Agricultural Water Management 165 (2016) 190–197

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Water-harvesting designs for fruit tree production in dry environments

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ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form 5 November 2015
Accepted 7 November 2015
Available online 24 November 2015

Keywords:
Water management
Dry areas
Fruit trees
Hillslopes
Olive trees
Soil moisture content

ABSTRACT

Water scarcity and increasing demand coupled with climate change require maximizing the use of available resources. Water harvesting (WH) systems are currently being used in many areas to sustain crops and increase water productivity. This study investigated the effect of three treatments (S15: 50-m^2 catchment area with 15% slope, S8: 50-m^2 catchment area with 8% slope, and L8: 70-m^2 catchment area with 8% slope) on the amount of water harvested in tree basin for young olive (*Olea europaea* L.) trees from November 2002 to July 2003. Soil moisture was monitored weekly during the rainy season and bi-weekly afterwards. To determine moisture changes in the catchment and target areas and amount of water harvested (in liters) for each tree, volumetric soil moisture content was measured at three or four points along the slope using a neutron probe down to a maximum depth of 120 cm, as soil depth allowed.

WH structures increased soil moisture content in the rootzone compared to the catchment area. The rainfall threshold for runoff generation was less than 15 mm. Land slope was more important than micro-catchment size for increasing the amount of water harvested. Compared to the 8% slope, the 15% slope resulted in larger harvested amounts for small storms, but the two were comparable when storms were large. The large micro-catchment size resulted in higher amounts of harvested water only in the presence of storms greater than 26 mm. After adding the amounts lost by evapotranspiration, the net amount of water harvested in the tree basin of each tree for the 2002–2003 rainy season reached 722 and 688 l (or 361 and 344 mm) for treatments S15 and S8, respectively. Deeper soil profiles (i.e., >90 cm) were important to ensure longer storage periods. By early July, soil moisture content in the tree basin for treatments S15, L8 and S8 was still higher by 38, 13, and 5% respectively, than the levels recorded at the onset of the experiment. WH increased soil moisture content during the spring and early summer, a critical period for olive production.

1. Introduction

In recent years, fruit tree production in the Mediterranean basin and areas of similar climate (e.g., California) has been expanding to drier inland areas where annual rainfall might not be enough for successful production and irrigation is limited or not available. Rainfed olive trees are most successfully grown in areas receiving more than 350 mm of annual rainfall, with some particular exceptions along the southern coast of the Mediterranean (Tubeileh et al., 2004). However, the low and erratic amount of rainfall in drier inland areas is not enough to support olives, especially during the hot dry season that lasts from May through October, which also coincides with the most active olive vegetative and reproductive growth stages (Tubeileh et al., 2004). Moreover, recent climate change forecasts are suggesting that olive evapotranspiration will increase by 8% and irrigation requirements will jump by 18.5% (Tanasijevic et al., 2014). A traditional method of increasing available water for the trees in dry environments consists of using water-harvesting (WH) techniques. WH implies the collection of water from one area (catchment or contributing area) in order to supply water to crops in another (target) area (Bruggeman et al., 2008; Oweis et al., 2012). These techniques have been known in the Middle East for several thousands of years (Reij et al., 1988), and are currently being used in many drought-suffering countries in the

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http://dx.doi.org/10.1016/j.agwat.2015.11.006
0378-3774/

dry strip from North and sub-Saharan Africa across the Middle East stretching to India, Afghanistan, and China.

WH is of particular interest in hilly areas due to the high runoff potential and the difficult accessibility for irrigation equipment. Optimum WH design depends on the site conditions, climate, purpose, and crops to be grown (Reij et al., 1988; Oweis et al., 1999). Other authors such as Bulcock and Jewitt (2013), concluded that soil characteristics and minimum slope were the most important factors for system efficiency. Slope angle and slope length of the micro-catchment are of primary importance for runoff generation (Oweis et al., 2012). Although there is a general agreement that increasing slope increases runoff coefficient, some authors argue that there is a maximum slope after which there is no increase in the amount of water harvested (Nassif and Wilson, 1975). In the same vein, under monsoon climate in India, Sharma et al. (1986) have shown that slopes of 5 and 10% did not have a significant difference in the amount of water harvested. Under a similar monsoon climate in Pakistan, Suleman et al. (1995) arrived at the same conclusion for 7, 10, and 15% slopes.

However, as the efficiency of WH systems is highly dependent on rainfall characteristics and the properties of the runoff area, the above results might not be valid for WH systems on stony hillslopes in Mediterranean climate areas. Achieving functional WH designs might minimize the need to buy and convey irrigation water from distant sources and therefore ensure the sustainability of fruit trees in drier environments.

The objective of this work was to study the effect of three different micro-catchment designs on the amount of water harvested under dry hillslope conditions in northern Syria in order to recommend the designs that are most capable of increasing soil moisture content in the rootzone of olive trees under semi-arid conditions.

2. Materials and methods

2.1. Site description

This experiment was carried out in a four-year-old olive grove (*Olea europaea* cv. 'Qaisi') in Habs village (35.49°N; 37.29°E), Khanasser Valley, 80 km to the southeast of Aleppo in northern Syria. This area is a typical example for arid inland areas on the eastern and southern parts of the Mediterranean basin. Upon establishment of the site, cultivar 'Qaisi', a dual-purpose variety (Tubeileh et al., 2008a), was chosen due to its high tolerance to drought and its popularity in the areas to the east of Aleppo (Tubeileh et al., 2004, 2008b). The valley is characterized by long dry and hot summers with maximum temperatures that can sometimes reach 50 °C in July and August. The monthly average maximum temperature in July (hottest month) is 37 °C, while the monthly average minimum temperature in December (coldest month) is 0.7 °C. Average annual rainfall recorded during the period 1957–2001 is 223 mm, received mainly from November through April. This small amount of rainfall is not homogenously distributed over the rainy season and is extremely variable from one year to another. High temperatures and low humidity lead to a high annual reference evapotranspiration that amounts to 1840 mm (2002–2004).

The soil of the experimental site is a Lithic Xerothent (U.S. Dept of Agriculture Soil Survey Staff, 1975) with 21% clay, 37% silt, and 42% sand in the top 15 cm. Table 1 shows the main physical properties of the soil. Overall, it can be classified as clay loam, with a top–down progressive increase in bulk density, field capacity, and permanent wilting point. The depth of this well-drained soil ranges between 60 and 90 cm for most of the trees and does not exceed 135 cm in best cases. The parent material is chalky limestone.

The land slope is east-facing and rather irregular, between 2 and 20% for most of the field. Before planting the trees, the site was a degraded, natural rangeland area. The trees were planted at an approximate spacing of 8 m × 10 m. When planted, each tree received 10 kg of unfermented sheep manure. In February 2003, each tree received 136 g nitrogen in the form of ammonium nitrate, which is consistent with the low-input systems in dry areas (Thomas et al., 2006). All the trees used in the experiment had a single trunk.

2.2. Procedure

Twelve trees were selected to study the effect of slope and micro-catchment size on the amount of runoff-water harvested. Two micro-catchment sizes (50 and 70 m^2) were selected according to topography, available space between the trees, and the direction of the slope. For the catchment slope, two predominant slopes were naturally present in the field; 8 and 15%, the treatments are described as follows:

- S15: catchment area of 50 m^2 with a slope of 15%.
- S8: catchment area of 50 m^2 with a slope of 8%.
- L8: catchment area of 70 m^2 with a slope of 8%.

The effect of the slope was investigated through the comparison of treatments S15 and S8, while the effect of catchment area was determined by comparing treatments S8 and L8. In addition to these three treatments, one 50 m^2 catchment with a slope of 5% was kept without a tree to serve as a control (C) for monitoring runoff water accumulation in the soil without tree transpiration. All treatments are described in Table 2.

2.3. Determination of soil moisture content

Soil moisture content was recorded from 17 November 2002 to 3 July 2003. Readings were taken every week during the rainy season and at two-week intervals thereafter (May–July). Soil moisture content of the upper layer (0–15 cm) was determined gravimetrically while an onsite-calibrated neutron probe (Type IH-II, Didcot Instruments Co. Ltd., Abington, UK) was used for the deeper layers. Aluminum access tubes were inserted at three locations around every tree; 0.5 m upslope from the trunk (inside the tree basin or target area), 1.2 m from the tree upslope, and 2 m from the tree downslope (outside the catchment area) to measure water infiltration in different locations of the micro-catchment (Fig. 1). For treatments S15 and S8, a fourth access tube was inserted at 4 m upslope for two trees each, to estimate soil moisture in the catchment area. These access-tube locations will be referred to as '0.5 m up', '1.2 m up', '2 m down', and '4 m up', respectively. These locations were selected based on previous research, and are supposed to represent soil moisture content in catchment area (4 m up), bottom-end of catchment area (1.2 m up), target area (0.5 m up) and lateral flow outside target area (2 m down).

Soil moisture content was measured in 15-cm soil increments to a maximum depth of 90 cm. This soil depth encompasses the olive root zone, as several studies have shown the vast majority of the olive root system to be in the top layers of the soil, especially for young trees (Fern&#x00E1ndez and Moreno, 1999). Rainfall was recorded using an automatic rain gauge installed in the middle of the grove.

2.4. Determination of the recharge area around the tree

The runoff target area was the tree basin, covering 2 m^2 (or 0.8 m radius around tree trunk) based on the different soil moisture contents measured at '0.5 m up' and '1.2 m up' from the trunk. With an

Table 1
Soil physical properties in the experimental site.

Soil layer (cm)	Particle size distribution (%)			Texture	Bulk density (g cm^{-3})	Field capacity (m^3 m^{-3})	Permanent wilting point (m^3 m^{-3})	Available water (m^3 m^{-3})
	Clay	Silt	Sand					
0–15	21.2 ± 1.59	36.7 ± 0.57	42.0 ± 1.02	Loam	1.07	0.331	0.157	0.174
15–30	33.2 ± 0.84	36.4 ± 0.31	30.4 ± 0.53	Clay loam	1.27	0.348	0.120	0.228
30–45	34.6 ± 0.93	35.9 ± 0.03	29.5 ± 0.90	Clay loam	1.28	0.354	0.143	0.221
45–105	31.4 ± 1.15	38.4 ± 1.47	30.1 ± 0.32	Clay loam	1.30	0.354	0.162	0.192
Average	30.1	36.9	33.0		1.23	0.347	0.146	0.201

Table 2
Description of the treatments.

Treatment	Micro-catchment size (m^2)	Slope (%)	Presence of a tree	Number of replicates	Range of soil profile depth (cm)
S15	50	15	Yes	4	60–135
S8	50	8	Yes	4	75–120
L8	70	8	Yes	4	45–90
C	50	5	No	1	90

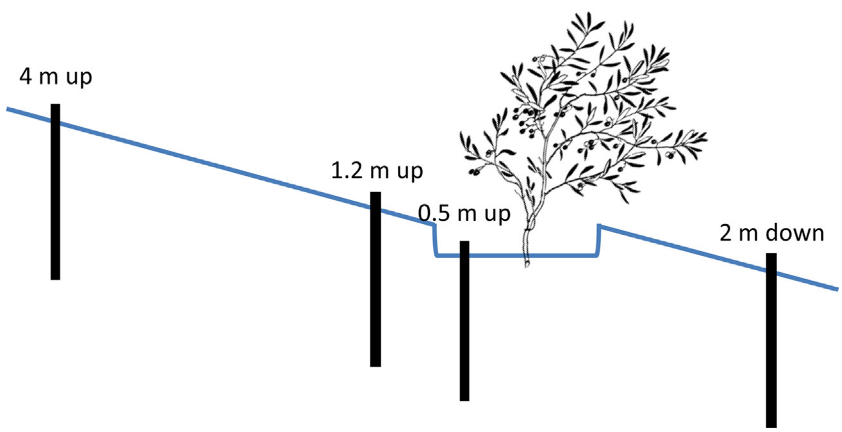

Fig. 1. A diagram showing the different locations for access tubes along the slope.

expected up- to downslope soil moisture gradient in the tree basin, the '0.5 m up' moisture measurements were assumed to represent soil moisture content of the 2 m^2 tree basin.

2.5. Number of replicates and statistical analysis

As indicated above, the location '4 m up' was applied only for treatments S15 and S8 (for two trees of each). For the locations '0.5 m up', '1.2 m up', and '2 m down' and the treatments S15, S8, and L8, the average of four replicates was computed and the results were expressed in terms of volumetric water content.

A one-way ANOVA test using IBM SPSS software version 22.0.0.0 (IBM SPS Statistics, 2013) was performed to assess the effect of the location in the catchment on soil moisture. For slope and catchment size effects, every slope-size combination was considered a treatment and a one-way ANOVA test was performed on soil moisture depth (in mm). Differences were considered significant at the $p < 0.05$ level, unless otherwise indicated. Mean separation was performed using Tukey Test at dates where there was a significant treatment effect.

3. Results and discussion

3.1. Rainfall during the experiment

The rainy season started on 11 September 2002 (DOY 254) and ended on 31 May 2003 (DOY 151). The amount of rainfall received before starting the experiment was 33.6 mm while the total amount recorded during this season was 301.8 mm, which represents 135% of the 45-year average rainfall. The maximum one-month rainfall was recorded in February with a total of 72.5 mm (24.1% of annual rainfall) while 94% of rainfall amount was received during the period November to March, inclusive.

3.2. Evidence of water harvesting

The occurrence of WH was determined by comparing soil moisture (to a depth of 90 cm) in the tree basin (location '0.5 m up') with that recorded at the other locations up- and down-slope ('1.2 m up', '2 m down', and '4 m up') (Fig. 2). The rainfall received between 9 December (DOY 343) and 14 December (DOY 348) (total of 15.9 mm) exceeded the threshold for runoff generation and WH. During this same timeframe, moisture content in the total soil profile at the location '0.5 m up' increased by 26.0, 28.8, 25.7, and 40.5 mm for treatments S15, S8, L8, and C, respectively (Fig. 3). This indicated that the threshold for runoff generation and WH is less than 15.9 mm and possibly less than the largest rain event received in this timeframe (12.9 mm). The analysis of variance showed that soil moisture content at the location '0.5 m up' was significantly ($P < 0.10$) higher than that for the other locations for all readings taken between 21 December 2002 (DOY 355) and 22 February 2003 (DOY 355). Until early December, soil moisture contents were very close at the different locations. A considerable difference appeared between the location '0.5 m up' and the other locations after a 46.6 mm rain storm on 19 December (DOY 353). Soil moisture contents on 21 December 2002 (DOY 355) for the three different treatments at the location '0.5 m up' ranged between 0.28 and 0.32 m m^{-3} versus 0.21–0.26 mm^{-3} for the location '1.2 m

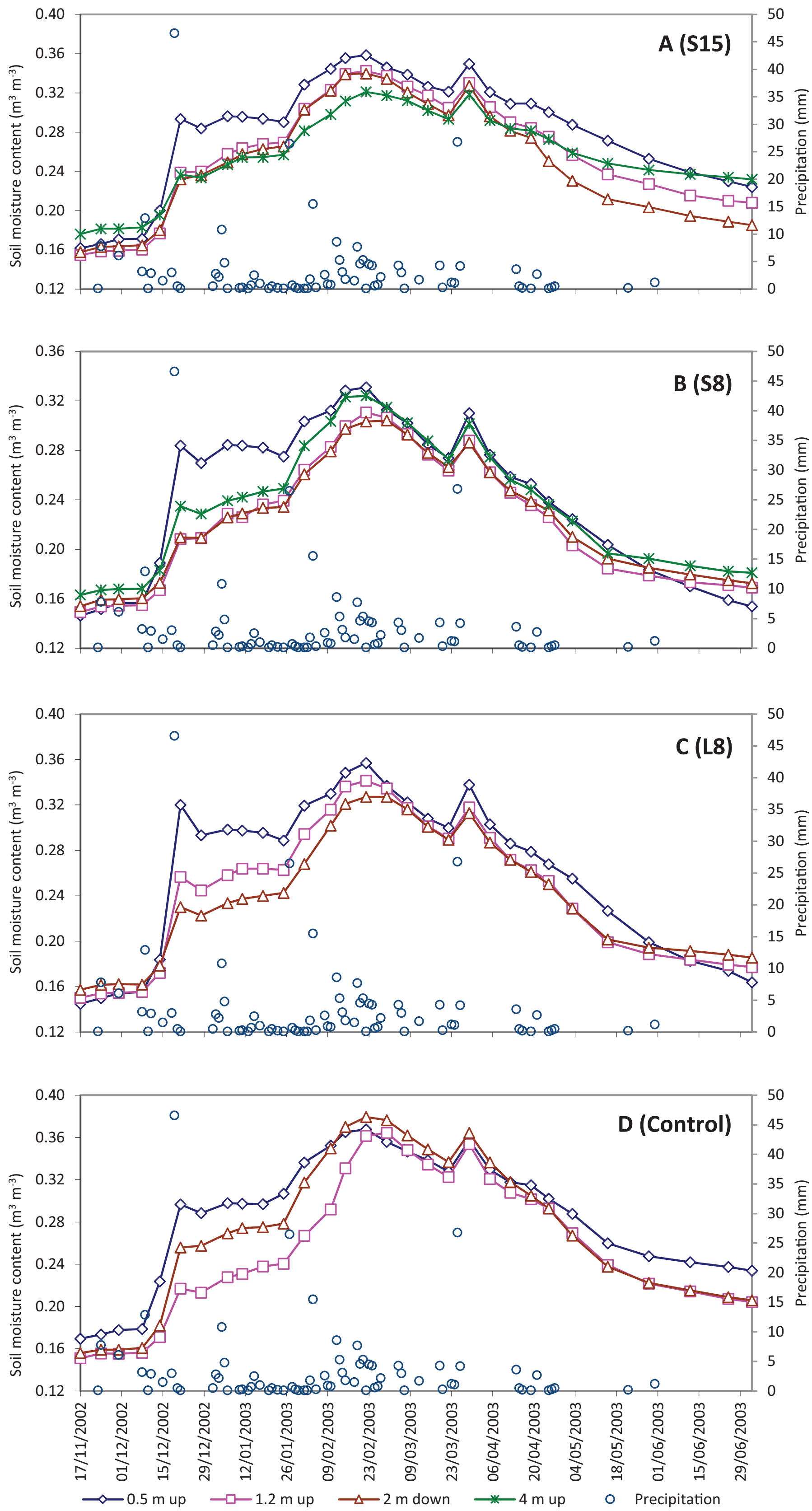

Fig. 2. Soil moisture content in the top 90 cm profile at different distances from the tree basin along the slope for the treatments: S15 (A), S8 (B), L8 (C) and control (D).

up', 0.21–0.26 m m^{-3} for '2 m down', and 0.24 m^3 m^{-3} for '4 m up'. After this date, the difference between locations decreased with time, especially in the case of treatment C (Fig. 2d). From 29 March (DOY 88) on, soil moisture content started to decrease linearly for all treatments and locations.

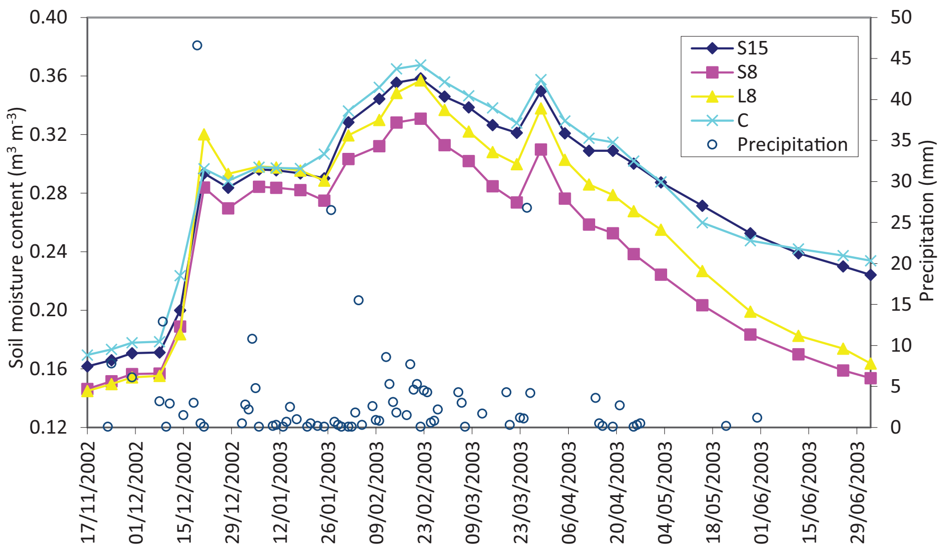

Fig. 3. Soil moisture content in a 90 cm soil profile at 0.5 m from the trunk as affected by the different WH treatments in addition to precipitation amounts.

For the treatments S15, S8, and L8, the locations '1.2 m up' and '2 m down' had similar moisture contents but differed at the beginning of the rainy season in the case of treatment L8 and at the end of the rainy season for treatment S15. For treatment L8, this difference was due to the fact that the rainstorm of 19 December (DOY 353) considerably increased soil moisture content at the location '0.5 m up', increasing therefore soil moisture content in the lower layers of location '1.2 m up' by mass flow. For treatment S15, the lower soil moisture content in the location '2 m down' observed from 20 April (DOY 110) onward compared to the location '1.2 m up' could be attributed to the presence of tree roots in the former location, which is almost at the same elevation level as the tree basin.

Although the effect of WH did not last long into the summer, the increase of soil moisture content in the winter and spring months is crucial for olives as it coincides with the highest crop coefficients reported by Orgaz and Fereres (1997) (cited in Fernández and Moreno (1999) Fernández and Moreno (1999)), and is very important for vegetative growth, flowering, and fruit set. Pierantozzi et al. (2013) have shown that full water requirements are needed approximately 2 months before flowering to avoid detrimental effects of water stress on biochemical–physiological and yield parameters. The generation of runoff and success of WH on our site are in agreement with the findings of Abu-Zreig and Tamimi (2011) under a similar climate and rainfall average in Jordan, using sand ditches to collect water on slopes and increase infiltration. Similarly, recent data on pistachio trees in a neighboring area in Turkey have shown that WH resulted in higher water accumulation in the target area compared to the catchment area, whether the catchment area was natural or covered with different materials (Yazar et al., 2014).

Table 3
P-value results for micro-catchment slope and size effects at all reading dates.

Date	*P*-value	
	Slope	Size
17-Nov-02	0.364	0.580
24-Nov-02	0.362	0.462
30-Nov-02	0.190	1.000
8-Dec-02	0.238	0.861
14-Dec-02	0.682	0.918
21-Dec-02	0.850	0.706
28-Dec-02	0.547	0.729
6-Jan-03	0.561	0.845
11-Jan-03	0.599	0.916
18-Jan-03	0.746	0.914
25-Jan-03	0.395	0.828
1-Feb-03	0.186	0.781
10-Feb-03	0.048	0.530
15-Feb-03	0.122	0.415
22-Feb-03	0.172	0.396
1-Mar-03	0.069	0.448
8-Mar-03	0.036	0.432
15-Mar-03	0.024	0.541
22-Mar-03	0.020	0.522
29-Mar-03	0.019	0.210
5-Apr-03	0.047	0.677
12-Apr-03	0.029	0.693
19-Apr-03	0.013	0.669
25-Apr-03	0.008	0.432
3-May-03	0.005	0.432
15-May-03	0.009	0.911
29-May-03	0.004	1.000
12-Jun-03	0.003	0.894
25-Jun-03	0.002	1.000
3-Jul-03	0.001	1.000

3.3. Effect of slope on soil moisture content

Table 3 shows ANOVA results for the slope and micro-catchment size effects. Treatment S15 had the highest soil moisture content during most of the experimental period (Fig. 3), with differences being significant on 10 February 2003 (DOY 41) and from 8 March (DOY 67) until the end of the experiment. For smaller rainfall events, soil moisture content tended to increase at higher rates for treatment S15 than for treatment S8 (Fig. 3). For instance, in the week from 26 January (DOY 26) to 1 February (DOY 32) (weekly rainfall of 27.7 mm) average soil moisture content increased by 0.038 $m^3\,m^{-3}$ for treatment S15 while it increased by 0.028 and 0.030 $m^3\,m^{-3}$ for treatment S8 and the control catchment (C), respectively. Similarly, this correlation between the slope and the amount of water harvested can also be assessed by comparing treatments S15 and C. These treatments still had very similar values of soil moisture content in spite of water uptake by the trees in treatment S15. These results disagree with the conclusions of Sharma et al. (1986), among others, who reported only a slight difference in runoff between slopes of 5 and 10% indicating the presence of a critical slope beyond which there is no increase in the amount of runoff-water harvested. The discrepancies between the two studies could be due to the higher storm intensity in their monsoon climate, where 49% of total rainfall occurred in storms with intensity >40 mm h^{-1}, while the highest hourly intensity at our site was 9.4 mm h^{-1}. This higher rain intensity allowed for significant WH to happen at 0.5% slope in the study of Sharma et al. (1986). Another difference with these authors is their higher topsoil bulk density (1.56 g cm^{-3}) compared to our experiment (1.07–1.37 g cm^{-3}). This higher bulk density in their study reflects a lower porosity, hence a lower water infiltration rate and higher runoff efficiency, therefore increasing WH efficiency and decreasing the slope effect.

In our site, the importance of a steeper slope for higher runoff generation diminished when rainstorms were large enough (∼10 mm or more). For example, on 9 December (DOY 343) (12.9 mm) and 19 December (DOY 353) (46.6 mm), the difference in slopes between 8 and 15% had no effect on the amount of runoff water harvested (Table 3). The change in soil moisture content at the location '0.5 m up' between 14 December (DOY 348) and 21 December (DOY 355) was identical for treatments S15 and S8. Average soil moisture contents increased between these two dates in treatments S15 and S8 by 0.093 and 0.095 $m^3\,m^{-3}$ respectively (corresponding to a relative increase of 47 and 50%, respectively) as a result of the highest rainfall event during the season recorded on 19 December (DOY 353) (Table 4). Another comparable increase between these two treatments was observed on 6 January (DOY 6) (right after two rain events of 10.8 and 4.8 mm) and 22 February (DOY 53) (weekly rainfall of 20.9 mm), in which soil moisture content in both treatments increased by 0.003 $m^3\,m^{-3}$.

Surprisingly, soil moisture content for treatment S8 increased at higher rates than that for treatment S15 on 15 February (DOY 46) and 29 March (DOY 88), and to some extent on 14 December (DOY 348) and 6 January (DOY 6). This exceptionally lower increase in treatment S15, as compared to S8, can be attributed to the deeper soil profile in S15, which enables the partitioning of the harvested water over a bigger volume of soil than in the case of S8, thus decreasing the relative increase per soil layer. This higher soil depth in S15 also explains the slower soil moisture depletion rate in this treatment (particularly observed in the deep layers) as compared to treatments S8 and L8 (Fig. 4). Furthermore, the lower soil moisture content before these rainfall events in S8, compared to the other two treatments (L8 and S15), enabled it to retain more extra water than those treatments, which were already at field capacity. This explanation agrees with the results of Oweis and Taimeh (1996) who reported that storage efficiency in the rootzone dropped when soil reached field capacity, inducing a loss of harvested water outside the rootzone by lateral seepage.

3.4. Effect of micro-catchment size on soil moisture contents

The effect of the micro-catchment size on soil moisture content was not significant at any date, possibly due to high tree-to-tree variability. In spite of that, the large micro-catchment size tended to result in more runoff generation during large storms. For the largest storm of the year (46.6 mm) on 19 December 2002 (DOY 353), treatment L8 had the highest increase in soil moisture content, which jumped by 74% (from 0.18 to 0.32 $m^3\,m^{-3}$) while it increased by 50% for treatment S8. In terms of absolute values, soil moisture content in the 90 cm soil profile increased by 61.5 and 42.5 mm (123 and 85 l for the 2 m^2 basin area) for treatments L8 and S8, respectively. In addition, the 26.5 mm storm that occurred on 27 January (DOY 27) represents another good example of this effect of the micro-catchment size. The increase in soil moisture, induced mostly by this rainfall event (26.5 mm) and recorded on 1 February (DOY 32), amounted to 0.031 $m^3\,m^{-3}$ versus 0.028 $m^3\,m^{-3}$ in S8.

This storm might be slightly higher than the threshold point beyond which the large micro-catchment used in this experiment induced more runoff water than the small one. This hypothesis is also supported by the reading taken on 29 March (DOY 88) where soil moisture in the rootzone of the trees with large or small micro-catchments of comparable slope (8%) increased by the same amount (0.036 $m^3\,m^{-3}$). There were also some less pronounced events (e.g., between 10 and 22 February (DOY 41-53)) where soil moisture increase in L8 was higher than that in S8. The difference in soil moisture content between treatments L8 and S8 persisted until the end of the experiment.

These results allow us to conclude that in case a region was characterized by small storms, such as most areas with Mediterranean climate, increasing the size of the micro-catchments beyond 50 m^2 would not have a major effect on the amount of water harvested, and would result in lower runoff efficiency. This finding confirms the observations of Boers et al. (1986) who reported that smaller catchments have higher runoff efficiency than larger ones although they might produce a lower absolute amount of runoff.

3.5. Amount of water gained by WH structures

An indication of the amount of water harvested in the presence of the tree can be obtained through the comparison of locations '0.5 m up' and '4 m up'. Soil moisture content (for a 105-cm soil profile) at the location '0.5 m up' was higher than that at the location '4 m up' by 71–129 mm for treatment S15 and 82–112 mm for treatment S8 (respectively equal to 142–258 l and 164–224 l for the 2-m^2 tree basin). Runoff efficiencies (water harvested divided by rainfall over the runoff catchment area) were 1.4% for S8 and S15 and 0.9% for L8. Nevertheless, these values are underestimated since we considered only the net positive change in soil moisture during the rainy weeks, not taking into account the amount of water that was taken up by the tree, percolated into the bedrock, lost through lateral seepage or evaporated from the soil surface between the rain event and the reading. The amount of actual evapotranspiration for the trees, average of five trees in the site, during the rainy season (1 November (DOY 305)—30 April (DOY 120)) amounted to 232 mm, which is equal to 464 l (for a 2 m^2 root area). If this evapotranspired amount were added to the aforementioned net soil moisture change, the maximum net amount of water harvested (minus rainfall) would be equal to 722 and 688 l for treatments S15 and S8, respectively, which also increases the runoff efficiencies mentioned above.

3.6. Storage of harvested water in the different soil layers

A closer look at different soil layers reveals that the increase in soil moisture on 21 December (DOY 355) was limited to the first three soil layers (0–45 cm) in the case of treatments S15, S8, and C while for L8 a considerable increase in soil moisture content was also observed in the two deeper layers (60–90 cm) (Fig. 4). The importance of soil depth as a storage reservoir is indicated in Fig. 5, which shows total soil moisture content in variable-depth soil profiles (75 to 120 cm) for trees of treatment S8. Total soil moisture amount (in mm) increased substantially with the increase in soil profile and was always highest for the tree that has the deepest profile. Furthermore, the tree with the shallowest profile showed less capacity to keep the harvested water than the other trees.

Land slope was more important than micro-catchment size for increasing the amount of water harvested. This was particularly true for smaller rainfall events (<4 mm) that characterize the Mediterranean climate. A good proportion of these events happen in the spring, which marks the start of the active olive growth season (Fernández and Moreno, 1999). Therefore, increasing water storage in the rootzone at this time through WH is of crucial importance for olive flowering and fruit set and for water supply in the dry months.

Our results show that deep soil profiles enable higher WH efficiencies and better storage of this harvested water (such as the case

Table 4
Weekly amounts of major rainfall events during the 2002–2003 rainy season and corresponding change in soil moisture content (in $m^3\ m^{-3}$) for each treatment.

Dates	Dec. 09-Dec. 14	Dec. 15-Dec. 21	Dec. 29-Jan 06	Jan. 26-Feb. 01	Feb. 02-Feb. 10	Feb. 11-Feb. 15	Feb. 16-Feb 22	Mar 23-Mar 29
Day of Year	343–348	349–355	363–6	26–32	33–41	42–46	47–53	82–88
Rainfall (mm)	15.9	51.7	21.2	27.7	22	18.8	19.2	33.3
S15	0.029	0.093	0.012	0.038	0.016	0.011	0.003	0.028
S8	0.032	0.095	0.015	0.028	0.009	0.016	0.003	0.036
L8	0.029	0.136	0.005	0.031	0.010	0.018	0.009	0.038
C	0.045	0.073	0.009	0.030	0.016	0.013	0.003	0.030

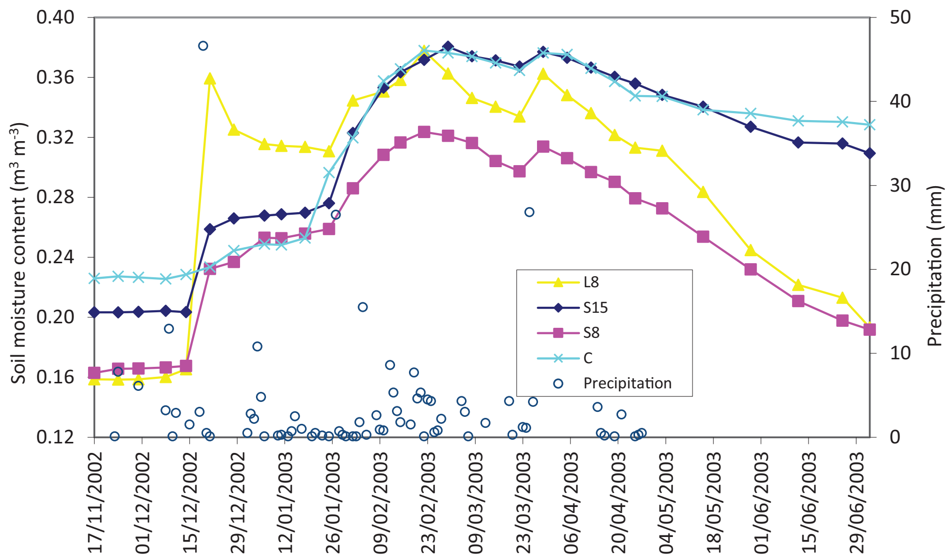

Fig. 4. Soil moisture content for the 60–90 cm soil layer, at 0.5 m from the trunk for the different treatments, which shows water storage deeper in the soil profile. Precipitation data are also added.

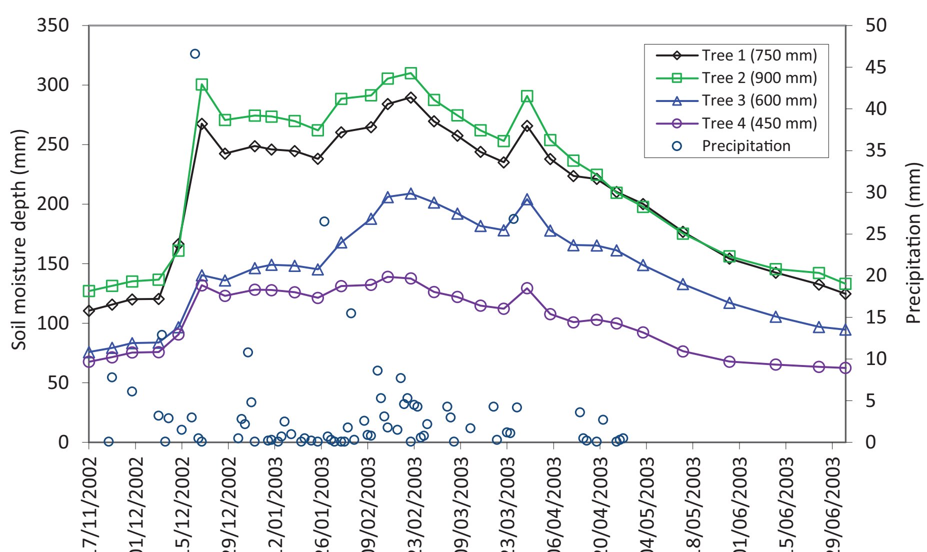

Fig. 5. Total soil moisture depth in the entire soil profile for individual trees of treatment S8. Readings were taken at 0.5 m from the trunk for the trees (soil profile depth between parentheses). Precipitation data are also added.

in treatment S15), which will be preferentially kept in the deep layers where olive roots can extract it. This finding confirms the literature information (e.g., Reij et al., 1988; Oweis et al., 1999) indicating the importance of having deep soil profiles in order to store the amount of water harvested, especially in the case of fruit trees.

Large amounts of harvested water were drained from the soil shortly (a few days) after rain events. This points to the need to increase soil water-holding capacity by improving soil structure. Soil organic matter in our soil is very low (around 10–15 g kg^{-1}), which is typical in dryland soils (Thomas et al., 2004). In sub-Saharan Zougmoré et al. (2003) pointed out that applying compost or animal manure (in addition to WH structures) increased soil moisture content and plant yield as compared to simple WH structures (without any amendments). Besides, the application of these organic substances can improve the fertility of the inherently poor soils of dry areas.

At the end of this experiment (3 July 2003) (DOY 184), soil moisture content in the tree basin for treatments S15, L8, and S8 was respectively higher by 38, 13, and 5% than the level recorded at the onset of the experiment on 11 November 2002 (DOY 315) (0.15–0.16 $m^3 m^{-3}$). All three treatments ensured olive survival through the spring and early summer. The effects of WH on tree growth in this site were published in Tubeileh et al. (2009). To adapt to water stress, olive trees have developed some anatomical and physiological mechanisms such as: a larger root:canopy ratio (Nuzzo et al., 1997), high absorption capacity at low soil water potentials (Abd-El-Rahman et al., 1966), root osmotic adjustment (Xiloyannis et al., 1996), wider root cortical tissues (Fernández et al., 1994), initiating new roots only in the spring (Fernández et al., 1990), lowering stomatal conductance (Fernández et al., 2006), accumulation of osmotically active substances (Pierantozzi et al., 2013), etc. However, as the trees grow and enter into their productive age, and given the low level of soil moisture recorded in early July, the trees would need supplemental irrigation if a commercial scale production is sought for. Supplemental irrigation during the critical stages for plant growth is needed to complement WH (Oweis and Hachum, 2006; Tubeileh et al., 2009).

The WH structures established on the slopes are likely to reduce flood risks to the annual field crops grown downslope. Given the small area of the field and absence of any permanent or ephemeral water courses in the area, it is unlikely for these systems to be creating any water distribution issues among local farmers.

4. Conclusions

The threshold for generating runoff in this rocky, sloping field was relatively low and WH measures increased the amount of water available for olive trees. A 15% slope resulted in an increase in the amount of water harvested, compared to an 8% slope, for small storms, while bigger storms (with rainfall events greater than 27 mm) resulted in the same amount of runoff for the two slopes at the same micro-catchment area. The large micro-catchment area resulted in higher amounts of harvested water only in the presence of storms greater than 26 mm, which occur once or twice per year. Therefore, it may be recommended to limit the catchment area to ~50 m^2. On those hillslopes, deeper soil profiles allowed for more water storage, which shows the importance of preparing deep, large-diameter holes for the trees. WH has increased soil moisture in the spring and early summer periods critical for olive growth, fruit set, and production. However, supplemental irrigation between July and September might still be needed to achieve commercial yields.

Acknowledgements

Thanks are due to Dr. Zuhair Masri and Dr. Michael Zöbisch for establishing this olive grove. We would also like to thank Christian Siderius for starting WH experiments on this site in 2001. We highly appreciate the technical assistance provided by Pierre Hayek, Ali Haj-Dibo and Mohammad al-Ali. We also acknowledge the cooperation of Mr. Faraj Issa who enabled us to work in his land. The funding provided by the German Federal Ministry for Economic Cooperation and Development (BMZ) is appreciated. The authors would like to thank the editor and three anonymous reviewers for their constructive comments.

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