Root System of Olive Trees (Olea Europaed L.) Based on Runoff Harvesting System During Dry Period

Hung-Phi Nguyen 1,2, Bich -Thao Nguyen 3

1 Department of Business Management, National Taipei University of Technology, Taiwan
2 Department of Business Management, FPT University, Vietnam
3 French Associates Institute for Agriculture and Biotechnology of Drylands, Ben-Gurion University of the Negev, Israel
* Correspondence: hungnp30@fpt.edu.vn; Tel.: (+886-901-325-817)

Abstract: This paper presents a study of a field trial experiment at olive orchard irrigated by runoff harvesting system under a dry climate which was carried out on 5-year-old olive trees (Olea europaea. L, cv. Barnea) in the middle of Negev desert, starting right after the floods, onwards during the summer growing season. The beginning of the experiment occurred after 2 years with little rain and no run-off events. The olive trees were under severe drought stress when we first initiated a controlled flooding in 2017. In the second research year (2018), a massive natural flood had occurred at the end of April. Results show that the water distribution within the soil was highly inhomogeneous even under flood conditions. Soil water loss rate, due to transpiration was mainly correlated with total amount of soil water and not atmospheric conditions. The relative root water uptake from shallow soil layers (0.3-1.5m) gradually reduced along the season, while the relative water uptake from the deeper layers (1.5-4m) became more pronounced.

Keywords: Olive tree, drought and re-watering, soil water balance, irrigation, root, neutron probe.

1. Introduction

Runoff irrigation is based on conveying runoff water associated with nutrients, seeds, sediments harvested from a large area through dirt channels and funneled into dike-surrounded micro/macro-catchments, where it percolates into the soil, stored in deeper layers and can be benefited for agricultural farming. The success of water-harvesting systems is highly dependent on the inherently variable characteristics of the land (slope angle and length, texture, etc.) and the precipitation [1] and the particular crops. The annual precipitation is deficient in this region and only occurs in the winter season with high variability [2]. Therefore, the success of perennial crops cultivation under runoff systems requires crop species characterized by deep root systems and drought tolerance. These traits are enabled plants to uptake water from the wet soil profile and withstand dry seasons or even dry years [3].

In agriculture, abiotic and biotic stress factors cause significant yield losses and become more widespread as a result of climate change [4]. Among the abiotic factors, drought is the most critical threat to world food security [5]. It not only affects plant growth and development [6] but also limits agricultural crop production [7]. The severity of drought is unpredictable as it depends on many factors such as occurrence and distribution of rainfall, evaporative demands, and moisture storing capacity of soils [8].

The symptoms of drought in plants vary depending on plant species, developmental stages, growth conditions, and other environmental factors such as drought severity, drought length, soil physicochemical condition [9]-[12]. Generally, drought symptoms include loss of leaf turgor,
drooping, wilting, etiolation, yellowing, and premature leaf downfall [13]-[16]. Under extreme drought conditions, plant deaths may occur.

We are seeking to grow olive orchard in the middle of Negev desert without high-tech irrigation and only through the collection of the winter floodwaters from the region’s usual four inches of 12 annual rainfall. Research of olive trees based on the run-off harvesting system (a modern version of Nabataeans construction from two thousand years ago) will help determine the sustainability and viability of this agricultural method. The main objective of this study is to determine the responses of olive trees irrigated by flooding after a prolonged dry period.

2. Materials and Methods

The experimental study was carried out during 2017-2018 in Wadi Mashash, an experimental farm based on the collection of runoffs, located about 20 km southeast of Beersheba, Israel (31°08’ N, 34°53’ E; 400 a.m.s.l). The climate of this area is the Mediterranean type with hot and dry summers from May to September. The annual average rainfall is approximately 115mm, most of which occurs between October and April. Air temperature reaches a maximum of approximately 42°C in July, and the minimum temperature is close to 0°C in January (Fig. 1). Annual class A evaporation fluctuates between 2500-3000 mm. The soil in the research site is light loess (sandy loam) containing 10% clay, 54% silt, and 36% sand with a field capacity and wilting point of 0.22, 0.06 by volume. The soil profile is relatively homogeneous down to the depth of 5-6 m, with thin stone layers irregularly distributed at depths greater than 1.5 m. The site is based on a runoff-harvesting system, where runoff water is

![Figure 1](image-url)
diverted from the main channel into various limans (floodwater irrigated areas) during winter flood events by means of shallow channels.

The water is trapped by the surrounding wall. Proper inlet and outlet structures (spillway) were built to controlling surplus water and safeguarding the walls against erosion. Spillway height is 30-40 cm higher than the inlet, thus ensuring sufficient water storage capacity per flood event. Trees planted within the liman can take advantage of the very deep wet soil profile and withstand dry seasons. Three plots located within the above-mentioned liman (0.81 ha) and planted to olive orchard (O. europaea, cv, Barnea) in 2012. Within each of the three randomly selected plots of 12 x 8 m (), there were nine trees. On the central tree in each plot, soil water content measurements were carried out (Fig.2).

Due to two floodless winters, 2016-2017 and 2017-2018, the trees were under severe drought stress at the beginning of the measurement periods during both seasons. Measurement periods initiated on June 19 day of year (DOY 170) and finished on September 25 (DOY 268) in 2017 and from April 24 to October 22 (DOY 114 to 294) in 2018. During the first year (2017), due to a lack of flood events, the plots were artificially flooded on 19 June (DOY 170). In 2018, two flood events occurred on April 26-28 (DOY 116-118). The soil was wetted to a depth of 1.5m in 2017 and more than 3m in 2018.

Soil water content was measured using a neutron probe (Model 4300, Troxler Electronic Laboratories, Inc., North Carolina, USA) technique [17]. A neutron probe (NP) consists of a probe and an electronic counting scaler, which are connected by an electric cable. The operational principle of neutron probe clearly described in [18] which was based on the interaction of neutrons with high energy emitted by a radioactive source into the soil with the hydrogen in the soil. Hydrogen (the primary component of water) can slow fast neutrons, therefore, the density of the resultant cloud of slow neutrons is a function of the soil moisture content. Slow neutrons returning to the detector per unit time are counted. The moisture content is determined from previously determined calibration curves relating volumetric water content with counts or count ratios (ratio of counts at a given depth to the standard count). The instrument is calibrated against gravimetric water content measurements, and the latter is multiplied by the corresponding bulk density in order to obtain volumetric soil water content (θv). A separate calibration curves for different soil layers in the orchard were used in this study.
For 15 cm top soil layer:
\[ \theta_v = CR \times 0.0004 + 0.0122 \]  
(1)

For deeper soil layer (from 30-510 cm):
\[ \theta_v = CR \times 0.0004 - 0.005 \]  
(2)

where \( \theta_v \) is volumetric soil water content (cm\(^3\) cm\(^{-3}\)), CR is neutron count ratio.

In 2015, eleven aluminum access tubes were installed in the soil in each experimental plot to depths of 3-5 m. The various depths being a result of the presence of stony layers that our drill could not penetrate. Soil water measurements were carried out every 15 cm from 0 down to 120 cm soil depth and every 30 cm onwards. The first soil water measurements were taken as soon as possible after the flood events on DOY 170 in 2017 and on DOY 135 in 2018. Following measurements were carried out every 7 to 10 days and increasing intervals thereafter (14-30 days), until no further change in water content in the scanned layers was observed. We calculated the amount of total soil water content, total available soil water and water loss over time during both years. Water losses in the soil were computed using the changes in volumetric soil water content and assuming that internal drainage and evaporation from the soil were negligible. To ensure the latter, shortly after flooding the soil was covered with polyethylene sheets. Internal drainage usually ceased a few weeks after flooding as expected. The total soil water loss for a given time interval was obtained by multiplying the average changes for the eleven tubes for each soil depth interval by the monitored area (6 m\(^2\)).

3. Results

3.1 Seasonal changes in the total soil water content

![Figure 3](image-url)  
**Figure 3.** Average of total soil water content (mm) over a depth of 4.2m in 2017 and 2018. Vertical bars indicate SD.

![Figure 4](image-url)  
**Figure 4.** Changes in total available soil water of three plots (D-E-F) in 2017 (DOY 170-228) and 2018 (DOY 135-295) (all regressions with \( R^2 = 0.99, P<0.001 \)).
Figure 3 shows the average of total soil water content (mm) over a depth of 4.2 m of three plots (D, E, F) in 2017 and 2018. The equivalent depth of applied water was much higher in 2018 than in 2017 (~639 mm and ~407 mm). The timing of water application was also different lagging behind by more than a month for 2017. It is worthwhile noting that while in 2017 water was applied by simulating a flood in 2018 a real flood occurred. The total soil water content when soil totally dried was similar for both years (close to 245 mm).

Figure 4 shows the changes in total available soil water (ASW) of three plots (D, E, F) in 2017 and 2018. It can be clearly seen that amount of ASW was varied among plots and among years. An estimate of 221, 169, 188 mm maximum available soil water in plot D, E, F, respectively was determined from the measurements of dry and wet soil in 2017. Same calculation for 2018, the maximum available soil water in three plots was much higher than those in 2017, precisely 441, 309, 517 mm corresponding to three plots. In 2017, the ASW declined dramatically in 58 days. Meanwhile, in 2018, it gradually decreased and exhausted after 160 days.

3.2 Temporal dynamics of soil water content within the soil profile.

The temporal evolution of volumetric soil water content profiles in plot D, E, and F in 2017 and 2018 are presented in Figure 5 and 6, respectively. The main characteristics shown in these figures may be summarized as follows: Every year before flood events, the soil was dry with a mean volumetric soil water content of about 6%. In 2017, the depth of infiltration was about 2.4 m, while in 2018 the maximum depth was approximately 5 m. In 2017, two months after flooding, the total soil water reached its lowest value; in 2018, it took almost four months to reach the same average water content. The soil water profiles for 2018 show great differences between the plots. In plot D, the closure of the soil water profile occurs at 5 m depth (Fig. 6a), while in plot E the closure is observed at about 3 m depth (Fig. 6b) and no closure was observed for plot F (Fig. 6c). The fractional water loss for each soil layer reflects the plants’ water uptake from each depth. This fraction is the ratio between the amount of water loss at a certain depth and the total amount of water loss from the whole soil profile. Figure 7 shows typical seasonal changes of fractional water loss patterns for three olive trees in 2018. The fraction from the upper layer (0 -120 cm) decreased in contrast to the increase observed in the lower (150 -270 cm) layer of all trees throughout the season.
Figure 2. Temporal-spatial dynamics of soil water content within the soil profile plot D (a), plot E (b) and plot F (c) in 2017. Bars indicate SE.

Figure 6. Temporal-spatial dynamics of soil water content within the soil profile plot D (a), plot E (b) and plot F (c) in 2018. Bars indicate SE.

Figure 7. Typical seasonal changes of fractional water loss patterns for olive trees in plot D (a), plot E (b) and plot F (c).

3.3 Spatial dynamics of soil water content within the soil profile.
Figure 8. Spatial and temporal soil water changes (mm) of three plots (D, E, F) in 2017 (a) and in 2018 (b). Note that the consecutive number of tubes does not mean the tubes are neighboring.

The distribution of access tubes in the soil gives us an insight of the spatial distribution of water loss around the tree. Figure 8 shows the seasonal changes in soil water throughout the drying-out period. Figure 8a shows the 2017 results since the total input of soil water was relatively small; all changes within the soil were only limited to the upper 240 cm. Thus, the data are presented down to this depth. Figure 8b shows the results for 2018, where soil water changes were observed down to a depth of ~500 cm. Since not all tubes reach this depth, the lower boundary of the graph is not constant.
In both graphs the tubes are presented according to their arbitrary numbering, which means that consecutive tubes (e.g. 3-4) may not necessarily be contiguous in space. The configuration of the 11 tubes is presented in Figure 2. The “hot” colors represent water loss, and “cold” colors water increment. Figure 8a shows that after the flood (DOY 170) in 2017 most of the water reached the depth of 120 cm, while in D plot, water penetrated down to 150 cm. One week later (DOY 178) increments at 1.5m for plots E, F and at 1.8m for plot D are evident and attributed to internal drainage. For the same time period losses are evident at ~100, 45 and 90 cm in plots D, E, F respectively. The most active period (larger losses) along the season appears to be one month after flooding (DOY 207), and the most active plot is D, with the major activity of the root system at 150-180 cm. Plot F also shows high water losses at 150-180 cm. These patterns are not common to all tubes (more clearly seen in plot D) which indicate non-uniform water uptake by roots. Figure 8b illustrates that in 2018 water reached the depth of 390 cm in plot D and F while it reached the depth of 300 cm in plot E - DOY 135). Internal drainage is displayed after more than a month (DOY 182), noticeably in plot D, where water percolated to a depth of 420 cm. The most significant change in soil moisture is shown along the soil profile of each plot on DOY 182. Thereafter water losses were dominant in the deeper soil layers (150-300 cm.). In plot F, a secondary peak of water loss can be observed at depth of 90 cm. From DOY 255, the rate of water loss declined, although high losses in the deeper layer are evident in plot F (180-300 cm). It should be noted that two months after the flood, a clear input of water is evident in the deepest layer of plot D. It is highly unlikely that this is due to gravitational flow (internal drainage) and we surmise that it may be related to lateral water movement, but it was not possible to collect data in support of this statement due to the arrangement of access tubes.

3.4 Seasonal changes in daily transpiration by soil water balance.

**Figure 9.** The seasonal changes in daily transpiration, obtained by the averaged soil water measurements for plots D E F.
The average daily water losses (transpiration) were determined as the differences between sequential spatially averaged soil water content measurements divided by the intervening time period in days. The general features are shown in Figure 9: After flooding, the typical pattern shows an increase in transpiration, a peak, and thereafter a reduction in transpiration rates. The rapid increase just after flooding is probably related to tree adaptation to the wet conditions after a prolonged drought. The peak width in 2017, is narrower than in 2018 due to the lower soil water availability. Generally, in both years, the reduction in transpiration rates appears sooner and much rapidly than shown for pan A, a fact that confirms that transpiration is limited by water availability. Plots E & F show very similar peak transpiration rates for both years, while plot D shows a lower peak value in 2018. Transpiration rates should decrease with soil water availability. Plot E does not follow this pattern and exhibits quasi-constant water loss rates during 2017 but conforms to the general trend in 2018. During the last measurement period the transpiration values for the three trees were similar for both years but overall lower during 2018.

4. Discussion

As mentioned before, the soil surface was covered with plastic sheets to avoid direct evaporation from the soil. Therefore, any soil water loss can be accounted for transpiration or water movement (lateral or vertical beneath the bottom of the access tube). Under such conditions, the profiles of the soil water reflect water uptake by the roots and loss of water by transpiration. The rate of decrease in soil water profile is similar for both years, even though the initial amount of water in the profile was much lower in 2017. A similar trend of water loss in drying season was also shown by Li et al. (2006) [19] and Song et al. (2017) [20]. In 2017, the depth of water infiltration was about 2.4 m while in 2018 the maximum depth was about 5 m (Fig. 5,6). This big difference was the result of natural flood events in 2018 instead of the artificial flood with lower water input. In plot D, soil water profile closure was seen at 5 m while such closure was observed at about 3 m depth in plot E probably due to smaller water infiltration (Fig. 6a, b). It is not clear why this difference occurred, and we can only surmise that this was due to local topographical differences and faulty leveling. In F plot, no water closure was observed (rather short measuring tubes), and water drainage was clearly observed at the deepest measuring point (Fig. 6c)[21]. Therefore, the results of plot F were not used for sap flow calibration.

A unique feature is observed in Figure 6a where the increase in soil moisture is seen on DOY 226 at a depth of 4.5m. This increase is not a measuring mistake since it was persisted in the measurements that followed. This unique feature is also clearly shown in the 2-D water loss profile (Fig. 17b, plot D, DOY 182). This behavior is not likely to be related to internal drainage (after 50 days from the flood), and probably due to the effect of lateral water movement [22]-[23]. Figure 7, which shows the typical seasonal changes of fractional water loss patterns for olive trees, indicates temporal changes in root activities along the drying period. The active zone is mainly found between 1.2-3 m although, shortly after the flood, root activity is also found between 0.3-1.2m. Later on, it is reduced while the deeper active zone became more pronounced. The same behavior of root activity responded to drying out soil was seen in Song et al. (2018) [24], Lobet et al. (2014) [25] and Schenk and Jackson, (2002) [26]. In the 2-D map of water loss (Fig. 8), it is not possible to discern a homogeneous thin layer of fine gravel or stone as observed by Lövenstein et al. (1991) [27]. This lack of homogeneity may be the reason for the lack of homogeneity in the spatial distribution of root and moisture, a common phenomenon
in studies under field condition [28]-[34]. Figure 9 shows the seasonal changes in daily transpiration, obtained by the averaged soil water measurements, also shown is Pan (A) daily evaporation. In general, a bell-shaped pattern is shown for most plots with a rather sharp increase in the daily transpiration after flooding. After that, it was followed by a peak (narrow or wide depending on the total amount of available water) and thereafter a decrease in daily transpiration values. There seems to be little correlation between the general pattern of daily transpiration and that of the potential evapotranspiration ETp (pan A). In 2017, during the measuring period, no significant change in ETp occurred. Therefore, it is reasonable to assume that the pattern of daily transpiration is mainly affected by physiological processes and soil water availability. In 2018, however, due to the larger amounts of water and longer drying period, the ETp started decreasing since DOY 225, while in plots D and E sharp reduction in transpiration had already started. With the highest amount of available water, F plot follows the ETp until DOY 250 where a sharper decrease in daily transpiration values (due to limited water in the soil) appears. Therefore, in 2018 stress behavior is evident as well, but less pronounced than in 2017. During the peak period (colored in light red), the daily transpiration values for plot E and F were similar for both years while plot D showed higher daily values in 2017. One should pay attention to a secondary minimum in daily values found for plot D (at ~ DOY 180), which occurred due to the abnormal water input by the effect of lateral water movement observed in the bottom layers (Fig. 6a & 8b). In this study, transpiration during the growing season mainly depends on the soil moisture content and on potential evapotranspiration. More specific, ETp affected the transpiration rate only under higher soil water content which was in agreement with da Silva et al. (2015) [35].

5. Conclusions

The primary findings in this research shows that the water distribution within the soil is highly inhomogeneous even under flooded conditions. Gravitational water movement was observed after the flood, as expected, but indications for lateral movements were also found two months after the flood event. Soil water loss rate, due to transpiration is mainly correlated with total soil water. A weak correlation with atmospheric conditions (ETp) was found when total available water was high. The spatial-temporal roots’ activity along the drying out periods showed that root water uptake initially occurred between 0.3-1.2 m then shifted to 1.2-3 m.

6. Patents

This section is not mandatory, but may be added if there are patents resulting from the work reported in this manuscript.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

Conflicts of Interest: The authors declare no conflict of interest

References


