hand, in *NV* column, the suction profile moved to the left because also at 0.6 m a reduction in suction was measured (Fig. 13a).

Discussion

The results of drying test on both *NV* and *V* soil columns can be used to predict the increment of soil suction induced by grasses. Figure 14 shows the experimental points of soil suction measurements respectively after 5 days (Fig. 14a) and after 10 days (Fig. 14b) of drying in *NV* column and *V* column for both wet season and dry season tests conducted in 2017, once the roots had already reached their maximum length (Tab. 2).

It is possible to quantify the change of suction induced by grass transpiration as the difference between the experimental point and the value along the bisector of the graph, which corresponds to the amount of soil suction measured in *NV* column.

As first observation, due to the higher evapotranspiration activity, the suction induced by the roots is higher in summer season compared to the wet season at all depths.

The duration of the drying is another important factor influencing the effect of roots on the induced soil suction. In fact, while the induced suction after 5 days were almost comparable for the shallowest depths (0.3 and 0.6m) in both dry and summer season (Fig. 14a), after 10 days of drying all these values were increased up to a maximum of 32.6 kPa recorded at 0.3 m in the dry season (Fig. 14b).

The calculated hydraulic head profiles with depth every 3 hours of the wetting tests are shown in Figure 15. For both the dry and the wet season, it is possible to observe the effect of the vegetation in delaying the water infiltration. For the wet season, the hydraulic head calculated in *NV* column increased after 6 hours in correspondence of 0.3 and 0.6 m (Fig. 15a), compared to the *V* column, where no changes were observed until 9 hours of applied rainfall (Fig 15b).

After 9 hours and 12 hours, the hydraulic heads at 0.3 m were the same for *N*V and *V* columns. A larger value, instead, was calculated at 0.6 m in *NV* column, confirming the larger water infiltration occurring in the bare soil compared to the rooted soil. Similarly, for dry season, the calculated hydraulic head increased quickly in the *NV* column, where already after 3 hours the profile changed (Fig.15c). After 9 hours the profile changed also in *V* column, despite the hydraulic head at 0.6 m did not increase as it did in *NV* column (Fig.15d), meaning that the water infiltrated did not reached yet that depth.

In conclusion it can be claimed that the vegetated soil leads to a delay of water infiltration which reduce the amount of water entering into the soil after a prolonged rainfall. This reduction can positively affect the slope stability, since no drop in suction at highest depths can be experimented also after many hours of rainfall, thus no reduction of shear strength is given.

These results match some previous findings of water infiltration reduction due to grass roots (Rahardjo et al., 2014; Sholl et al., 2014) whereas the roots of trees have higher probability of creating macro-pores and enhancing the infiltration (Leung et al., 2018).

Figure 16 shows the monthly average suction for the two years monitoring period and the final suction values of the 15 days of drying tests for both wet season (V_D_A1, V_D_A2) and dry season (V_D_Jul1, V_D_Jul2). At all depths monthly average values increased from one year to another, especially in the spring period (from April to June), which coincides with the peak growth season for this species. High difference in suction values among the same months of two consecutive years are observable for March 2016 and March 2017, where also the bigger difference in terms of RD was found. Indeed, in March 2016 the measured RD was equal to 16.4 cm (Fig. 3), against the RD (185. 6 cm) in March 2017 that had already reached the bottom of the column since November 2016. The monthly suction measures in March 2016 and March 2017 can be representative of the difference in terms of suction that the soil can experience while having a short rooting system (March 2016) and a totally developed root system (March 2017). This confirms that vegetation with a long root system improves substantially the induced suction of a vegetated soil, not only at the shallowest layers, where also an increase of induced suction is observed, but especially at deepest depths, were the induced suction is doubled. The local values of final suction after each drying test are reasonably equal or larger than the monthly average, except for the lowest depths (1.2 m and 1.8 m) where the final suction in test V_D_A2 and V_D_Jul2 were lower than the monthly average. This might be due to an enhanced roots activity also during a normal period (when no

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drying cycle occurs), where more water exchange could occur also at the interface between the bottom boundary of the column and the atmosphere. Despite controversial results in literature, this study can give another confirmation that roots of grasses during and after 1 year of their establishment, can positively contribute to the hydraulic response of the soil both in drying and wetting conditions.

Conclusions

This experimental study was aimed to quantify the effect of long root grasses on the variables responsible of the hydraulic behavior of soil in partially saturated conditions. Two twin columns 2 meters high, one Vegetated (*V*) and the other No-Vegetated (*NV*), have been instrumented at 4 depths to measure soil suction and volumetric water content during the root growth within two vegetative years. The root growth was measured monthly together with the height of foliage. As first important finding, this type of grass can easily grow in pyroclastic soils under natural atmospheric conditions within one year, by reaching the maximum depth of roots (coinciding to the bottom limit of the soil column) after around 9 months (end of summer 2016) and showing a typical growing behavior of "evergreen" grasses: two peaks of growth respectively in summer and fall season. During the first vegetative year, the measured root depth (*RD*) showed a clear positive correlation with height of foliage (*HF*).

Hydraulic variables were monitored along the two years and differences have been found for *V* column when compared to *NV* column. The water retention ability of *NV* soil was similar to previous findings for the same type of soil. The main effects of the presence of vegetation on the water retention ability were:

1) The differences in s-S_r curves for the vegetated column at different depths are mostly due to the root growth.

2) Compared with bare soil, the pair s-S_r for vegetated soil showed a tendency to flatten out with the time. This might be due to the tendency of the roots to fill the available voids and thus modify the void size distribution of the soil matrix.

During evapotranspiration in wet season it was found that the presence of roots almost doubles the daily soil suction increment at shallowest layers compared with the bare soil. This effect is slightly reduced at deepest layers, because root network is less dense than that in superficial layer. These results are promising also when compared to other types of grass species, which registered lower increased suction at the shallowest layers (Ng et al., 2013b). In dry season the effect of roots is more pronounced also at deepest depths due to the higher evapotranspiration activity, and the daily suction increment is from 4 to 10 times higher than that observed in *NV* column at shallowest layers.

Wetting tests were performed in both wet and dry season starting from different initial conditions. The variable investigated was soil suction, since it undergoes significant drops due to rainfall and thus consequently is the responsible of a reduction of soil shear strength and potential slope failures.

Results in both seasons showed that the presence of grasses leads to a delay of water infiltration which reduces the amount of water entering into the soil after a prolonged rainfall. In fact, the vegetation can reduce the water infiltration at deeper layers due to the combined effect of both the delay of water flux and the continue roots activity (root water uptake).

An empirical correlation between the suction in *NV* soil and the induced suction by roots after 5 and 10 days of drying was provided in order to predict possible increase in suction due to the presence of vegetation for a given soil suction that can be found in a bare soil.

In conclusion, the presence of vegetation can change the soil response to the atmospheric actions as well as the initial conditions of the partially saturated pyroclastic covers of Campania region. This means increased soil suction over time and a delay of water infiltration, which are both key factors in the rainfall-induced shallow landslides. Further topic worth of investigation may be the effect of grass leaves on the rainfall interception and thus on the hydrological balance, as well as the determination of the variation of the soil permeability with the root growth.

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Table 1. Calibration parameters for polynomial fitting equation

Sensor ID	Calibration parameters a	b	c	d
SM100_1	261.71	-566.12	354.84	-0.72
SM100_2 SM100_3 SM100_4	279.97	-559.64	329.32	-1.15

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Table 2. Summary of the test program followed for the drying and wetting tests on bare and rooted-soil

Objectives	Test ID	Vegetation	Root age (months)	Month	Root length (cm)	Drying	Wetting
Effect of root growth on increasing suction during evapotranspiration	V_D_A1	Grass	3	April	57.8	ET	
	V_D_A2	Grass	15	April	185.6		
	NV_D_A	Bare	-	April	-	ET	
	V_D_Jul1	Grass	6	July (2016)	147.6	ET	
	V_D_Jul2	Grass	18	July (2017)	185.6		
	NV_D_Jul	Bare	-	July (2017)	-	ET	
Effect of roots on decreasing suction during infiltration	V_W1	Grass	15	April (2017)	185.6		Artificial Rainfall
	NV_W1	Bare	-		-		
	V_W2	Grass	18	June (2017)	185.6		
	NV_W2	Bare					

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Figure 1. Scheme of the experimental set-up of vegetated column: frontal view. Note: all dimensions are in mm

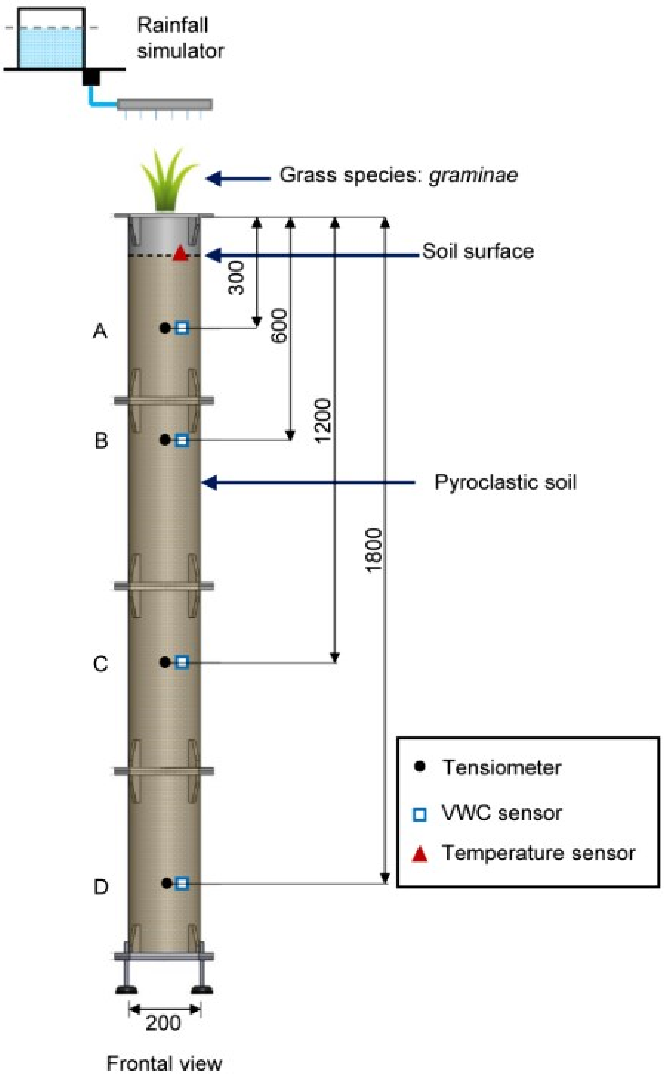

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Figure 2. a) Calibration points for sensors SM100_1, SM100_2, SM100_3 and SM100_4 where η is the output electrical signal, η_a and η_w respectively the lower boundary and the upper boundary, and *VWC* is the fixed volumetric water content; b) measured *VWC* vs η_{rel} and relative fitting curves

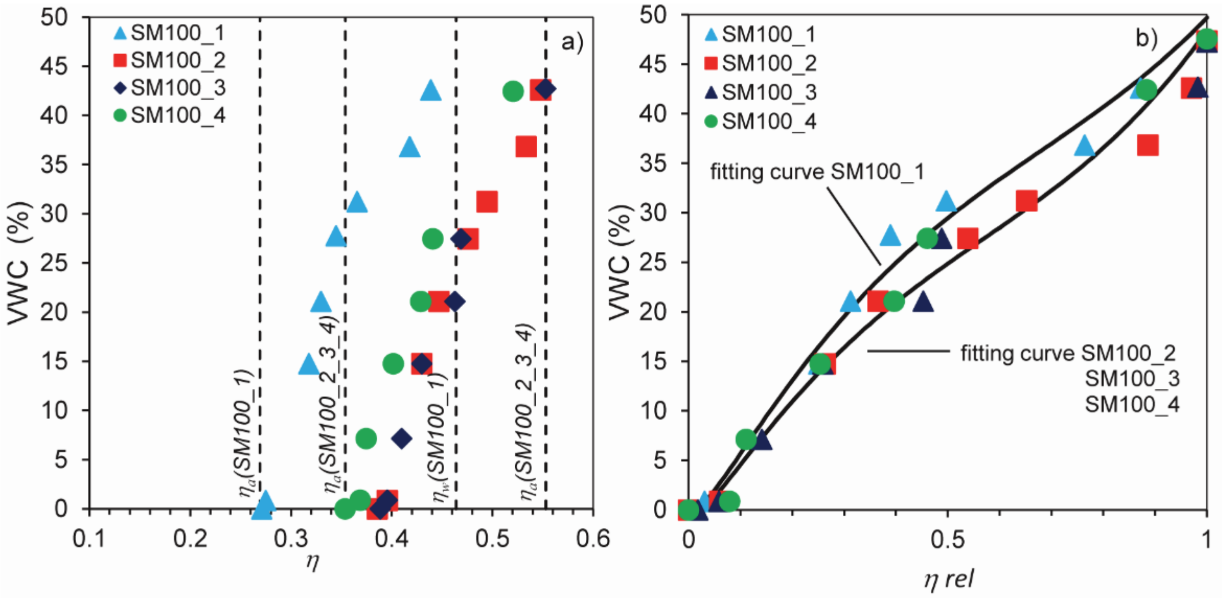

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Figure 3. Root Depth (*RD*) and Height of Foliage (*HF*) with time and b) relationship of *HF* with *RD*recorded during the first vegetative year. The numbers refer to the month: from "0" January 2016 to "12" January 2017. (Capobianco et al., 2018 modified)

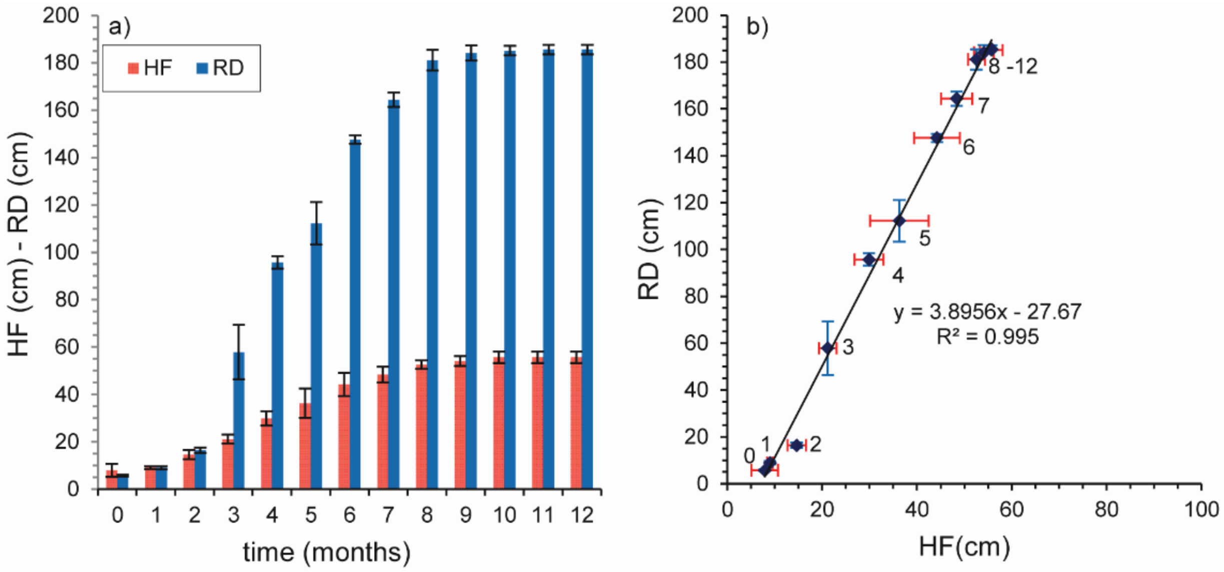

Figure 4. a) Soil suction (*s*) and b) volumetric water content (*VWC*) monitoring data at 4 depths of the *V* column: row A (blue line) at 0.3 m depth, row B (red line) at 0.6 m depth, row C (dark blue line) at 1.2 m depth and row D (green line) at 1.8 m depth. The periods in between two dashed lines are the 15 days of drying tests in the two different seasons of the years. The red arrows fall in correspondence of the two wetting tests

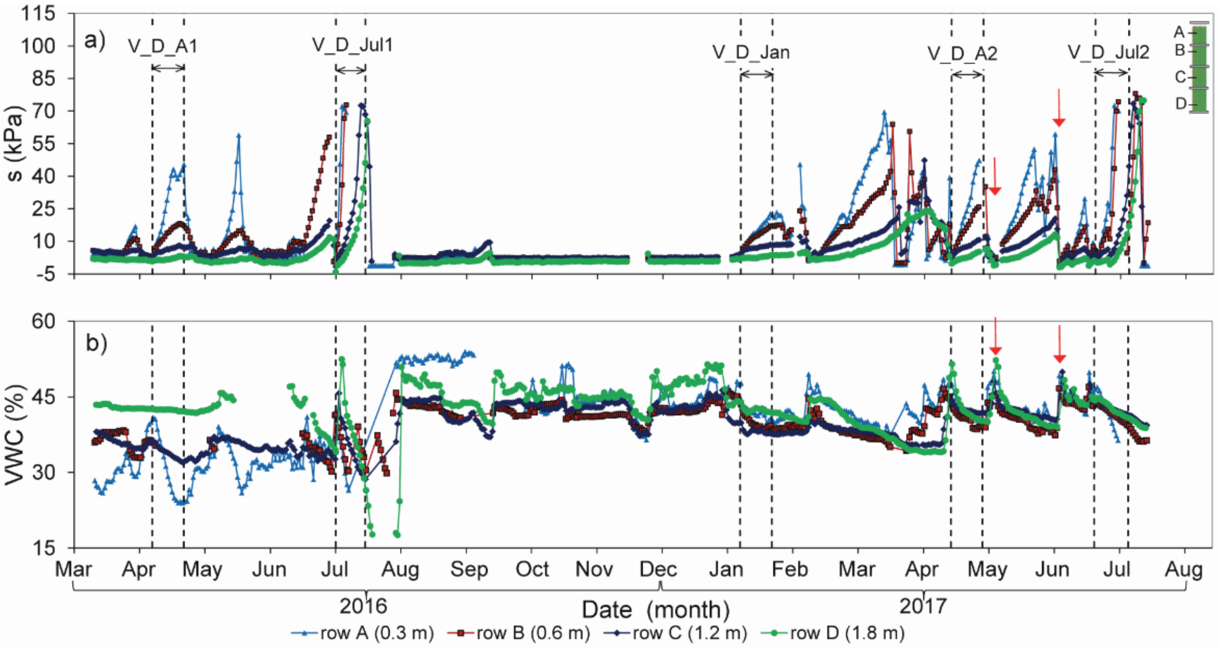

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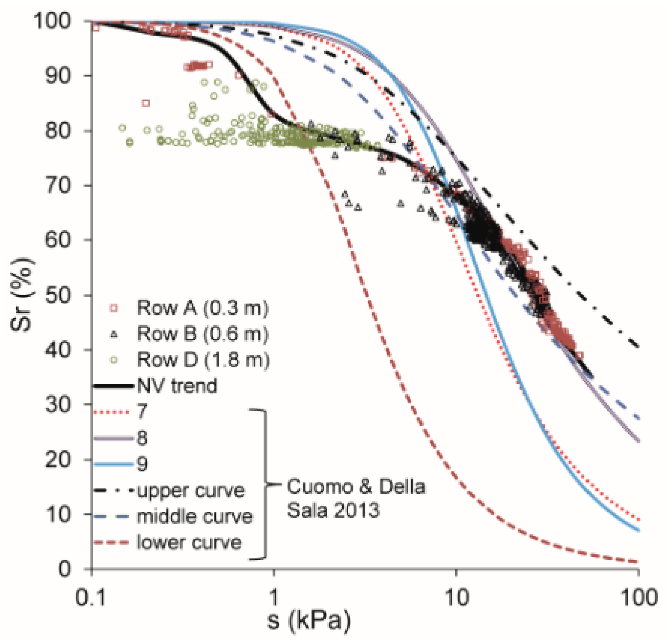
Figure 5. Soil suction (*s)* and Saturation degree (S_r) monitoring pairs for the *NV* column at three different monitoring depths and representative SWRCs from literature (Cuomo and Della Sala, 2013)



ID	n	m	α kPa^{-1}
7	1.90	0.47	0.14
8	1.60	0.38	0.11
9	2.10	0.52	0.11
upper curve	1.30	0.23	0.20
middle curve	1.40	0.29	0.25
lower curve	2.10	0.52	0.50

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Figure 6. *s*-S_r monitoring pairs in the *V* column per month or per group of months respectively at a) 0.3 m, b) 0.6 m, c) 1.2 m and d) 1.8 m depth

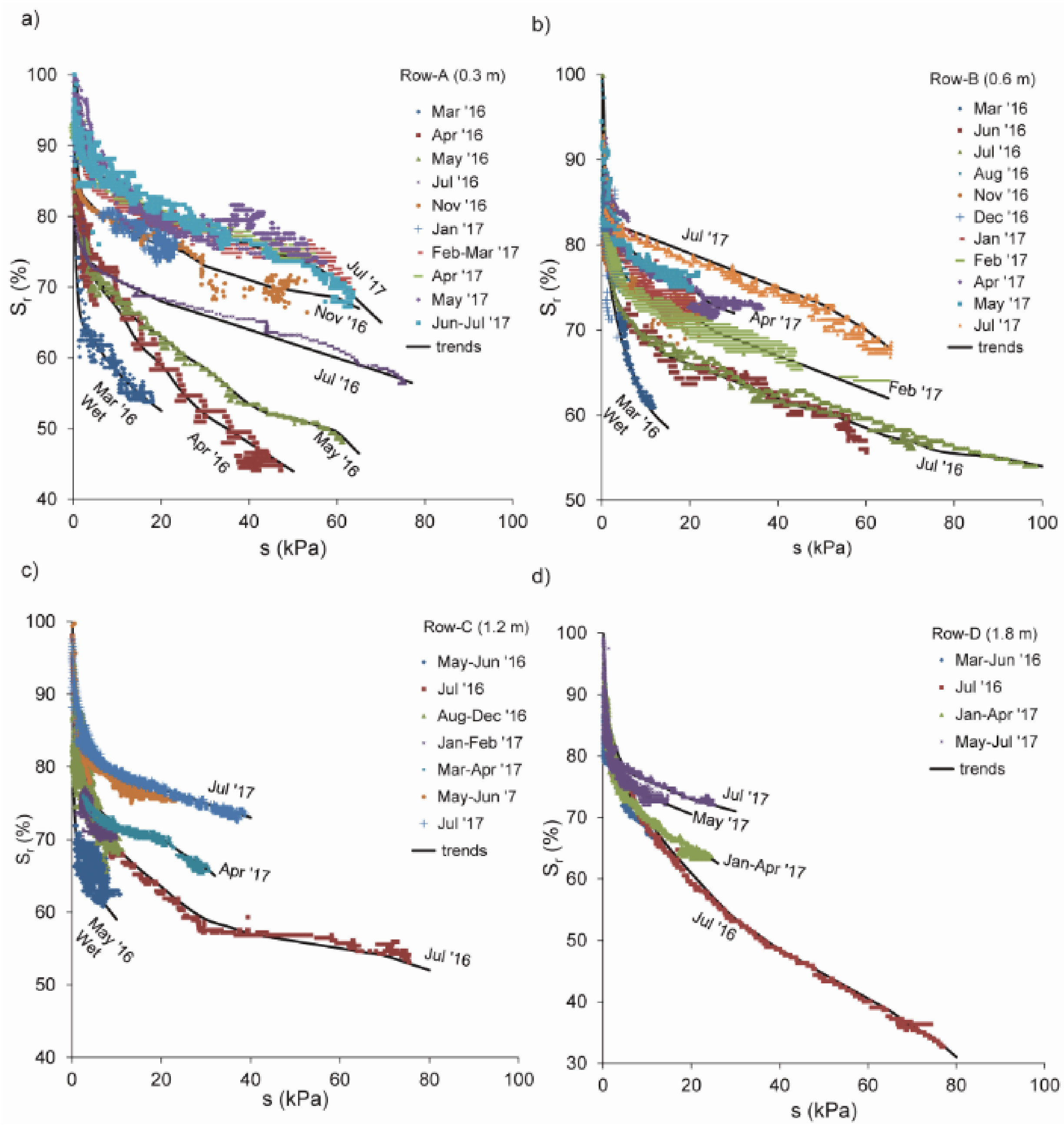

Figure 7. Trend curves of the *V* column for all depths (compared to the trend curve of *NV* column) at three stages: a) beginning, b) middle vegetation growth, c) end of the monitoring period

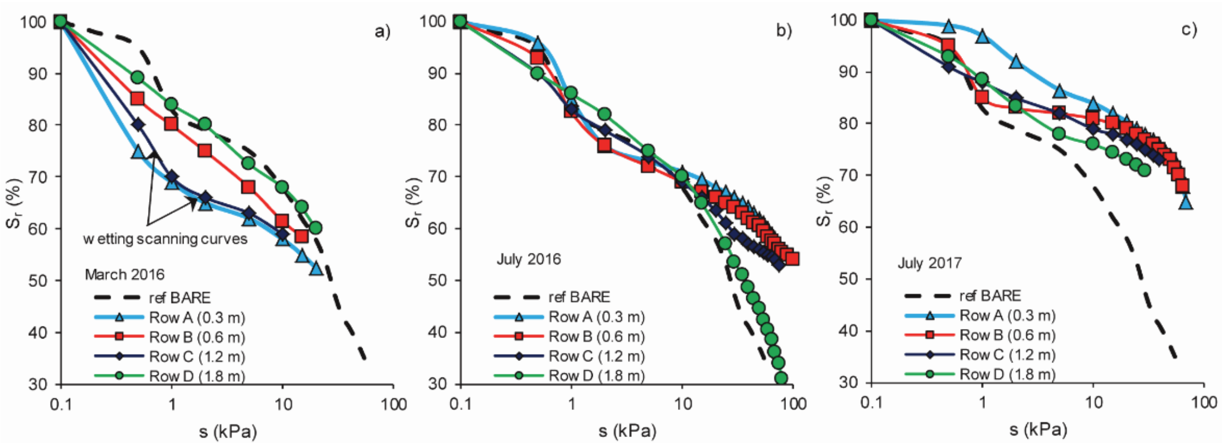

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Figure 8. Daily suction (*s*) vs time for the 15 days drying test in the wet season. a) Drying test on the *NV* column in April (NV_D_A2) with the calculated Potential Evapotranspiration (PET) and Actual Evapotranspiration (AET), b) drying test on *V* column in April 2016 (V_D_A1) and c) drying test for *V* column in April 2017 (V_D_A2) (modified by Capobianco et al., 2018)

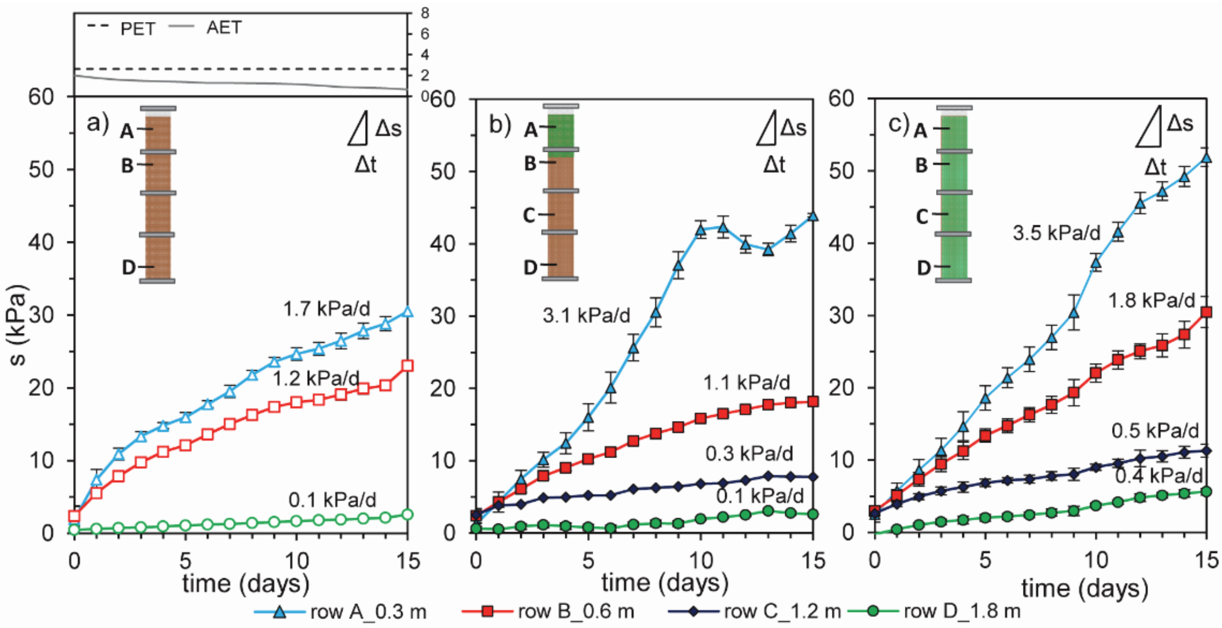

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Figure 9. Daily suction (*s*) vs time for the 15 days drying test in the dry season. a) Drying test on the *NV* column in July (NV_D_Jul2) with the calculated Potential Evapotranspiration (PET) and Actual Evapotranspiration (AET), b) drying test for *V* column in July 2016 (V_D_Jul1) and c) drying test for *V* column in July 2017 (V_D_Jul2)

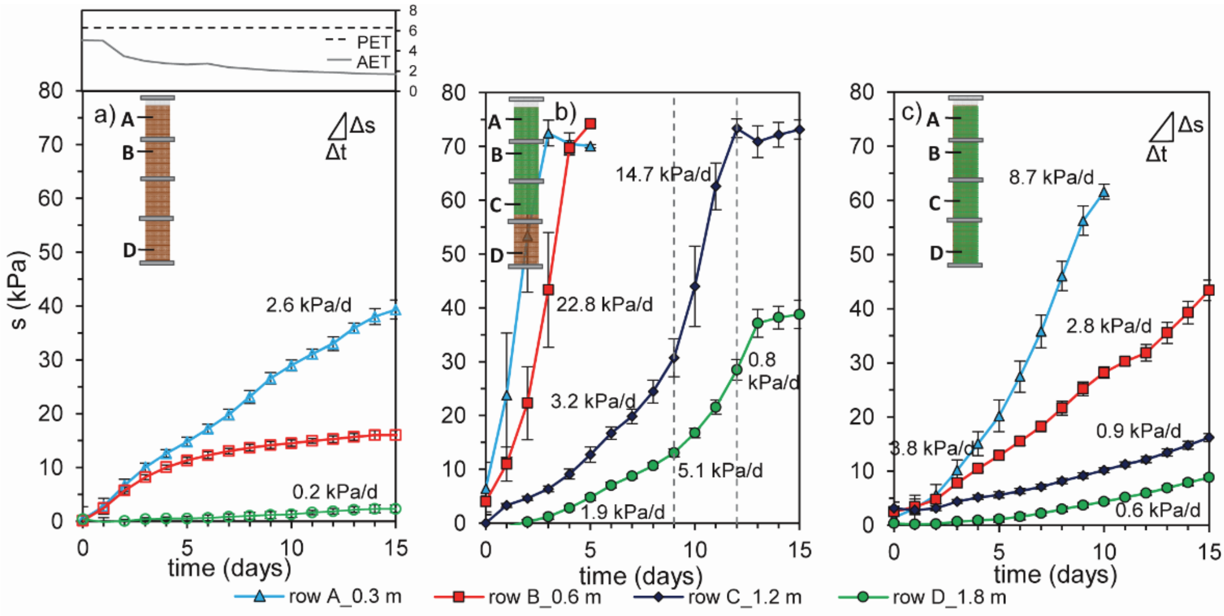

Figure 10. Soil suction (*s*) vs time during applied artificial rainfall in wet season for a) *NV* column (NV_W1) and b) *V* column (V_W1)

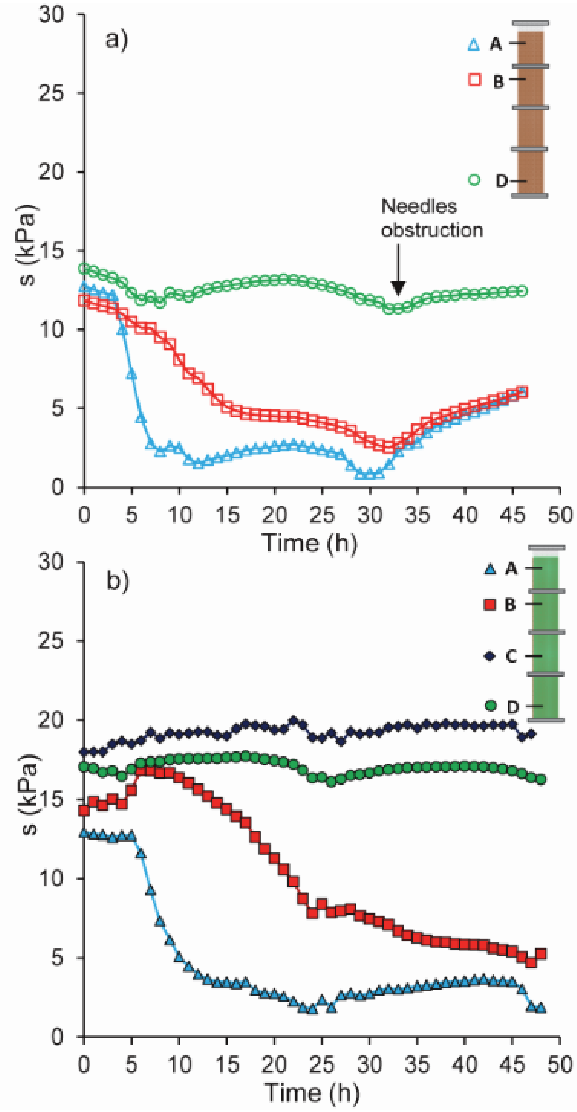

Figure 11. Soil suction profiles with depth respectively at initial conditions and after 3, 6, 9 and 12 hours of applied rainfall in wet season, for a) *NV* column and b) *V* column

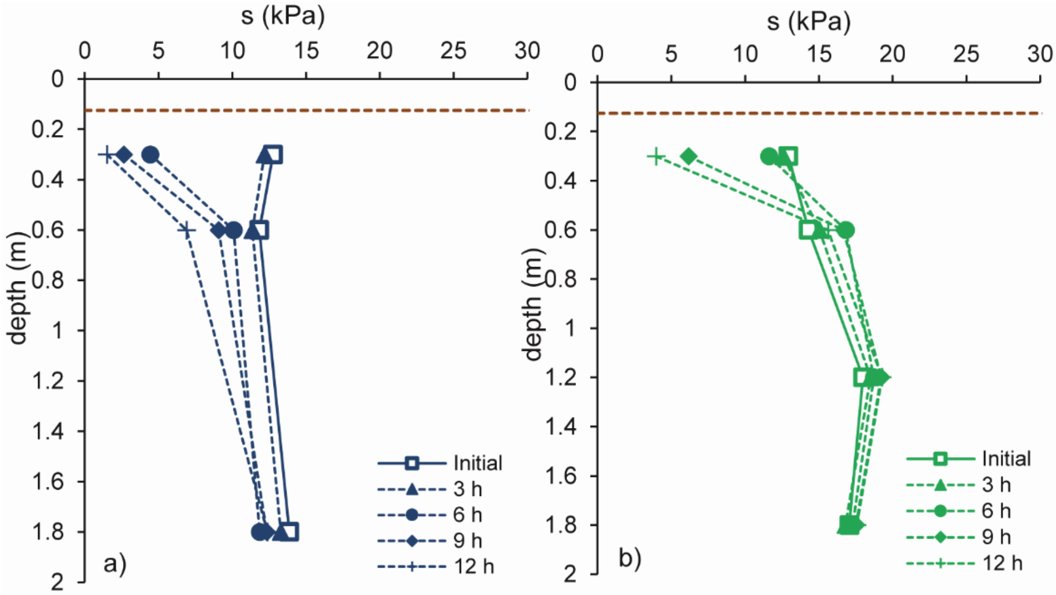

Figure 12. Soil suction (*s*) vs time during applied artificial rainfall in dry season for a) *NV* column (NV_W2) and b) *V* column (V_W2)

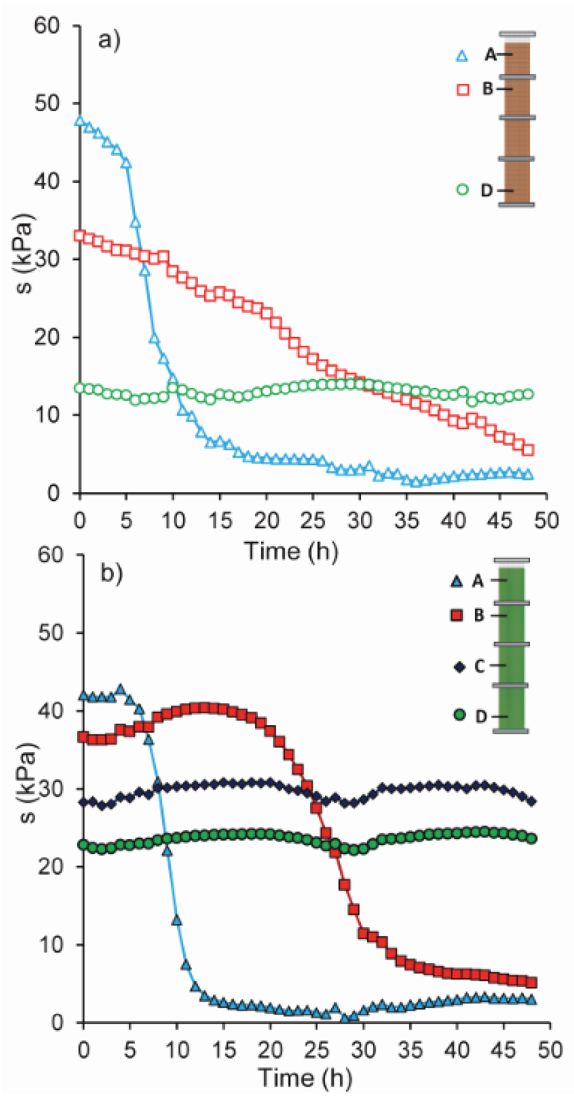

Figure 13. Soil suction profiles with depth respectively at initial conditions and after 3, 6, 9 and 12 hours of applied rainfall in dry season, for a) *NV* column and b) *V* column

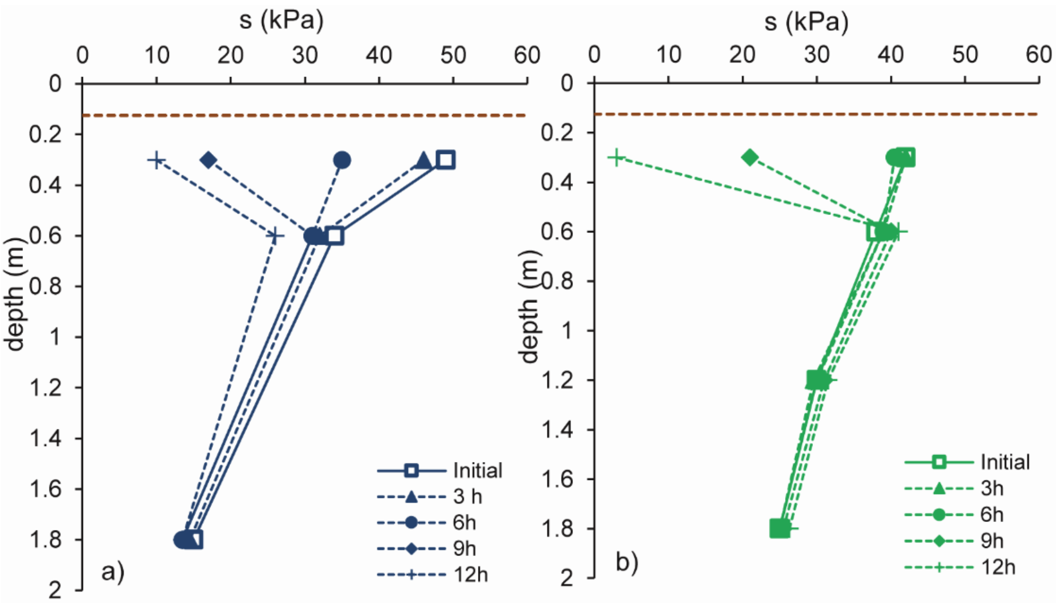

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Figure 14. Soil suction in *V* column vs soil suction in *NV* column after a) 5 days of drying and b) 10 days of drying in both wet and dry season of the second year

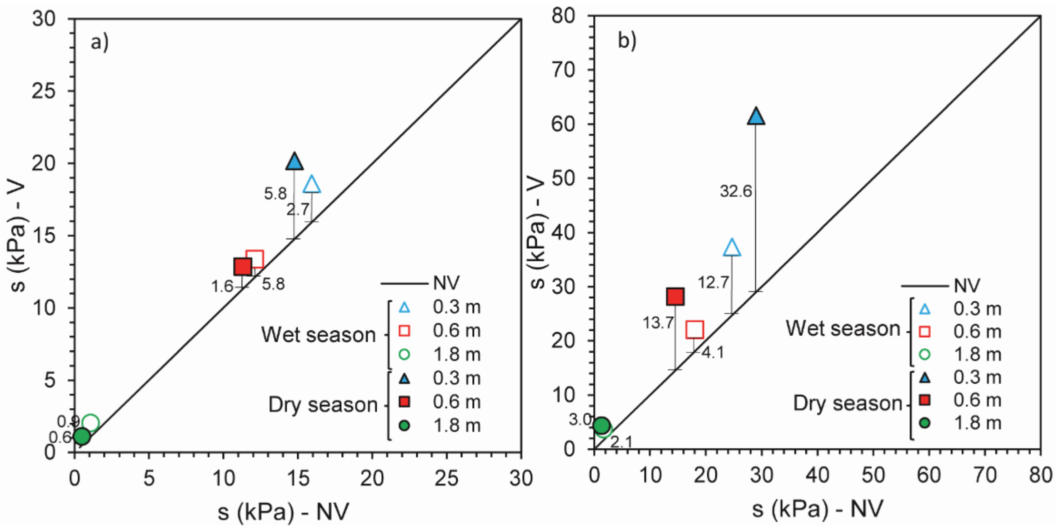

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Figure 15. Hydraulic head profiles with depth every 3 hours of applied rainfall for a) *NV* column and b) *V* column in wet season and c) *NV* column and d) *V* column in dry season. The horizontal dashed line indicates the soil surface

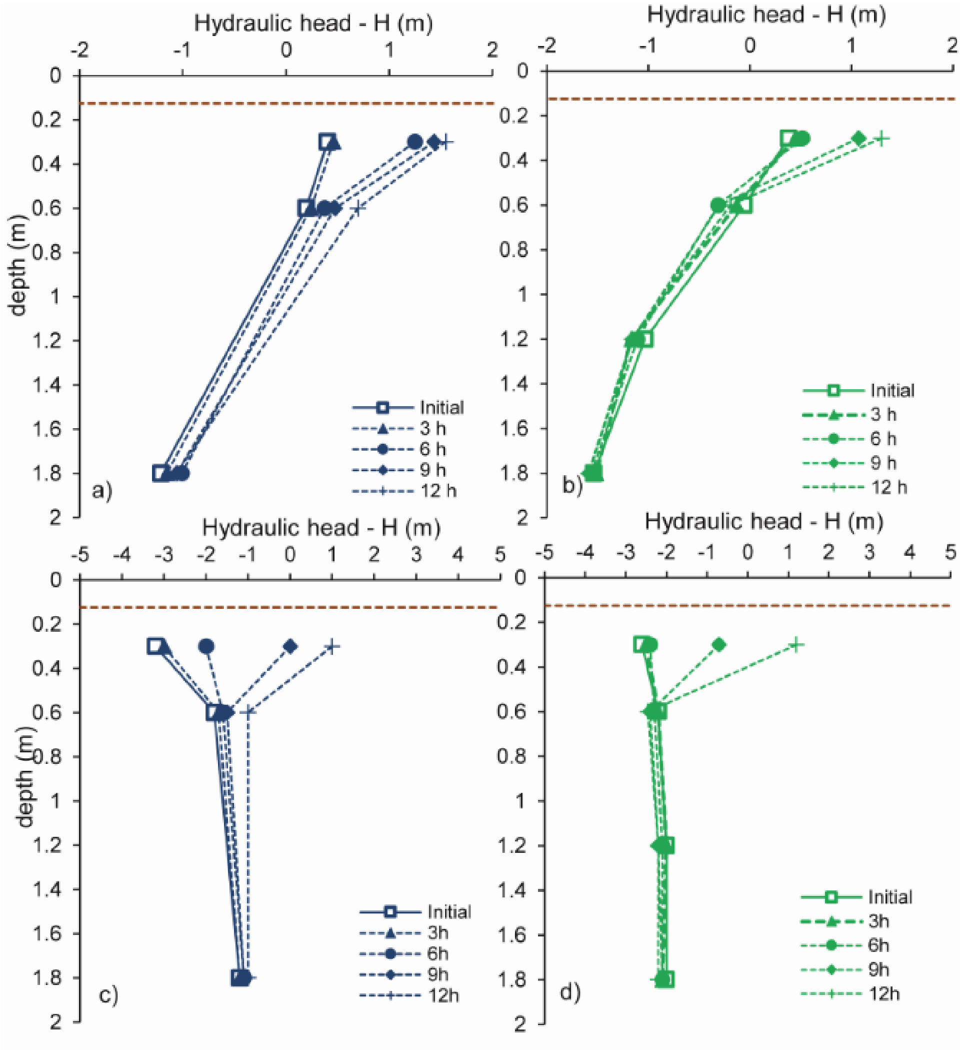

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Figure 16. Monthly average suction in *V* column and final suction values measured after the drying tests at all depths