Water uptake by date palm on Haplic Luvisols in the Djibouti coastal plain

Hami Saïd, Yves Coquet

Accepted Manuscript

Water uptake by date palm on Haplic Luvisols in the Djibouti coastal plain

Hami Saïd Ahmed, Yves Coquet

PII:	S2352-0094(18)30043-9
DOI:	doi:10.1016/j.geodrs.2018.e00189
Article Number:	e00189
Reference:	GEODRS 189
To appear in:	*Geoderma Regional*
Received date:	13 February 2018
Revised date:	25 August 2018
Accepted date:	30 August 2018

Please cite this article as: Hami Saïd Ahmed, Yves Coquet , Water uptake by date palm on Haplic Luvisols in the Djibouti coastal plain. Geodrs (2018), doi:10.1016/j.geodrs.2018.e00189

Water uptake by date palm on Haplic Luvisols in the Djibouti coastal plain

Hami Saïd Ahmed[a], Yves Coquet[b,*]

[a]Soil Department, CERD - Centre d'étude et de recherche de Djibouti, BP486, BP2241, Ministère de l'Enseignement Supérieur et de la Recherche (MENSUR), Djibouti.

[b]ISTO – Institut des Sciences de la Terre d'Orléans, UMR 7327 Université d'Orléans, CNRS, BRGM, 1A rue de la Férollerie, 45071 Orléans cedex 2, France.

Abstract

Date palm tree (*Phoenix dactylifera* L.) has been cultivated since Anquity under arid and semi-arid climates. This symbolic oasis plant is an important resource for valuing water resources in harsh environments. The Djibouti Republic sustains the expansion of date palm cultivation as a way to settle nomad populations and fight hunger but lacks local references on date palm tree water requirements. This paper establishes the first set of reference data on date palm tree water uptake under the pedoclimatic conditions of Djibouti using an original setup. Date palm tree water uptake was estimated by modelling a succession of 3 infiltration-redistribution experiments, first in the presence of the palm tree, then under bare soil condition, and finally with a no-flow condition at the soil surface. The no surface flow (internal drainage) experiment allowed estimating soil hydraulic parameters, which were then used to simulate the other two experiments including soil evaporation or palm tree evapotranspiration, respectively. Actual evapotranspiration was estimated to 5.6 mm/d between February and April that is during the mild season in Djibouti (25-28 ° C). The corresponding daily water uptake was 60 L/d/tree. Daily irrigation need was calculated as 125

* Corresponding author: yves.coquet@univ-orleans.fr, tel. + 33 2.38.49.49.68

L/d/tree assuming a leaching fraction of 40%, which is 4 times smaller than current recommendations. However, calculated daily irrigation need reached nearly 300 L/d/tree in the hot season. Additional studies are needed to confirm this estimation. Reducing the irrigation doses currently in use could lead to precious water savings, given the high pressure put on water resources in the Djibouti district.

Keywords: Water requirements; *Phoenix dactylifera* L.; Evapotranspiration; Fluvisol; Neutron probe; Internal drainage; HYDRUS-1D

1. Introduction

Date palm tree (*Phoenix dactylifera* L.) is an essential resource for the populations living in semi-arid and arid environments. This majestic plant has been cultivated for more than 4 millenia for its date fruits (Munier, 1973). Increasing population, shortage of fresh water resources related to climate change, volatility of food prices are major issues in Sub-Saharan Africa, and the Djibouti Republic is no exception (FAO, 2005). Recurring droughts in these last years have moved rural populations toward the capital city of Djibouti leading to an increased social pressure on an already-vulnerable suburban population (WAP, 2012). To face this situation, the government of the Djibouti Republic sustains the expansion of date palm cultivation with the double objective of encouraging the settlement of nomad populations and fighting hunger. A first step in this strategy was the setup of a successful research program on in vitro multiplication of date palm tree (Daher et al., 2015). The implementation of date palm tree groves implies also the mentoring of the agronomic characteristics of the date palm tree by farmers. Among them, knowledge of the water requirements is essential.

According to an Arabic adage, ‘the palm tree lives with its feet in the water and its head in the fire of the sky’. In other words, the date palm tree is well adapted to a very dry atmosphere and strong sunshine as long as its water requirements are met. Date palm tree water requirements have been studied under various climate conditions using different methods. Saeed et al. (1986) and Mazahrih et al. (2012) have been using neutron probe measurements to study the water uptake of date palm trees in Saudi Arabia and the Jordan Valley, respectively. Mazahrih et al. (2012) estimated an annual water requirement of 53 m^3 per tree per year. Sellami and Sifaoui (2003) used sap flow measurements to estimate daily actual transpiration of date palm tree in an Oasis of Southern Tunisia (Tozeur), and found an average value of 1.9 mm/d for the Autumn period. Tripler et al. (2007, 2011, 2012) used weighing lysimeters to measure the water uptake of juvenile date palms in the Southern Arava region of Israël for various salinity concentration levels. Sperling et al. (2012) used the same set-up to validate estimations of date palm tree transpiration by sap flow measurement. Haj-Amor et al. (2016) used the HYDRUS-1D model (Šimůnek et al., 2016) to estimate the actual transpiration of date palm trees in Tunisia. The model was calibrated on soil water content measurements made using TDR probes. They found an average value of date palm tree actual evapotranspiration of 3.8 mm/d for the 2013 year. Askri et al. (2014) used also HYDRUS-1D to estimate date palm tree actual evapotranspiration in the same region, but relied on sap flow measurements for calibration. Actual daily transpiration rate of the date palm grove was found to vary between 0.3 and 6.8 mm/d during the 2006-2007 agricultural year for a water table at 1-m depth with an average of 2.2 mm/d. Sabri et al. (2017) evaluated undersupplying irrigation strategies for date palm in Morocco. They showed that the current irrigation strategy of farmers (69.6 m^3/y/tree) was largely above the water requirements of the date palm trees (50.4 m^3/y/tree).

No scientific data is available regarding the water requirement of date palm tree in the specific pedoclimatic context of Djibouti except for one evaluation based on reference evapotranspiration (Peyron, 2000). This study estimated that a 1-ha date palm grove located at Ambouli in Djibouti Town would need 13.000 m^3 of fresh water per year.

The objective of the study was to establish a first set of reference data on date palm tree water requirements under the specific climate conditions of Djibouti. As methods for measuring date palm tree evapotranspiration such as eddy covariance or sap flow methods could not be afforded, we used a more drastic one by measuring the soil water balance before and after palm tree removal. Three infiltration-redistribution experiments were performed successively, first in the presence of the palm tree, then under bare soil condition, and finally with a no-flow condition at the surface of the soil. The various terms of the soil water balance could then be quantified by modelling the three experiments.

2. Materials and Methods

2.1 Study site

The study has been performed in a 3.5 ha date palm grove located in the Damerjog village (11°29'01.12''N, 43°11'50.39''E) on the coastal plain 15 km south of Djibouti town. The cultivated date palm trees are of the Barhi cultivar. The date palm grove was set up in 2004. The date palm tree used in this experimentation was chosen for its representativity of the date palm grove. It was 10 years old at the time of the experiment.

The local climate is arid with a mean annual temperature of 31.3°C and daily temperatures reaching 39°C during the hot season. Mean annual solar radiation and relative humidity are 162.8 $W.m^{-2}$ and 52.4 %, respectively. Mean monthly potential evapotranspiration is 161.3 mm. Low annual rainfall is recorded at the study site (e.g., 71 mm in 2013).

The terrain of the coastal plain is made of recent (≤ 1My) fine sedimentary deposits of marine origin, mainly sandy or clayey alluvium and madrepores (Jalludin and Rasack, 2004; Bouh, 2006). These sedimentary deposits are very suitable for agriculture. The soil is a Haplic Fluvisol according to the WRB. Its profile is heterogeneous with a sand texture in the top 90 cm and a loamy texture below 100 cm (Table 1). The soil bulk density profile is quite homogeneous except the 20-30 cm depths that have lower values.

A large pit (240 cm wide and 200 cm deep) was dug at the foot of the palm tree stem after the end of the experiments. A 20 cm-mesh grid was applied to the vertical face of the pit located below the tree and the number of root impacts counted in each cell of the grid (Böhm, 1979). All roots were counted whatever their size. The Surfer® 10 software was used to build a root density map using kriging interpolation.

2.2 Experimental set-up

For the calculation of reference evapotranspiration ET_0 by the Penman-Monteith-FAO method (Allen et al., 1998), it is necessary to know several climatic parameters: air temperature, solar radiation, air humidity, and wind speed. To measure all these parameters, a WatchDog model 2900ET 2000 series weather station (Technologies Spectrum, Inc., Illinois, USA) was installed in the palm grove. The measurements were acquired every 30 min, transferred to a computer via an AUX port and processed through the Specware 9 Pro version 9.03 software (Spectrum Technologies, Illinois, USA). Climate was monitored from January 2013 to June 2014 (Table 2).

Six neutron probe access tubes down to a depth of 160 cm and 25 tensiometers from 10 to 150 cm depth have been put in place in the soil in a radial pattern around the date palm tree (Fig. 1). The closest access tube and tensiometers to the palm tree were located just at the foot of the palm stem, i.e. 40 cm from the center of the irrigation pond. The diameter of the palm tree was around 80 cm at its junction to the soil surface. The farthest access tube and tensiometers were located 2 m from the center of the irrigation pond, i.e. 1.6 m from the palm stem, in the ridge delimitating the pond. The deepest access tube was chosen to monitor soil water content given that only one access tube could be monitored during infiltration. Measurements were performed every 10 cm from 10 to 160 cm depth with a CPN® 503 neutron Hydroprobe (CPN, California, USA) with an Americium-241/Berylium radioactive source of 50 mCi (1.85 GBq) activity. For matric potential, the tensiometer whose behavior was closest to the mean behavior of all the tensiometers installed at the same depth was selected. Tensiometers (SDEC, France) were installed vertically from the soil surface at 10, 20, 30, 40, 60, 100, and 150 cm depths, filled with de-aerated water, and sealed with a neoprene stopper, allowing for the insertion of a movable pressure transducer system (SMS 2500S, SDEC, France) to measure soil water pressure head with a 1-cm precision.

2.3 Experimentations

Three successive in situ infiltration experiments have been performed to characterize palm tree water uptake: an internal drainage experiment, a bare soil experiment and an experiment with palm tree. The internal drainage experiment will allow the determination of the soil hydraulic properties (Hillel et al., 1972). The comparison of the bare soil experiment with the internal drainage experiment will allow the quantification of soil evaporation. Finally, the comparison of the palm tree and bare soil experiments will allow the quantification of the palm tree water uptake. The 3 experiments have been performed at the same site, starting with the palm tree experiment. The palm tree was then cut off and the bare soil experiment performed. The infiltration was then repeated and the soil surface sealed with a plastic sheet to prevent any water flux at the soil surface during the internal drainage experiment.

For the palm tree experiment, water was brought to the soil as a 10 cm-thick layer the 27/2/2014 from 10:00 a.m. (T_0) to 11:30 p.m. (T_f). Soil water content and pressure head were measured every 30 min during the irrigation phase and up to 1/3/2014, and then every day from 2/3/2014 up to 2/4/2014 10:00 a.m. The infiltration period lasted 13h and 30 min and was followed by 32 days of soil water redistribution. Details of the irrigation are given in Table 3 as several water inputs were needed to maintain ponding at the soil surface.

The same infiltration and redistribution processes were then monitored under a bare soil surface condition without palm tree. Measurements started 25/4/2014 at 11:00 a.m. and stopped at 29/5/2014 10:00 a.m.. Irrigation started 25/4/2014 at 11:01 a.m. (T_0) and ceased at 11:05 p.m. (T_f). Measurements were taken every 30 min up to 27/4/2014, and then on a daily basis from 28/4/2014 to 29/5/2014. The infiltration period lasted 12 h and 4 min followed by 32 days of soil water redistribution.

Finally, infiltration and redistribution were monitored again during an internal drainage experiment from 6/6/2014 10:00 a.m. to 10/7/2014 10:00 a.m.. Irrigation took place the 6/6/2014 from 10:15 a.m. (T_0) to 11:05 p.m. (T_f). Neutron probe and tensiometer readings have been taken every 30 min up to 8/6/2014 and then on a daily basis from 9/6/2014 to 10/7/2014. The infiltration period lasted 13 h and 5 min followed by 33 days of soil water redistribution.

2.4 Modelling

Water transport in the soil–date palm tree-atmosphere continuum was simulated using HYDRUS-1D (Šimůnek et al., 2016). Initial values of the soil water retention parameters were determined from soil water retention curves measured in the laboratory on undisturbed soil cylinders using Richards's apparatus. Saturated hydraulic conductivities were estimated by Rosetta's pedotransfer functions (Schaap et al., 2001) based on measurements of particle size fractions, bulk density, and water content at -330 and -15,000 cm matric potentials. The hydraulic parameters of each soil material were then optimized successively (Hopmans et al., 2002) using the field monitoring data of the internal drainage experiment starting with the bottom layer upwards and again until no further improvement in the objective function. Soil hydraulic parameter values were then fixed and the bare soil experiment was simulated using the measured meteorological data. The simulated dynamics of soil evaporation was compared to field measurements. Finally, the last experiment including date palm tree transpiration was simulated, using the observed palm tree root distribution, and the soil water profile data was compared to model outputs. The parameters of the Feddes et al. (1978) water stress function were taken from Kroes and van Dam (2003) (deciduous fruit). This final experiment allowed calculating the palm tree water uptake during the experiment.

3. Experimental results

3.1 Date palm tree root density

Maximum root density was found between 0 and 80 cm depth. Nutrition and absorption roots could not be distinguished (Fig.2). A high root density was measured in the first 50 cm of the soil profile with values larger than 27 roots/4 dm^2 at the foot of the stem (Fig. 2 and 3). Root density decreases rapidly below this zone to values smaller than 4 roots/4 dm^2 below 80 cm depth. First-order root (auxirhyze) density may reach values up to 40 roots/4 dm^2 for nutrition roots and 8 roots/4 dm^2 for absorption roots (Oihabi, 1991; Djerbi, 1994; Daddi-Bouhoun, 2010).

3.2 Date palm tree experiment

At the beginning of the experiment (T_0), the soil was quite dry with a matric head between -320 and -630 cm (Fig. 4b). The matric head variations observed in the profile highlighted the heterogeneity of the soil related to the stratification of the alluvium. They may also be due to technical problems such as a non-homogeneous stabilization of the water pressure in the tensiometers that were purged just before the start of the experiment. The water content profile at the beginning of the experiment varied from 0.12 at the 10 cm depth to 0.30 $cm^3.cm^{-3}$ at the 160 cm depth (Fig. 4a) reflecting the higher water retention capacity of the deep layers, which is consistent with their finer texture (Table 1).

Hydraulic head profiles indicate that the infiltration front was located between 60 and 100 cm in depth at the end of irrigation T_f (Fig. 4b) while water content profiles show that the infiltration front reached the 90 cm depth (Fig. 4a). In the deeper soil between 100 and 160 cm, no change in water content was observed during the infiltration phase.

Four hours after the end of irrigation (T_f+4h), the soil hydraulic head (*H*) profile began to move away from the gravitational potential line in the topsoil (Fig. 4d). The tensiometer at 100 cm no longer gave reliable values from T_f+1d on. The *H* gradient between 10 and 60 cm remained close to zero from T_f to T_f +4d, which means that no vertical water flux happened at that time. However, the water content in the same layer was rapidly decreasing in the same time (Fig. 4c) due to root water uptake by the palm tree. Water content decreased in the topsoil (0-70 cm depth) from the end of infiltration (T_f) on while it continued to increase in the lower part of the soil (below the 100 cm depth) up to 4 days after the end of infiltration (T_f+4d) due to water redistribution within the soil profile. At the end of the experiment, all tensiometers had disconnected because of the increasing soil dryness except at the 150 cm depth where the tensiometer still gave values.

3.3 Bare soil experiment

By the end of the infiltration (Tf), the infiltration front was a bit deeper (Fig. 5a) than in the palm tree experiment (Fig. 4a). This result could be related to the absence of water uptake by the palm tree during the infiltration process.

The soil hydraulic head profile began to move away from the gravity potential line in the topsoil (10 to 60 cm depth) right after the end of the irrigation (T_f+4h) (Fig.5d), while soil water content declined at the 10 and 20 cm depths (Fig. 5c). It can be seen from Fig. 5c vs. Fig. 4c that water content variations during the redistribution phase are much small between the 30 and 90 cm depths in the bare experiment than in the palm tree experiment. This difference clearly exemplifies the role of the palm tree water uptake in the soil water dynamics.

Comparing the water content profiles at initial time (T_0), end of irrigation (T_f) and end of experiment (T_f+32d) for the scenario without palm tree (Fig. 6a) and the scenario with palm tree (Fig. 6b), we note that at the end of the experiment without the palm tree, the water content profile did not returned to its initial state, while it did for the experiment with palm, except below the 90 cm depth. In this upper part of the soil profile, the water brought by irrigation was exhausted by root absorption in the palm tree experiment. This is indeed in this part of the profile that the most important root densities were located (Fig. 3).

3.4 Internal drainage experiment

The soil hydraulic head profile (Fig. 7b) shows that the soil profile was relatively wet at the beginning of the experiment (T_0). This wet initial condition was due to the fact that the preceding experiment (under bare soil) left a wetter soil than the previous one (with palm tree) (Fig. 6). As a result, the infiltration front moved much more quickly within the profile and reached the bottom depth at the end of irrigation (Tf) (Fig. 7a,b).

Four hours after the end of irrigation (T_f+4h), the hydraulic head profile started to move away from the gravity potential line in its upper part (above the 60 cm depth) while remoistening took place in the lower part of the profile (Fig. 7d). The whole hydraulic head profile was then almost parallel to the gravity potential line, indicating a gravity flow in the whole profile. These variations of the soil water status are less sensible in the water content profile (Fig. 7c). This can be explained by a higher sensitivity of tensiometers to water status variations close to saturation compared to the neutron probe. Hydraulic head gradient dH/dz was very low near the surface of the soil during the redistribution phase (Fig. 7d), which confirms the no-flux condition imposed at the soil surface. It started to become slightly negative after Tf+3d, which can let think that the plastic tarp used to maintain a no-flux condition at the top of the soil was not perfectly tight. Guehl (2010) was faced with the same situation. Thirty-two days after the end of irrigation, the soil profile returned to its initial state (Fig. 7a, c), to the difference of what was observed for the bare soil experiment (Fig. 6a).

4. Modelling

4.1 Internal drainage experiment: characterization of the soil hydraulic parameters

The soil profile was discretized into 9 layers (Table 4) according to observed water content dynamics (Fig.4-7). A specific top layer (0-5 cm) had to be added in order to be able to simulate properly the dynamics of infiltration. The dynamics of soil water observed in the internal drainage experiment could not be described using the hydraulic properties measured in the laboratory or estimated using Rosetta's PTFs (Fig. 8) (R^2 smaller than 0.25). The inability of laboratory-derived hydraulic parameters to describe actual soil behavior in the field has been shown by several authors (e.g., Mermoud and Xu, 2006; Chalhoub et al., 2013).

After optimization of the soil hydraulic parameters, the variations of the measured soil water content and pressure head were satisfactorily simulated with R^2 ranging from 0.74 to 0.96 (Fig. 9).

Values of the saturated water content, θ_s, were generally lower (Table 4) than those measured in the laboratory or estimated as 90 % of the soil porosity calculated from the bulk densities measured in situ (Table 1). Most of the optimized residual water contents were found different from zero (Table 4). Optimization of the Mualem tortuosity parameter, *l*, was essential to get proper simulations.

Most of the infiltrated water drained from the soil profile during the experiment (255 out of 298 mm). The difference corresponds to an increase of the soil water storage from 453 to 496 mm. This behavior can be explained by the fact that the soil was already quite wet at the start of the experiment (Fig. 7b). The internal drainage experiment has been performed after the bare soil experiment, where the soil was submitted only to evaporation after rewetting of the upper part of the soil profile by infiltration (Fig. 5).

4.2 Bare soil experiment: quantification of soil evaporation

The hydraulic parameter values obtained after optimization on the data of the internal drainage experiment allowed a good representation of the soil water content and pressure head dynamics under evaporation with R^2 values ranging from 0.52 to 0.98 (Fig. 10). The lowest R^2 values were found for the 10 cm depth, where the model tended to underestimate pressure head during redistribution, while it overestimated it at the 150 cm depth. At this last depth, the model simulated an arrival of the infiltration front earlier than that actually measured. Given that no optimization of the soil hydraulic parameters was done on this new set of data, the results of the simulation can be considered quite satisfactory and give some confidence in both the values of the hydraulic parameters obtained from the internal drainage experiment and the ability of HYDRUS-1D to simulate soil evaporation properly.

Over the 294 mm of water infiltrated during the course of the bare soil experiment, 18 % (54 mm) left the soil though evaporation and 54 % (158 mm) through drainage at the bottom of the soil profile. In the meantime, the soil water storage increased by 82 mm. The lower drainage observed in the bare soil experiment compared to the internal drainage experiment can be explained not only by the fact that some of the infiltrated water was returned to the atmosphere as evaporation, but also by the fact that the soil profile was drier at the start of the experiment (Fig. 6a). By the end of infiltration, water had reached the bottom of the soil profile in the internal drainage experiment (Fig. 7a) while it reached only the 100 cm depth in the bare soil experiment (Fig. 5a).

4.3 Date palm tree experiment: quantification of root water uptake

The soil water content and matric head were well simulated given that no further optimization had been performed either on the soil hydraulic parameters or on those impacting soil evaporation or palm tree transpiration (Fig. 11). Only the observed root density distribution was accounted for as specific data. The simulations were surprisingly good in the upper part of the soil, down to the 60 cm depth, where R^2 remained larger than or equal to 0.80. They were less good at the 100 and 150 cm depths. The simulation gave an R^2 of 0.38 for matric potential at the 100 cm depth because of the lack of data due to a technical failure of the tensiometer (Fig. 4d). During the redistribution phase, the model predicts larger water content variations than observed at that depth (Fig. 11). At the 150 cm depth, the model predicts a much earlier arrival of the infiltration front than observed and overestimates water content.

A slightly higher quantity of water was infiltrated (316 mm) in the date palm tree experiment than in the other two experiments (Table 3). In presence of the palm tree, soil evaporation was reduced to less than half of that observed in the bare soil experiment (23 mm vs. 54 mm). This can be explained by the interception of radiation by the canopy of the palm tree before it reaches the soil surface. Potential soil evaporation in the experiment with the palm tree was calculated to be 126 mm, while it was 193 mm for the bare soil experiment. Further, the large difference between the real (23 mm) and the potential evaporation (126 mm) highlights the mulching effect of the dry upper soil that limits soil evaporation (Brisson and Perrier, 1991). Forty one percent (131 mm) of the infiltrated water had drained at the end of the date palm tree experiment, while soil water storage was reduced by 11 mm. At that time, the combined effect of drainage, soil evaporation and root water uptake had exhausted the soil water reserve. The palm tree was not in hydric comfort anymore 17 days after the end of irrigation. By the end of the experiment, the actual cumulated transpiration of the date palm tree was 170 mm for a potential transpiration of 200 mm. Using the root water uptake compensation option in HYDRUS-1D led to a much later entry of the palm tree in water stress (28 days after the end of irrigation), and a larger palm tree transpiration (198 mm).

5. Discussion

The depth of the maximum root density zone (Fig. 3) was small compared to those described by Munier (1973), Djerbi (1994) et Peyron (2000) who found a value of 1 m for nutrition roots up to 2 m for absorption roots (Fig. 2b). Palm tree rooting depth is influenced by multiple factors such as cultivation practices, water availability, and cultivar type (Peyron, 2000). Daddi-Bouhoun (2010) observed a small root depth (61 cm) in an Algerian palm grove because of a petrogypsic horizon located between the 46 and 120 cm depth. Water table depth was also found to influence palm tree rooting depth. No mechanical obstacle or water table was present in the soil profile that we studied. The shallow root depth that we found was probably linked to the irrigation practices used in the palm grove. Allam et al. (1973) found that most of palm tree water absorption was localized between 60 and 150 cm depth where 95 % of the absorption roots were found. Irrigation in the grove that we studied is applied with a high frequency, which probably puts the palm tree roots in hydric comfort down to the 80-cm depth.

Actual evapotranspiration of the date palm tree was estimated to 5.6 mm/d in our experiment. It was estimated to 4.5 mm/d under the climate conditions of Saudi Arabia (Kaseem, 2007). Under the warm and arid climate conditions of Koweit, daily actual evapotranspiration was found to vary between 2.72 and 14.21, 2.05 and 11.66, and 2.46 and 14.62 mm, for the Siwi, Nabusaif and Khalas cultivars, respectively (Bhat et al., 2012). Daily palm tree transpiration was estimated to 4.8 mm in our experiment. Values measured in Tunisia using the sap flow method vary between 0.2 and 3.5 mm (Ben Aïssa et al., 2009). Sellami and Sifaoui (2003) established an empirical relationship between transpiration and net radiation. They found that the transpiration of the date palm trees plus the apricot trees composing the grove represented 86 % of the net radiation. Other authors found similar values for forest canopies (Tournebize, 1994; Granier and Loustau, 1994; Diawara et al., 1991). In our study, daily net cumulated radiation was 18.3 MJ/m^2 and palm tree transpiration represented 75 % of it, which is in between what was found by Sellami and Sifaoui (2003) for the date palm trees (53 %) and the whole canopy (86 %). This relationship between transpiration and net radiation could be used to estimation date palm tree transpiration where only net radiation data is available.

Based on the observed cumulated actual transpiration of 170 mm over 35 d, the average daily water uptake of the date palm tree could be estimated at 0.06 m^3/d. Peyron (2000) recommends a water input of 0.56 m^3/d for date palm tree irrigation in Djibouti, so 9 times the water uptake that we measured here. According to this author, large quantities of water are needed to rewet the soil in depth beneath the palm tree root zone. Our results show that this recommendation may lead to large quantities of water lost by drainage. Using sap flow measurements, Green et al. (2014) estimated the daily water uptake of date palm trees at 50 L during the fresh season, which is close to what we found in our study. We used our HYDRUS-1D parameterization to simulate irrigation during winter (Jan.-Feb. 2014) with a target value for the leaching fraction of 40% based on FAO's recommendation (Zaid and Arias-Jiménez, 2002). A dose of 90 mm every week was found, leading to an average daily water requirement of 160 L/d, which is still 3 times smaller than the recommendation of Peyron (2000). The average daily water requirement can be even smaller (125 L/d) if water is brought to the soil every two weeks because of reduced evaporation due to the mulching effect: the average daily evaporation rate decreases from 2.3 to 1.5 mm/d when passing from a weekly to a biweekly irrigation schedule. Our estimation is limited to the fresh period however, during which our experiments have been conducted. According to Green et al. (2014), a palm tree absorbs around 150 L/d during the hot season. We found the same result using HYDRUS-1D during summer (Jun.-Jul. 2014). Keeping the same leaching fraction, we found a water requirement of 290 L/d (160 mm every week), which is still largely smaller than Peyron's recommendation.

For the first time, we could establish of crop coefficient, kc, for date palm trees under the pedoclimatic conditions of Djibouti. We found a value of 1.39, which is larger than that recommended by the FAO (0.95). For a mature date palm tree under hot and arid climates, Allen et al. (1998) recommend kc values between 0.9 and 0.95, while Doorenbos and Pruitt (1977) suggested a kc between 0.8 and 1. Saeed et al. (1990) found a kc varying between 0.85 and 1.37 for the Khalas cultivar in January and February in Saudi Arabia. For the same cultivar, Bhat et al. (2012) found a kc between 0.68 and 1.15. Phylogenetic studies (Askari et al., 2003) showed that our cultivar, Barhi, was genetically identical at more than 76 % to the

Khalas cultivar. We did not find any reference for the Barhi cultivar. We found that kc was sensitive to the LAI value. Using a LAI of 2 instead of 5 in our simulations leads to a kc of 1.05.

6. Conclusion

Promotion of date palm tree cultivation can be a useful strategy for fighting hunger in many arid or semi-desert areas of our warming globe. The date palm tree is indeed a very resilient complementary food resource for growing populations. In the Republic of Djibouti, the implementation of date palm groves is faced with a lack of local references for date palm tree water requirements. In this paper, we presented the first set of data defining water requirements for date palm trees under the pedoclimatic condition of the coastal plain of Djibouti.

The daily water need of date palm trees was estimated in our study as 125 L per tree, including a leaching fraction of nearly 40 %. This estimation is for the fresh season (October to April), when the North-East alizees bring some mild temperatures (22 to 30°C). Requirement during the hot season needs further field references, but estimates could reach more than twice the quantity required in the fresh season (290 L/d). Both figures are well below the current recommendations and practices, though. We showed here that reducing the irrigation doses currently in use could lead to precious water savings, given the high pressure put on water resources in the Djibouti district.

The data presented in this paper is a first set of results that needs to be expanded to other regions of the Djibouti Republic with different soil types and different local climates. The original method used in this paper is quite drastic (removal of the palm tree), but could be made less disturbing by using sap flow measurement tools.

Acknowledgements

The authors thank the President of the Republic of Djibouti Ismaël Omar Guelleh for access to the Djibouti presidential palm grove, as well as Dr Nabil Mohamed, Ministry of Higher Education and Research, and Dr Jalludin Mohamed, Director of the CERD, for their support in the project. The authors thank also the Service de Coopération et d'Action Culturelle (SCAC) of the French Ambassy in Djibouti for financial support. Many thanks to the staff of CERD soil laboratory for its support and commitment.

References

Allam H., Hussein M., and Abdalla K. M., (1973). Sesonal requirement of water by "Sakkoti" dates grown at Asswan, High Polytech. Inst., Moshtohor, Cairo, Res. Bull. 39: 11 p.

Allen R.G., Pereira L.S., Raes D., Smith M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements - FAO Irrigation and drainage paper N°56, FAO, Rome, 300 p.

Askari E., Al-Khalifa N.S., Ohmura T., Al-Hafedh Y.S., Khan F.A., Al-Hindi A., and Okawara R., 2003. Molecular phylogeny of seven date palm (Phoenix Dactylifera L.) cultivars by DNA fingerprinting. Pak. J. Bot., 353: 323-330.

Askri B., Ahmed A.T., Abichou T., Bouhlila R., 2014. Effects of shallow water table, salinity and frequency of irrigation water on the date palm water use. J. Hydrol. 513:81-90.

Ben Aïssa I., Bouarfa S., Perrier A., 2009. Utilisation de la mesure thermique du flux de sève pour l'évaluation de la transpiration d'un palmier dattier. Actes du quatrième atelier régional du projet Sirma, Mostaganem, Algérie, 26–28 mai 2008. Cirad, Montpellier, France, colloques-cédérom, 12 p.

Bhat N.R., Lekha V.S., Suleiman M.K., Thomas B., Ali S.I., George P., Al-Mulla L., 2012. Estimation of water requirement for young date palms under arid climatic condition Kuwait. World Journal of Agricultural Sciences 8(5): 448-452.

Böhm W., 1979: Methods of Studying Root Systems. Ecological Studies 33. Springer, Berlin, Heidelberg, New York. 188 p.

Bouh H., 2006. Etude de l'aquifère basaltique de Djibouti et des aquifères adjacents: Approche hydrochimique et isotopique. Ph. D. thesis, Université de Paris XI, France, 205 p.

Brisson N., Perrier A., 1991. A semi-empirical model of bare soil evaporation for crop simulation models. Water Resour. Res., 27, 5: 719-727.

Chalhoub M, Coquet Y, Vachier P. Water and bromide dynamics in a soil amended with different urban composts. Vadose Zone J 2013;12:1–11.

Daddi-Bouhoun M., 2010. Contribution à l'étude de l'impact de la nappe phréatique et des accumulations gypso-salines sur l'enracinement et la nutrition du palmier dattier dans la cuvette d'Ouargla (Sud-est algérien). Ph. D. thesis, Badji Mokhtar University, Annaba, Algeria, 393 p.

Daher A., Mohamed N., Aberlenc-Bertossi F., 2015. Date Palm Status and Perspective in Djibouti. In: Al-Khayri J., Jain S., Johnson D. (eds) Date Palm Genetic Resources and Utilization. Springer, Dordrecht, pp. 429-444.

Diawara A., Loustaud D., Berbigier P., 1991. Comparaison of two methods for estimating the evaporation of a Pinus pinaster stand: sap flow and energy balance with sensible heat flux measurements by an eddy convariance method. Agric. For. Meteorol, 54 : 49-66.

Djerbi M., 1994. Précis de phoeniciculture. F.A.O., Rome, 192 p.

Doorenbos J., Pruitt W.O., 1977. Guidelines for Predicting Crop Water Requirements. FAO, Rome, p. 144 (FAO Irrig. Drain. Paper 24, Revised).

FAO (Food and Agriculture Organization of the United Nation), 2005. Irrigation in Africa in figures: Djibouti. Aquastat survey, FAO water report, vol. 29, 89 p.

Feddes, R.A., P.J. Kowalik and H. Zaradny, 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc. Wageningen. 189 p.

Granier A., Loustau D., 1994. Mesasuring and modeling the transpiration of maritime pine canopy from sap flow data. Agric. For. Meteorol. 71: 61-81.

Green S., Mc Cann I., Clothier B., Abdelfattah M., Al Dakheel A., Al Yamani W.F., Pangilina R., 2014. Water Use of Date Palms in the United Arab Emirates. A newsletter about Water in the Soil-Plant-Atmosphere System (WISPAS), Plant and Food Research, 119.

Guehl J.M., 1984. Utilisation des méthodes tensio-neutroniques pour l'étude des transferts hydriques dans le sol en milieu ferralitique Guyanais, Science du sol. vol.22, 35-49.

Haj-Amor Z., Ibrahimi M.K., Feki N., Lhomme J.P., Bouri S., 2016. Soil salinisation and irrigation management of date palms in a Saharan environment. Environ. Monit. Assess. 188:497. DOI 10.1007/s10661-016-5488-8.

Hillel D., Krentos V.D., Stylianov Y., 1972. Procedure and test of an internal drainage method for measuring soil hydraulic characteristic in situ. Soil Sci., 114:395-400.

Hopmans J.W., Simunek J., Romano N., Durner W., 2002. Simultaneous determination of water transmission and retention properties. Inverse Methods. In: Methods of Soil Analysis. Part 4. Physical Methods. (J.H. Dane and G.C. Topp, Eds.). Soil Science Society of America Book Series No. 5., pp. 963-1008.

Jalludin M., Razack M., 2004**.** Assessment of hydraulic properties of sedimentary and volcanic aquifer systems under arid conditions in the Republic of Djibouti (Horn of Africa). Hydrogeol. J. 12:159–170.

Kassem M.A., 2007. Water requirement and crop coefficient of date palm trees “Sukariah cultivar”. Misr J. Ag. Eng., 24(2): 339-359.

Kroes, J.G., van Dam J.C., 2003. Reference Manual SWAP version 3.0.3. Wageningen, Alterra, Green World Research, Alterra-report 773.

Mazahrih N.Th., Al-Zubi Y., Ghnaim H., Lababdeh L., Ghananeem M,, Ahmadeh H.A., 2012. Determination actual evapotranspiration and crop coefficients of date palm trees (Phoenix dactylifera L.) in the Jordan Valley. American-Eurasian Journal of Agriculture and Environmental Science 12 (4): 434–443.

Mermoud A., Xu D., 2006. Comparative analysis of three methods to generate soil hydraulic functions. Soil & Tillage Research 87: 89-100.

Munier P., 1973. Le Palmier-dattier. Techniques agricoles et productions tropicales. Maison Neuve et Larose, 217 p.

Oihabi A., 1991. Effect of vesicular arbuscular Mycorrhizae on Bayoud disease and date palm nutrition. Ph.D. thesis, University of Marrakech, 199 p.

Peyron G., 2000. Cultiver le palmier dattier. Groupe de Recherche et d'Information pour le Développement de l'Agriculture d'Oasis, édition GRIDAO, 109 p.

Sabri A., Bouaziz A., Hammani A., Kuper M., Douaik A., Badraoui M., 2017. Effect of regulated deficit irrigation on growth and development of leaf date palm (Phoenix dactylifera L.). Cahiers Agricultures 26, 55005. DOI:10.1051/cagri/2017033.

Saeed A.B., Etewy H.A., Duheash O.A., Aly-Hassan O.S., 1986. Assessment of date palm water requirements under Al-Hassa conditions. Proceedings of the second symposium on the date palm in Saudi Arabia. March 3-6, 1986. 1406H. Date Palm Research Center, King Faisal Univ., Al-Hassa, Saudi Arabia, pp. 376-374.

Saeed AB., Etewy HA., Hassan O.A., 1990. Watering requirement and scheduling of date palm. Agricultural Mechanization in Asia, Africa and Latin America, Vol. 21, No. 4: 49-52.

Schaap M.G., Leij F.J., van Genuchten M.Th., 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251:163-176.

Sellami H.M., Sifaoui S.M. 2003. Estimating transpiration in an intercropping system: measuring sap flow inside the oasis. Agric. Water Manag. 59:191-204.

Šimůnek J., van Genuchten M.T., Šejna M., 2016. Recent developments and applications of the HYDRUS computer software packages. Vadose. Zone J. .

Sperling O., Shapira O., Cohen S., Tripler E., Schwartz A., Lazarovitch N., 2012. Estimating sap flux densities in date palm trees using the heat dissipation method and weighing lysimeters. Tree Physiol. 32(9):1171-1178.

Tournebize R., 1994. Microclimat lumineux et transpiration d'une association arbuste/herbe, en milieu tropical : mesures et modélisation. Ph.D. thesis, Université Paris XI, France, 311 p.

Tripler E., Ben-Gal A., Shani U., 2007. Consequence of salinity and excess boron on growth, evapotranspiration and ion uptake in date palm (Phoenix dactylifera L., cv. Medjool). Plant Soil 297:147-155. DOI 10.1007/s11104-007-9328-z.

Tripler E., Shani U. Mualem Y., Ben-Gal A., 2011. Long-term growth, water consumption and yield of date palm as a function of salinity. Agric. Water Manag. 99:128-134.

Tripler E., Shani U., Ben-Gal A., Mualem Y., 2012. Apparent steady state conditions in high resolution weighing-drainage lysimeters containing date palms grown under different salinities. Agric. Water Manag. 107:66-73.

World Alimentation Program (Programme Alimentaire Mondial), 2012. Evaluation de la sécurité alimentaire en situation d'urgence en zone rurale. Service de l'Analyse de la Sécurité Alimentaire (VAM), 67 p.

Zaid A., Arias-Jiménez E.J., 2002. Date Palm Cultivation. FAO Plant Production and Protection paper 156, rev. 1. FAO, Rome.

Fig. 1. Experimental set up (access tubes for the neutron probe and tensiometers) installed around the stem of the date palm tree.

Fig. 2. (a) Picture of the date palm tree root system; (b) Scheme showing the four types of roots of the date palm tree (Peyron, 2000).

Fig. 3. Root density map (left) and average root density profile (right) of the date palm tree.

Fig. 4. Soil water content (a, c) and hydraulic head (b, d) during infiltration (a, b) and redistribution (c, d). Scenario with palm tree. T0, start of infiltration ; Tf, end of infiltration.

Fig. 5. Soil water content (a, c) and hydraulic head (b, d) during infiltration (a, b) and redistribution (c, d). Scenario without palm tree but with evaporation. T0, start of infiltration ; Tf, end of infiltration.

Fig. 6. Soil water content profile during the scenario without (a) and with (b) date palm tree. T0, start of infiltration ; Tf, end of infiltration.

Fig. 7. Soil water content (a, c) and hydraulic head (b, d) during infiltration (a, b) and redistribution (c, d). Scenario without palm tree and without evaporation (internal drainage). T0, start of infiltration ; Tf, end of infiltration.

Fig. 8. Pressure head and volumetric water content at the 20-cm depth measured (symbol) and simulated (line) using HYDRUS-1D with hydraulic parameters obtained from laboratory data and PTFs. Saturated water content was fixed at 90% of porosity.

Fig. 9. Water dynamics measured (symbol) and simulated (line) at the various depths instrumented in the soil profile for the internal drainage scenario. Pressure head was measured with tensiometers and water content with a neutron probe. Start of infiltration is at T_0=887.42 d.

Fig. 10. Water dynamics measured (symbol) and simulated (line) at the various depths instrumented in the soil profile for the scenario with evaporation and without palm tree. Pressure head was measured with tensiometers and water content with a neutron probe. Start of infiltration is at T_0=845.42 d.

Fig. 11. Water dynamics measured (symbol) and simulated (line) at the various depths instrumented in the soil profile for the scenario with palm tree. Pressure head was measured

with tensiometers and water content with a neutron probe. Start of infiltration is at T_0=788.42 d.

Table 1

Particle size distribution and bulk density of the soil profile.

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)
10	62.15	28	9.85	1.36
20	71.5	19	9.5	1.18
30	59.55	29.75	10.7	1.2
40	56.4	28.5	15.1	1.32
50	57.85	30.2	11.95	1.27
60	57.8	28.8	13.3	1.35
70	61.2	28.25	10.55	1.35
80	52.25	33.05	14.7	1.35
90	50.35	35.5	14.15	1.38
100	35.6	46	18.5	1.37
110	26.5	49	24.5	1.38
120	36.5	44.2	19.3	1.27
130	48.2	34.9	16.92	1.28
140	21.85	56.65	21.5	1.28
150	30.4	50.75	18.85	1.37
160	29.45	48.55	22	1.28

Table 2

Climate data measured at the date palm grove from January 2013 to June 2014.

Month	Mean temperature (°C)	Mean solar radiation (W/m^2)	Mean relative humidity (%)	Mean wind speed (m/s)	Rainfall (mm)	Calculated ET_0 (mm)
Jan-13	25.90	175.37	61.85	0.61	2.5	163.11
Feb-13	25.87	210.23	60.75	0.63	0.0	173.26
Mar-13	27.55	195.53	67.27	0.66	54.2	178.45
Apr-13	30.33	235.03	62.77	0.67	1.1	214.23
May-13	32.31	221.93	59.67	0.47	6.7	203.07
Jun-13	35.63	197.40	36.10	0.51	0.0	218.53
Jul-13	38.31	195.74	26.92	1.28	0.2	290.49
Aug-13	41.00	336.81	24.57	1.09	0.0	300.00
Sep-13	33.81	213.57	52.01	0.50	0.7	163.76
Oct-13	30.93	205.21	57.24	0.42	0.0	199.23
Nov-13	28.26	187.98	61.41	0.44	5.9	170.74
Dec-13	25.97	182.36	58.54	0.44	0.0	169.20
Jan-14	25.22	180.00	61.79	0.48	0.2	163.24
Feb-14	25.87	173.09	63.29	0.49	0.0	142.19
Mar-14	27.50	210.36	63.70	0.56	0.2	191.91
Avr-14	29.86	229.31	61.67	0.47	0.0	206.78
May-14	32.24	216.60	60.11	0.49	0.0	211.85
Jun-14	33.86	195.35	42.62	0.47	0.0	149.28

Table 3

Water inputs during the infiltration phase of the three experiments.

Experiment	Water input number	Duration (min)	Water input (mm)
Internal drainage experiment	1	90	75.4
	2	25	34.9
	3	38	53
	4	7	9.8
	5	90	59.7
	6	34	31.8
	7	55	51.5
	8	51	43
Bare soil experiment	1	130	119.4
	2	60	60.5
	3	51	54.6
	4	46	46.6
	5	8	9.5
	6	52	45.9
	7	50	43.4
Palm tree experiment	1	135	125.7
	2	50	52.9
	3	40	19.9
	4	22	16.2
	5	86	45.7
	6	180	80.7

Table 4

Values of the optimized Mualem-van Genuchten parameters obtained by fitting the data of the internal drainage experiment. Initial values are given in parenthesis.

Depth (cm)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	α (cm^{-1})	n	l	K_s ($cm.d^{-1}$)
0-5	0.300	0.028	0.069	1.058	-2.000	9.00
	(0.440)	*(0.0)*	*(0.417)*	*(1.241)*	*(-2)*	*(113.0)*
5-15	0.450	0.050	0.480	1.334	-0.263	545.0
	(0.440)	*(0.0)*	*(0.417)*	*(1.241)*	*(-2)*	*(113.0)*
15-35	0.387	0.050	0.070	1.240	2.545	1172
	(0.495)	*(0.0)*	*(0.570)*	*(1.176)*	*(-2)*	*(217.5)*
35-75	0.350	0.114	0.035	1.400	-0.240	223.6
	(0.446)	*(0.001)*	*(0.620)*	*(1.170)*	*(-2)*	*(65.65)*
75-105	0.360	0.072	0.014	1.887	2.343	50.73
	(0.435)	*(0.0)*	*(0.028)*	*(1.326)*	*(-2)*	*(74.51)*
105-145	0.412	0.120	0.134	1.182	7.920	639.6
	(0.466)	*(0.0)*	*(0.036)*	*(1.182)*	*(-2)*	*(40.54)*
145-155	0.400	0.200	0.036	1.182	12.00	900.0
	(0.466)	*(0.0)*	*(0.036)*	*(1.182)*	*(-2)*	*(40.54)*
155-165	0.401	0.159	0.009	1.272	5.356	832.7
	(0.466)	*(0.0)*	*(0.036)*	*(1.182)*	*(-2)*	*(40.54)*
165-180	0.378	0.000	0.060	1.435	10.66	945.2
	(0.466)	*(0.0)*	*(0.036)*	*(1.182)*	*(-2)*	*(40.54)*

Highlights

- This paper presents the first dataset on date palm tree water uptake for Djibouti
- Date palm tree evapotranspiration was 5.6 mm/d during the mild season
- Date palm tree water requirement was 60 L/d/tree during this season
- Irrigation dose should be 125 L/d/tree for a 40% leaching fraction
- Large water savings can be achieved by reducing current irrigation doses

Figure 1

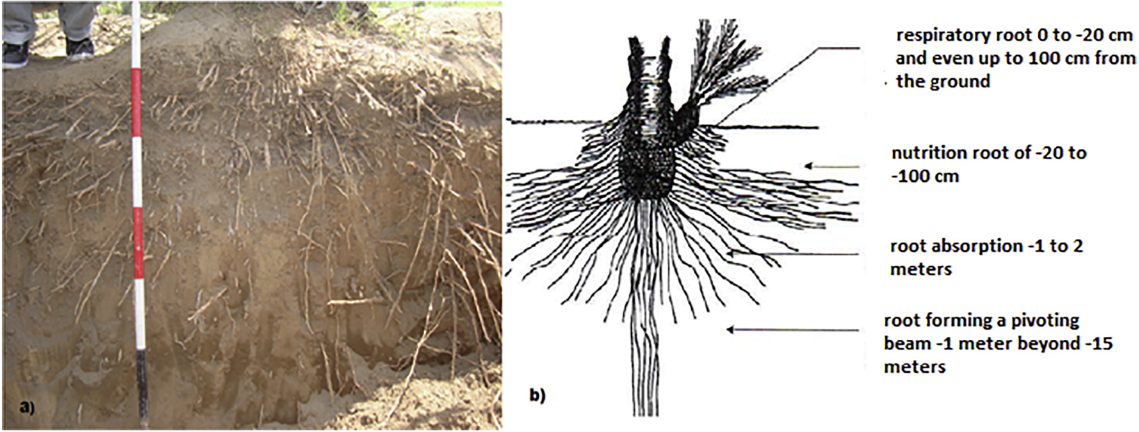
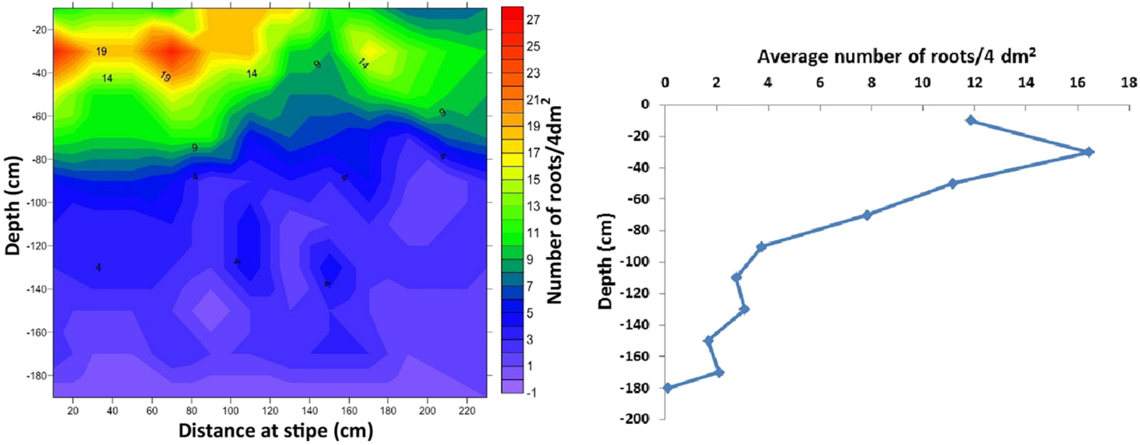

a)
b)
respiratory root 0 to -20 cm and even up to 100 cm from the ground
nutrition root of -20 to -100 cm
root absorption -1 to 2 meters
root forming a pivoting beam -1 meter beyond -15 meters

Figure 2



Depth (cm)
-20
-40
-60
-80
-100
-120
-140
-160
-180
20
40
60
80
100
120
140
160
180
200
220
Distance at stipe (cm)
19
14
19
14
9
14
9
9
4
4
4
4
4
4
4
27
25
23
21
19
17
15
13
11
9
7
5
3
1
-1
Number of roots/4dm2
Average number of roots/4 dm²
0
2
4
6
8
10
12
14
16
18
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Depth (cm)

Figure 3

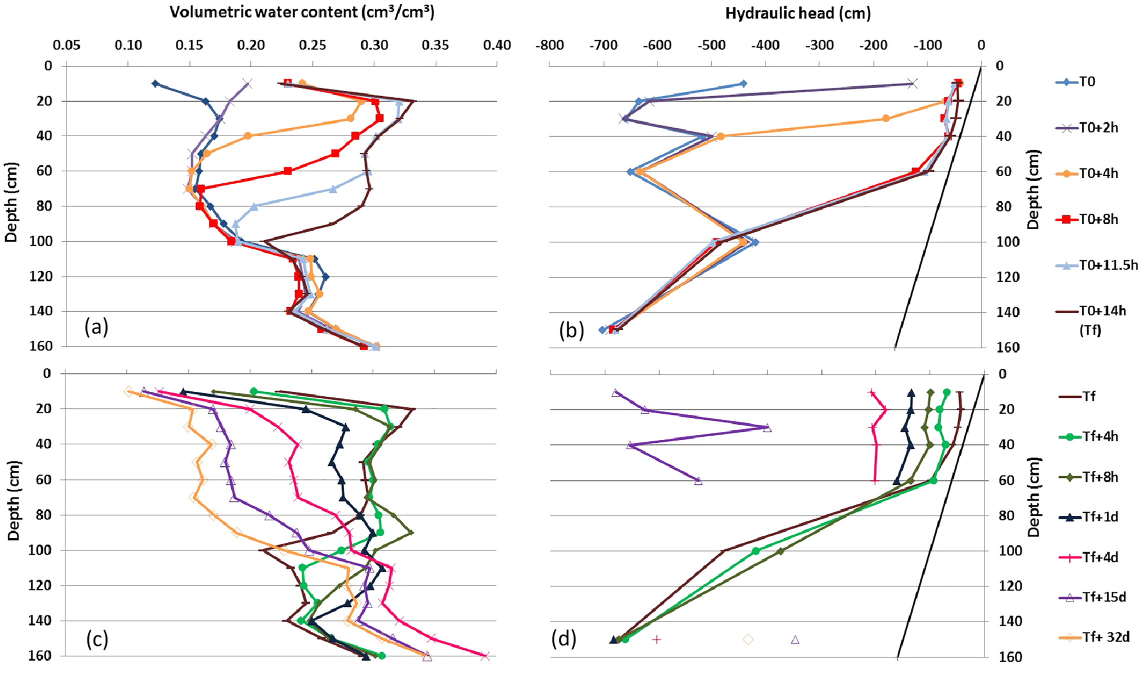
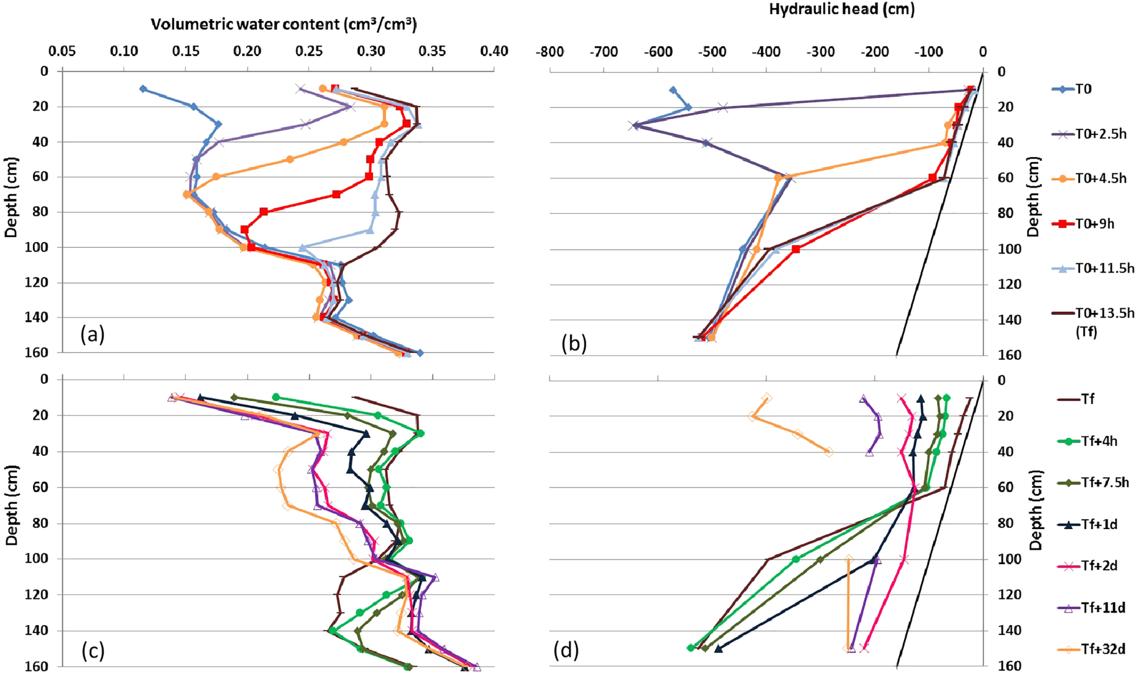
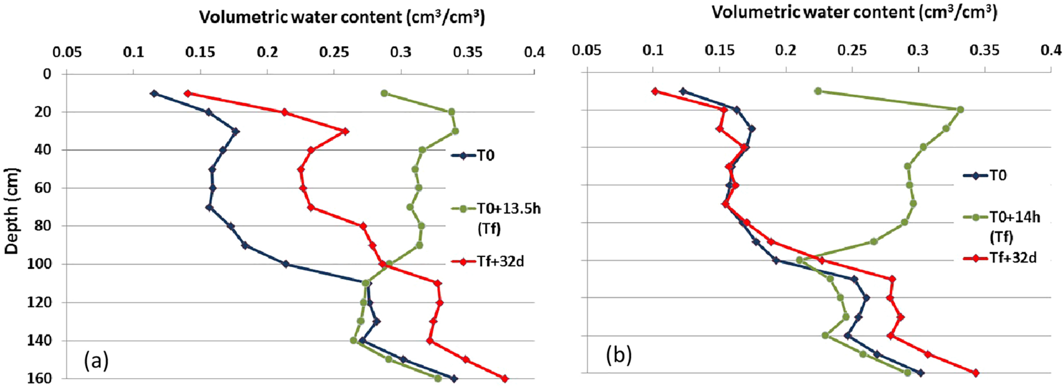

Volumetric water content (cm³/cm³)
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Hydraulic head (cm)
-800
-700
-600
-500
-400
-300
-200
-100
0
Depth (cm)
0
20
40
60
80
100
120
140
160
(a)
(b)
(c)
(d)
T0
T0+2h
T0+4h
T0+8h
T0+11.5h
T0+14h (Tf)
Tf
Tf+4h
Tf+8h
Tf+1d
Tf+4d
Tf+15d
Tf+ 32d

Figure 4



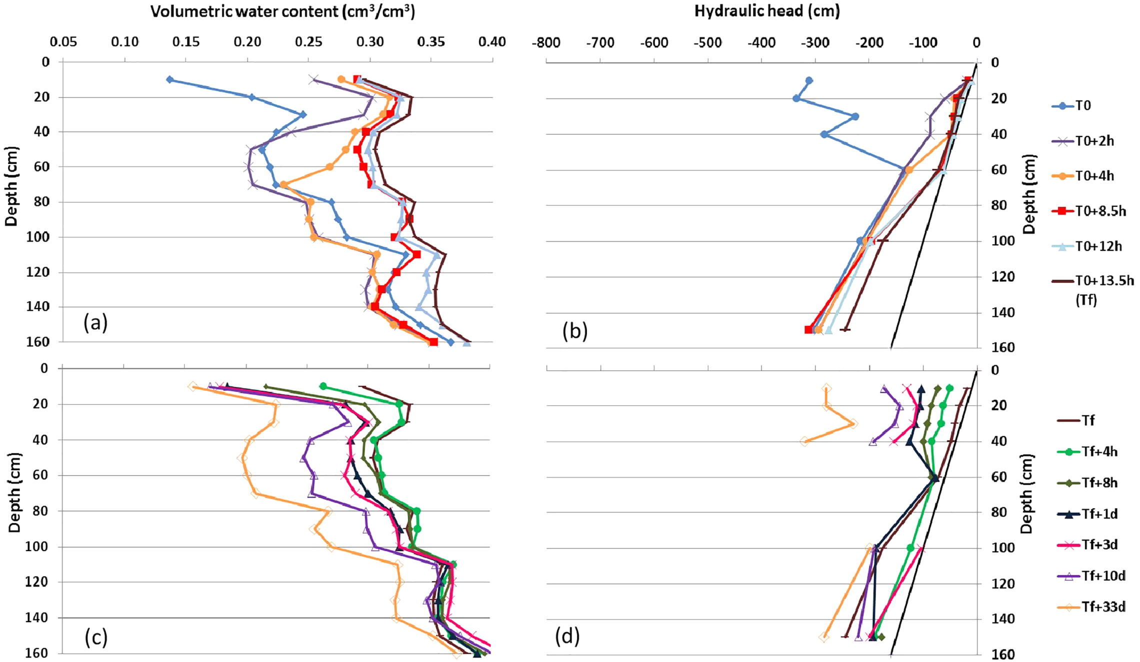
Volumetric water content (cm³/cm³)
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Hydraulic head (cm)
-800
-700
-600
-500
-400
-300
-200
-100
0
Depth (cm)
0
20
40
60
80
100
120
140
160
(a)
(b)
(c)
(d)
T0
T0+2.5h
T0+4.5h
T0+9h
T0+11.5h
T0+13.5h (Tf)
Tf
Tf+4h
Tf+7.5h
Tf+1d
Tf+2d
Tf+11d
Tf+32d

Figure 5



Volumetric water content (cm³/cm³)
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Depth (cm)
0
20
40
60
80
100
120
140
160
T0
T0+13.5h (Tf)
Tf+32d
(a)
Volumetric water content (cm³/cm³)
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
T0
T0+14h (Tf)
Tf+32d
(b)

Figure 6



Volumetric water content (cm³/cm³)
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Hydraulic head (cm)
-800
-700
-600
-500
-400
-300
-200
-100
0
Depth (cm)
0
20
40
60
80
100
120
140
160
(a)
(b)
(c)
(d)
T0
T0+2h
T0+4h
T0+8.5h
T0+12h
T0+13.5h (Tf)
Tf
Tf+4h
Tf+8h
Tf+1d
Tf+3d
Tf+10d
Tf+33d

Figure 7

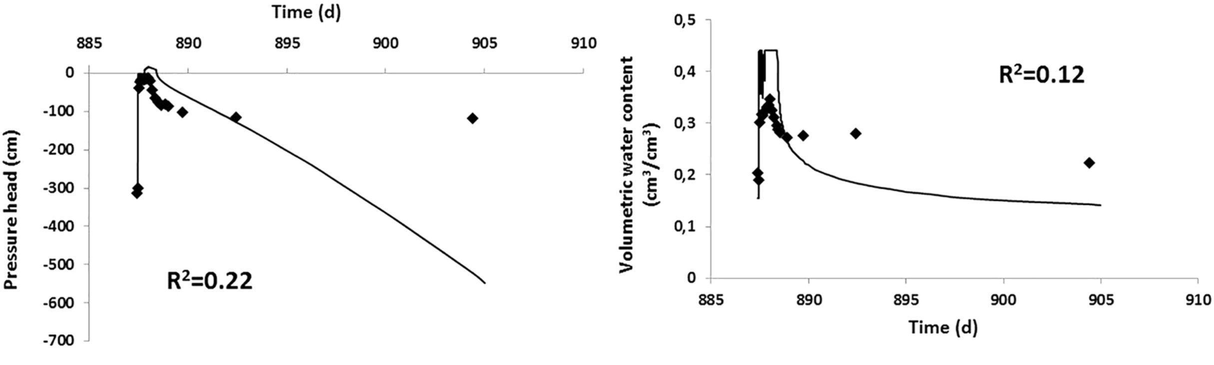
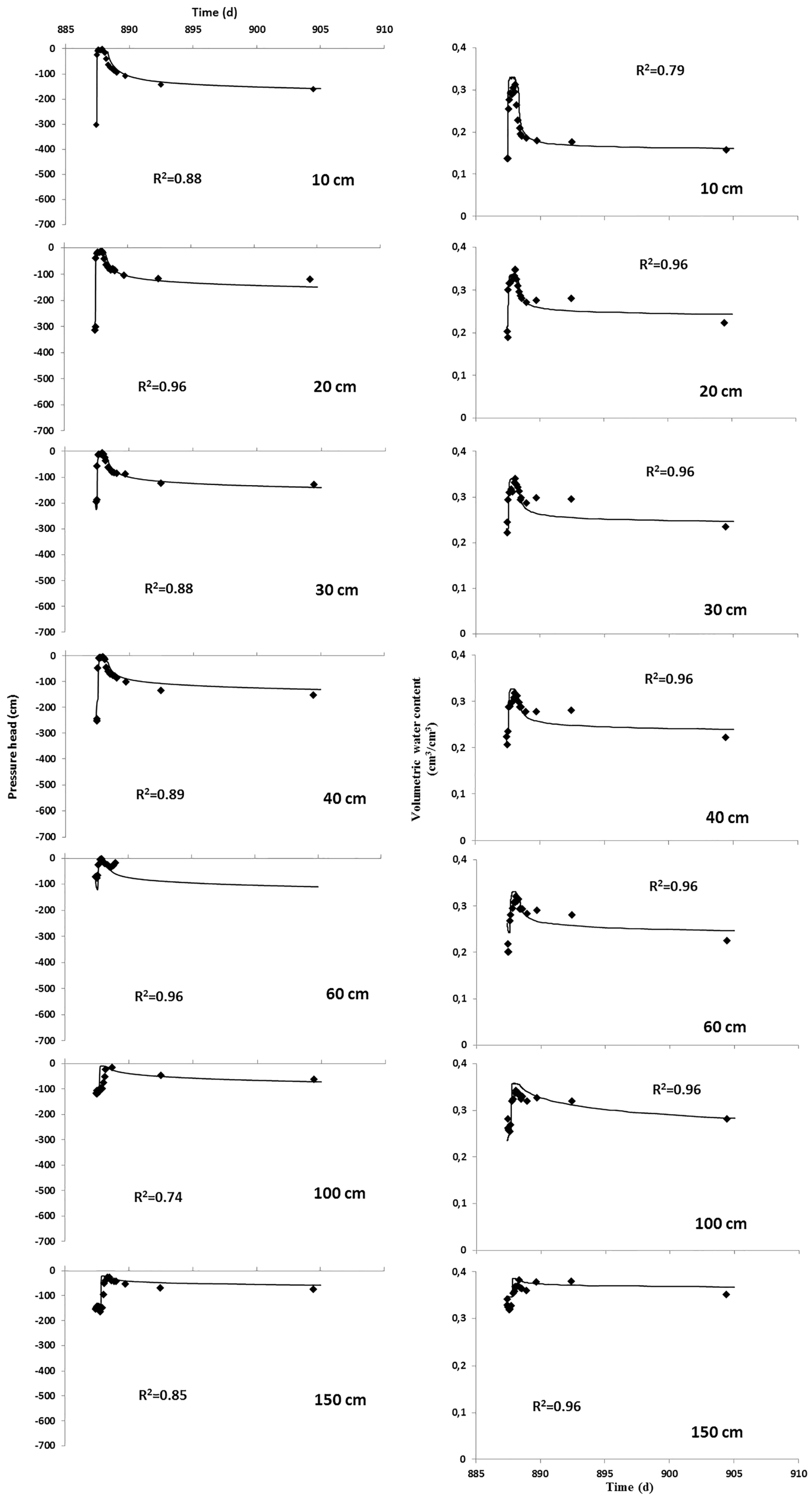
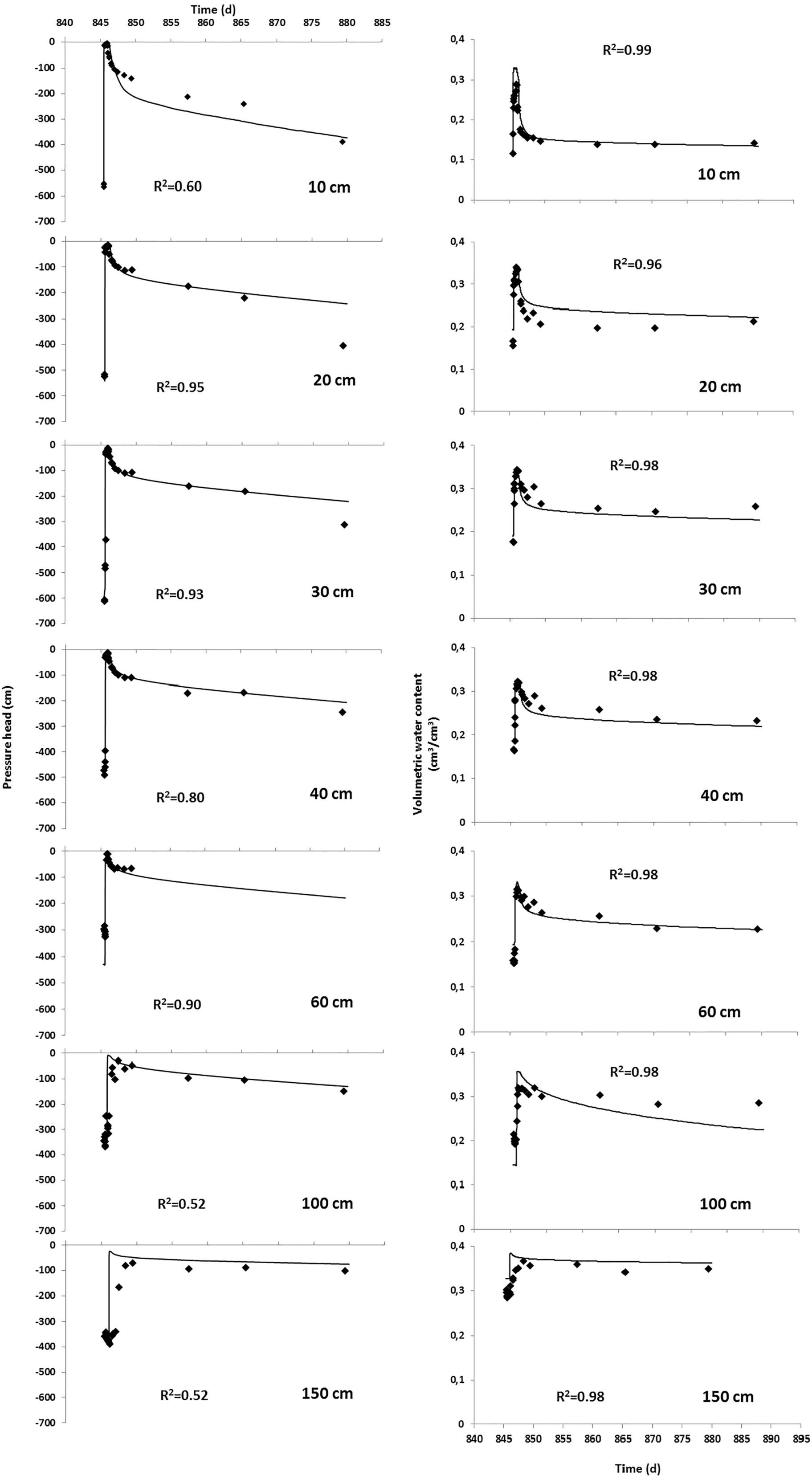

Time (d)
885
890
895
900
905
910
0
-100
-200
-300
-400
-500
-600
-700
Pressure head (cm)
R2=0.22
0,5
0,4
0,3
0,2
0,1
0
Volumetric water content (cm3/cm3)
R2=0.12
885
890
895
900
905
910
Time (d)

Figure 8



Time (d)
Pressure head (cm)
Volumetric water content (cm^3/cm^3)
R^2=0.88
10 cm
R^2=0.79
10 cm
R^2=0.96
20 cm
R^2=0.96
20 cm
R^2=0.88
30 cm
R^2=0.96
30 cm
R^2=0.89
40 cm
R^2=0.96
40 cm
R^2=0.96
60 cm
R^2=0.96
60 cm
R^2=0.74
100 cm
R^2=0.96
100 cm
R^2=0.85
150 cm
R^2=0.96
150 cm
Time (d)

Figure 9



Time (d)
Pressure head (cm)
Volumetric water content (cm³/cm³)
R²=0.60
10 cm
R²=0.99
10 cm
R²=0.95
20 cm
R²=0.96
20 cm
R²=0.93
30 cm
R²=0.98
30 cm
R²=0.80
40 cm
R²=0.98
40 cm
R²=0.90
60 cm
R²=0.98
60 cm
R²=0.52
100 cm
R²=0.98
100 cm
R²=0.52
150 cm
R²=0.98
150 cm
Time (d)

Figure 10

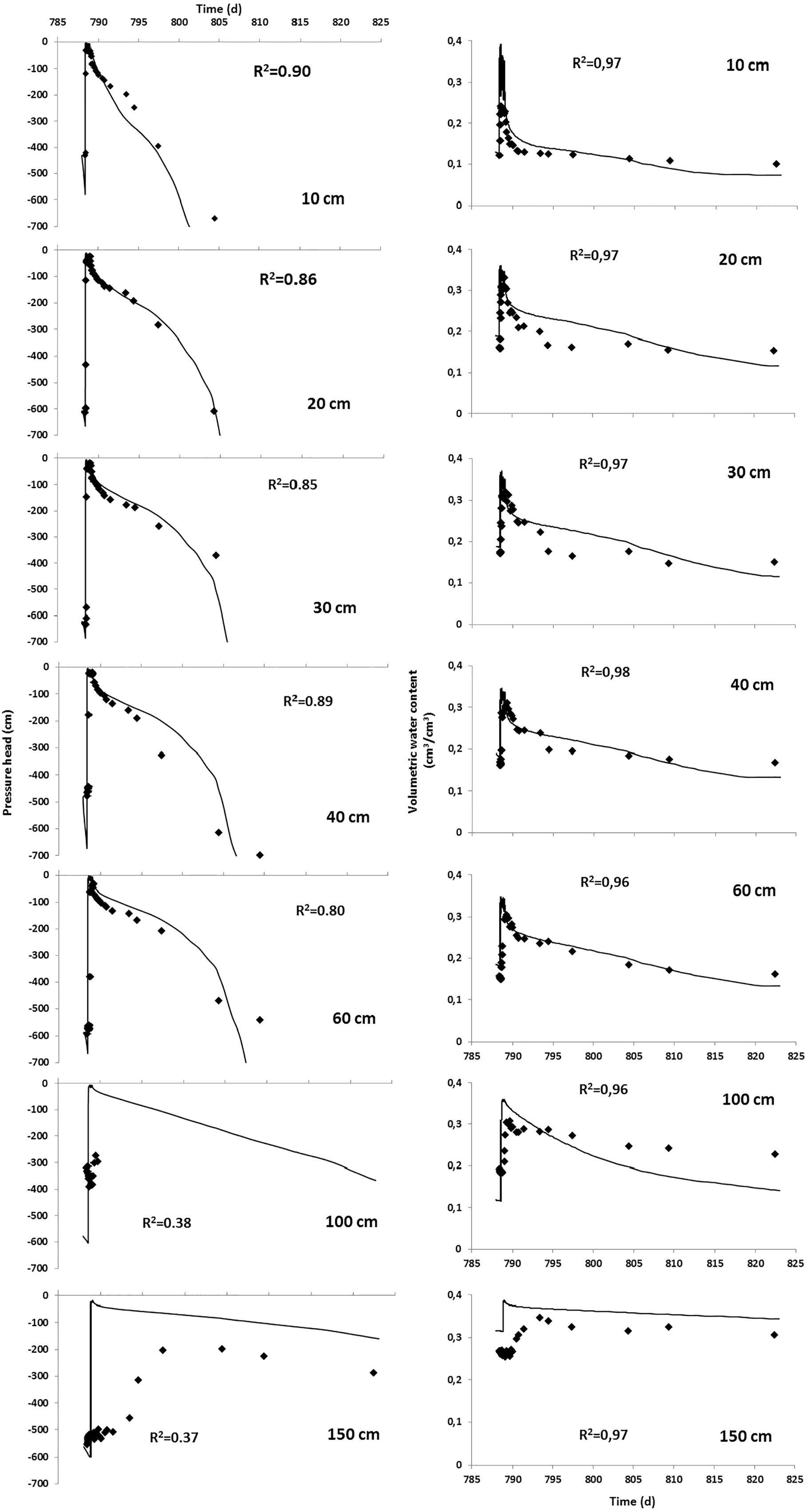

Time (d)
Pressure head (cm)
Volumetric water content (cm³/cm³)
R²=0.90
10 cm
R²=0,97
10 cm
R²=0.86
20 cm
R²=0,97
20 cm
R²=0.85
30 cm
R²=0,97
30 cm
R²=0.89
40 cm
R²=0,98
40 cm
R²=0.80
60 cm
R²=0,96
60 cm
R²=0.38
100 cm
R²=0,96
100 cm
R²=0.37
150 cm
R²=0,97
150 cm

Figure 11