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Water harvesting techniques for improving soil water content, and morpho-physiology of pistachio trees under rainfed conditions

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ABSTRACT

Water harvesting techniques have shown promising outcomes in mitigating risks, increasing yields and delivering positive influences on other ecosystems. A field study was conducted in Northern Jordan to assess the influence of combined in-situ water harvesting techniques, micro-catchment and mulching on soil moisture content, plant morphology, gas exchange [photosynthesis (*Pn*), transpiration (*E*), and stomatal conductance (*gs*)] and midday stem water potential (Ψsmd) of young pistachio (*Pistacia vera* cv. Ashori) trees. Four mulching treatments [straw, vertical gravel, horizontal gravel and control (no mulching)] and three micro-catchment areas (36, 64 and 100 m^2) were used. Pistachio trees were grown under rainfed conditions for two growing seasons. Gravel mulching (vertical and horizontal) and 36 m^2 micro-catchment had the highest percentage increase in plant height compared with other treatments. In addition, 36 m^2 micro-catchment significantly increased gas exchange variables (*Pn, gs*, and *E*). We partially attributed that to higher soil water content and Ψsmd in the 36 m^2 compared with 64 and 100 m^2 micro-catchment. Interestingly, the runoff water collected from 36 m^2 treatment was 75 % higher than 64 m^2 (53.4 vs. 30.6 L) and 28 % higher than 100 m^2 (53.4 vs. 41.7 L). Therefore, the 36 m^2 is the best micro-catchment area in term of runoff efficiency. Overall, the combined water harvesting techniques, gravel mulching (vertical and horizontal) and the 36 m^2 micro-catchment hold promise for improving the morphology and physiology of young pistachio trees grown under rain-fed regime.

1. Introduction

Arid lands cover approximately 26 % of the earth's surface and accommodate 2 billion people (Vettera and Rieger, 2019). These regions are sensitive to climatic changes, economic and political levels. In fact, the combination of rapid population growth, drought, poor management and governance practices, and the political status have increased the pressure on natural resources in those dry lands (Sawalhah et al., 2018; Vettera and Rieger, 2019). Managing land in a sustainable way requires a comprehensive approach that considers both bio-physical and socio-economic aspects with a long-term vision (Visser et al., 2019). Healthy soils and healthy land are the basic components to achieve the sustainable development goals (Visser et al., 2019). The transition towards integrated solutions based on concepts such as nature-based solutions has been suggested recently to achieve land degradation neutrality by 2030 (Keesstra et al., 2018a). Nature-based solutions such as the sustainable use and management of the soil-water systems are associated with healthier soil system (Keesstra et al., 2018a).

Drought is considered the main factor limiting crop growth and productivity in arid and semi-arid region, including Jordan. In fact, Jordan is among the poorest countries in water resources worldwide (Denny et al., 2008). According to the UNDP, more than 90 % of Jordanian (nine million hectares) land receives less than 250 mm precipitation annually. High demands for water coupled with frequent drought encourage growers, researchers and policy makers to pay more attention to appropriate water management practices to achieve greater production and to use soil and water resources in an appropriate way (Pourmohammadali et al., 2019). Water scarcity, unreliable rainfall and soil water stress make water management practices including rain water harvesting important interventions for water supply and food production in arid and semi-arid regions (Muriu-Ng'ang'a et al., 2017).

Water harvesting process through the collection and utilization of runoff water for productive purposes instead of runoff being left to cause erosion remains a promising alternative for sustainable agricultural

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intensification in arid and semi-arid regions, resulting in both risk reduction and yield improvements (Critchley and Siege, 1991; Dile et al., 2013). In fact, this rudimentary form of irrigation is an effective alternative to mitigate water scarcity in arid and semi-arid regions (Critchley and Siege, 1991; Oweis and Taimeh, 1996). Water harvesting techniques prolong the availability of water in the root zone by reducing the evaporation from the soil surface and surface runoff, and enhances the infiltration (Vohland and Barry, 2009). Ojasvi et al. (1999) found that growing jujube (*Zizyphus mauritiana*) seedlings with micro-catchment (conical micro-catchments of 1.0 m radius) had better chances of establishment in rainfed conditions as compared with conventional plantation technique. The adoption of irrigation management strategies, specifically water harvesting and deficit irrigation strategies in rainfed regions, Andhra Pradesh, India, had the potential to improve the productivity by 20 % and bring more area under irrigation with an increase of 140 % (Mandal et al., 2020).

In addition to water harvesting, mulching technique improves soil properties, soil-water storage, as well as crop yield (Chakraborty et al., 2008). In pecan (*Carya illinoensis*), straw mulching increased flowering, fruit set, fruit retention and yield compared with control (Mark et al., 2014). A 12 year-study on water harvesting showed that straw mulching technique reduced soil erosion rates two orders of magnitude lower than in the control (bare-soil) treatment (Cerdà et al., 2017). Keesstra et al. (2019) found that straw mulching (60 g m^{-2}) was able to delay the time to runoff initiation from 57 to 129 s, sediment concentration from 16.7 g l^{-1} to 3.6 g l^{-1} and the soil erosion rates from 439 g to 73 g. Additionally, the combinations of micro-catchment and mulching can significantly increase soil water storage and improve plant productivity (Grum et al., 2017; Li et al., 2016). For example, fish-scale pits with mulching (semicircular mini-catchment) increased soil water storage at soil layer depths of 0–180 cm by 14.2 %–21.8 % when compared with control (Li et al., 2016). When jujube trees were grown under combined micro-catchment (fish-scale pits + branches or straw), trees leaf transpiration significantly increased by 45.6 %–53.1 % (compared with bare land) and the evaporation decreased by 42.5 %–53.5 % (Li et al., 2018). Furthermore, the combined terracing (half-moon terrace) and mulching (pruned jujube branches and maize straw) enhanced soil water use in deep layers during both normal and drought years and consequently, helping jujube trees to tolerate drought (Gao et al., 2020). The combined gravel–sand mulching method provided a favorable environment for plant growth than non-mulched fields by reducing soil temperature, evaporation, wind speed, water erosion and runoff, improving infiltration, and enhancing biological activity and soil fertility (Li, 2003). Interestingly, a field study conducted in Northern Ethiopia revealed that the combined used of water harvesting and mulching techniques had greater positive effect on runoff and soil-moisture compared with water harvesting or mulching methods. In that study, tied ridges (water harvesting) reduced runoff by 56 %, straw mulch by 53 %, and combined tied ridges and straw mulch by 78 % when compared with control (Grum et al., 2017). In addition, soil-moisture content in the combined tied ridges and straw mulch (22.4 %) was greater than the control (19.9 %). Therefore, they recommended the combined straw mulching and tied ridges as an efficient in-situ water harvesting technique for improving on-site water availability and consequently, protect crops from dry periods.

Nuts including pistachio are high valuable crop and rich source of protein, fiber, phytosterols, antioxidants, monounsaturated and polyunsaturated fatty acids, which are known to be beneficial for human health. The daily intake of 44 g pistachios for 12-weeks improved linoleic acid, thiamin, pyridoxine, copper, manganese, and zinc intake without affecting body weight or composition (Fantino et al., 2020). Pistachio is a drought tolerance species; able to survive under drought conditions with as little as 100 mm of rainfall (Goldhamer and Beede, 2004). However, a supplemental irrigation has a positive effect on pistachio growth and productivity. In fact, greater yield can only be achieved when water supplies are adequate (Kanber et al., 1993; Pourmohammadali et al., 2019). Assessment of water harvesting on plant growth and yield is not new. However, few studies were on pistachio (Marino et al., 2018). In addition, no research we are aware of studied the combined effect of water harvesting and mulching on young pistachio growth dynamic and leaf gas exchange [photosynthesis (*Pn*), transpiration (*E*), and stomatal conductance (*gs*)]. We hypothesize that water harvesting × mulching can significantly improve soil moisture content. In addition, this combined effect (harvesting × mulching) has positive and significant effects on shoot morphology and physiology. The overall goal of this research was to sustain young pistachio trees in arid and semi-arid regions using simple, cheap, efficient and adaptable water management technique. To achieve this goal, our objective was to assess the influence of combining in-situ water harvesting techniques, micro-catchment and mulching on soil moisture content, plant morphology, gas exchange and midday stem water potential (Ψsmd) of young pistachio trees.

2. Materials and methods

2.1. Site description and plant material

A two year study was conducted at Jordan University of Science and Technology, Jordan (35° 59’ 28.32” E, 32° 29’ 42” N, elevation of 520 m) during 2011 and 2012 seasons. The study area has a semi-arid climate with hot summer and cold winter and annual average rainfall of 150–200 mm. The study location at the northeast of the campus (slope about 12 %) was prepared to establish the plantings following a 10m × 10m (between rows x between plants) planting arrangement. The 7 year old pistachio (*Pistacia vera* cv. Ashori) trees used in the study were grown in clay-silty soil with low infiltration rate and soil depth of about 1 m (Table 1). During the study period, trees were sustained on rain-fed regime and no supplementary irrigation was applied.

2.2. Treatments

During the experimental period, four mulching techniques [straw, vertical and horizontal gravel and control (no mulching)] and three micro-catchment area (36, 64, and 100 m^2) were evaluated (Fig. 1). For vertical gravel treatment, a 10 mm-size gravels was placed 50 cm away from the tree trunk forming an arc (semi-circle) shape; 25 cm depth and 20 cm wide. The horizontal gravel (10 mm-size) treatment covered an area of 1 m^2 below the trunk of the tree with one layer of gravel (depth of 2 cm). Straw treatment was laid out by adding dried straw (5 cm thickness) to cover the whole block. To minimize the cost of labor (straw application), purchase cost, and the transport of bales we used the minimum thickness that recommended in the literature (less thickness were not stable and blown by wind). Diamond-shape micro-catchment blocks (36, 64, and 100 m^2) were structured by covering the block edges with 25 cm height earth bund. In this study, the thickness of mulching materials laid on micro-catchments was different between straw and

Table 1
Soil physical and chemical properties.

	Soil depth	
	0–25 cm	25–50 cm
Clay (%)	59	48
Silt (%)	24	26
Sand (%)	17	26
pH	8.08	8.18
Electrical conductivity (dS m^{-1})	0.31	0.38
Field capacity (%)	35.5	46.1
Wilting point (%)	20.2	30.1
Bulk density (g cm^{-3})	1.17	1.45
N (%)	1	1.5
Soluble P (mg L^{-1})	2.91	0.51
Soluble K (mg L^{-1})	470	247

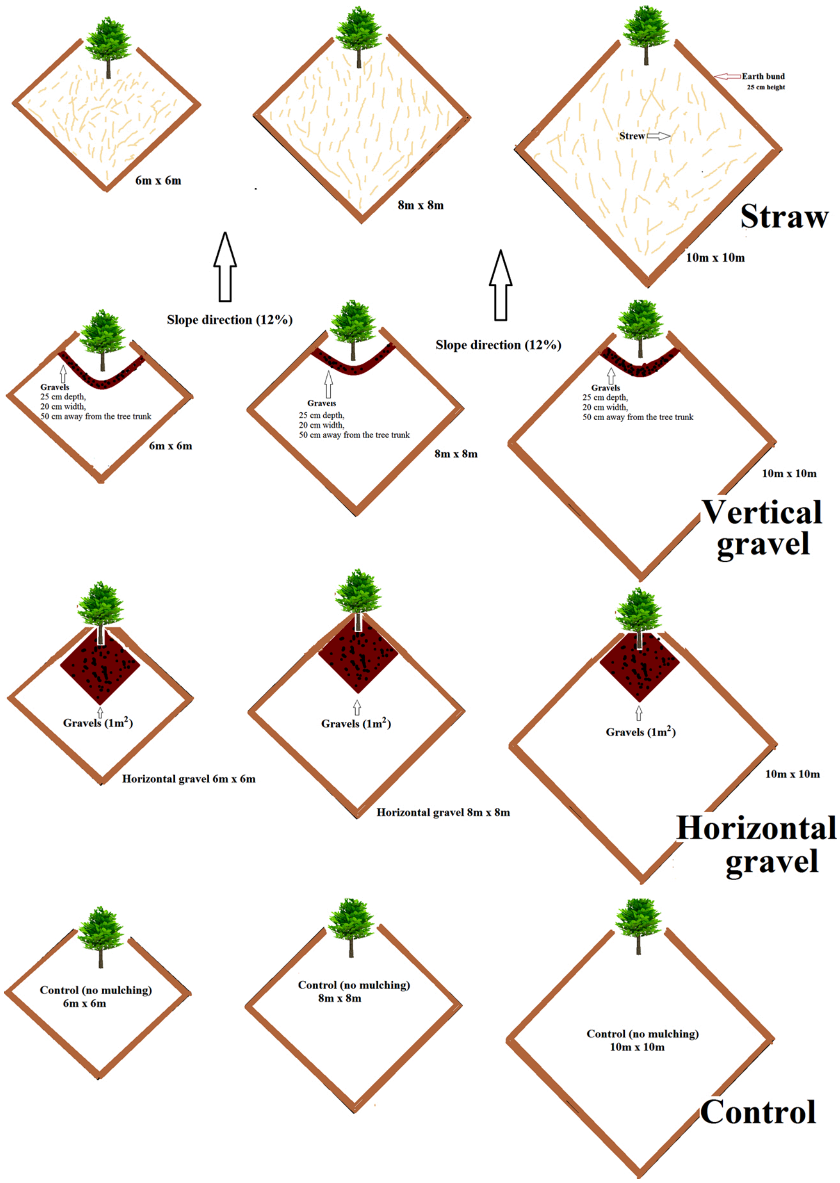

Fig. 1. Schematic diagram of the experimental area. Treatments (4 mulching techniques, 3 micro-catchment areas) were assigned at random within blocks.

gravels. This is because these two materials are different in their response to moisture, heat and future stability. However, the minimum recommended thickness were selected for each mulching type to reduce the input cost for farmers. The trees are planted in the lowest corner of diamond and at the center of semi-circle shapes.

The experimental study was laid out in a complete randomized block design (RCBD) with 4 replications. We used RCBD to minimize the variability within each block and to make sure that treatments (mulching techniques, micro-catchment areas) were compared under similar circumstances. In fact, the experiment was conducted on a sloped area (slope about 12 %). Accounting for spatial effects in the field was necessary to control variation in the experiment.

2.3. Measurements

Soil water content was calculated using time domain reflectometary (TDR) system, TRIME®-PICO IPH/T3 (IMKO, Ettlingen, Germany). For each experimental unit, two TDRs were installed at 25 and 50 cm depth and 20 cm from the tree trunk. Then, values from each soil depth interval were averaged to one value prior to statistical analysis.

Plant morphology (plant height and number of leaf per plant) were collected at the end of each growing season. Gas exchange (*Pn*, *E* and *gs*) and Ψsmd were measured (5 times) during the 2012 growing season. Gas exchange measurements were determined using a handheld photosynthesis system (CI-340, CID Bio-Science, WA, USA). Gas exchange measurements were conducted between 11:00 am and 1:00 pm from two sun-exposed and fully-mature leaves. Midday stem water potential was measured following the procedures of Othman et al. (2014a). A fully expanded leaf selected from the middle of shoot (one year old) were measured using pressure chamber (Model 600, PMS Instruments, Corvallis, OR, USA).

Runoff volume was determined following the procedure of Li et al. (2000). Runoff volume for micro-catchments was determined in 2011. Twelve micro-catchments [(36, 64 and100 m^2) × 4 replicates)] without plants were constructed near the pistachio growing field. A 20 L barrel was installed at the corner of each micro-catchment plot (lowest point of the slope) and collected the runoff volume from each plot after the rainfall events. The barrel was covered with plastic lid to prevent it from collecting precipitation and to prevent the evaporation of the collected runoff water. The runoff volume was measured after each rainstorm. The amount of rainfall was measured using standard rain gauge.

2.4. Graphing and statistical analysis

The study was laid out using a randomized complete block design with 4 replications and two factors (4 mulching techniques, 3 micro-catchment areas). The analysis of variance (ANOVA) and the least significant deference test ($P < 0.05$) in SAS (Version 9.4 for Windows; SAS Institute, Cary, NC, USA) were used to identify differences between mulching techniques, micro-catchment area and their interactions. Sigmaplot (Version 14.0 for Windows; Systat Software, San Jose, CA, USA) was used to graph the results.

3. Results

3.1. Soil moisture content

Soil mulching increased soil moisture content (compared with control) in both years, specifically between February and April, 2011–2012 (Fig. 2). However, there were no significant differences between mulching treatments (horizontal gravels, vertical gravels and straw) except for straw mulching in April 7, 2011. In addition, there were no significant differences between mulching treatments (horizontal and vertical gravels, straw and control) from mid-April to December, 2011 and 2012. Interestingly, soil water content of 36 m^2 micro-catchment was consistently and significantly higher than 64 m^2 treatment across the study period, except in April 7, 2011, February 12 and June 15, 2012. In addition, the 36 m^2 soil water content was higher than the 100 m^2 treatment in 2011 (except in January 20, April 7, and June 5). In 2012, soil moisture content of 36 m^2 was higher than 100 m^2 micro-catchment in March 3, April 4, and October 20 (Fig. 2).

3.2. Morphology and physiology

Mulching and micro-catchment area significantly affected pistachio plant morphology (plant height, and number of leaves per plant) across the experimental period (Table 2, Fig. 3). Vertical and horizontal gravel mulching had the highest percentage increase in plant height while vertical gravel treatment had the highest percentage increase in leaf number per tree (Table 2). The percentage increase in plant morphology (plant height, and number of leaves per plant) for 36 m^2 micro-catchment was significantly higher than the 64 and 100 m^2 treatments. The mulching × micro-catchment interaction for plant morphology was significant across the study period (Table 2 and Fig. 3). The interactions results revealed that, gravel (vertical and horizontal) mulching × 36 m^2 interaction had the highest percentage increase in plant height compared with other treatments (Fig. 3). In addition, vertical and horizontal mulching and 36 m^2 interaction as well as the horizontal mulching and 64 m^2 interaction treatments had the greatest percentage increase in leaf number per tree.

The response of gas exchange (*Pn, gs*, and *E*) and stem water potential (Ψsmd) to mulching, micro-catchment and their interaction are given in Table 3. While mulching technique had no potential effect on leaf gas exchange variables (especially, overall means), micro-catchment area treatments significantly affected *Pn, gs*, and *E* across the study period, except for *E* in June, 2012. Pistachio trees grown in gravel or straw

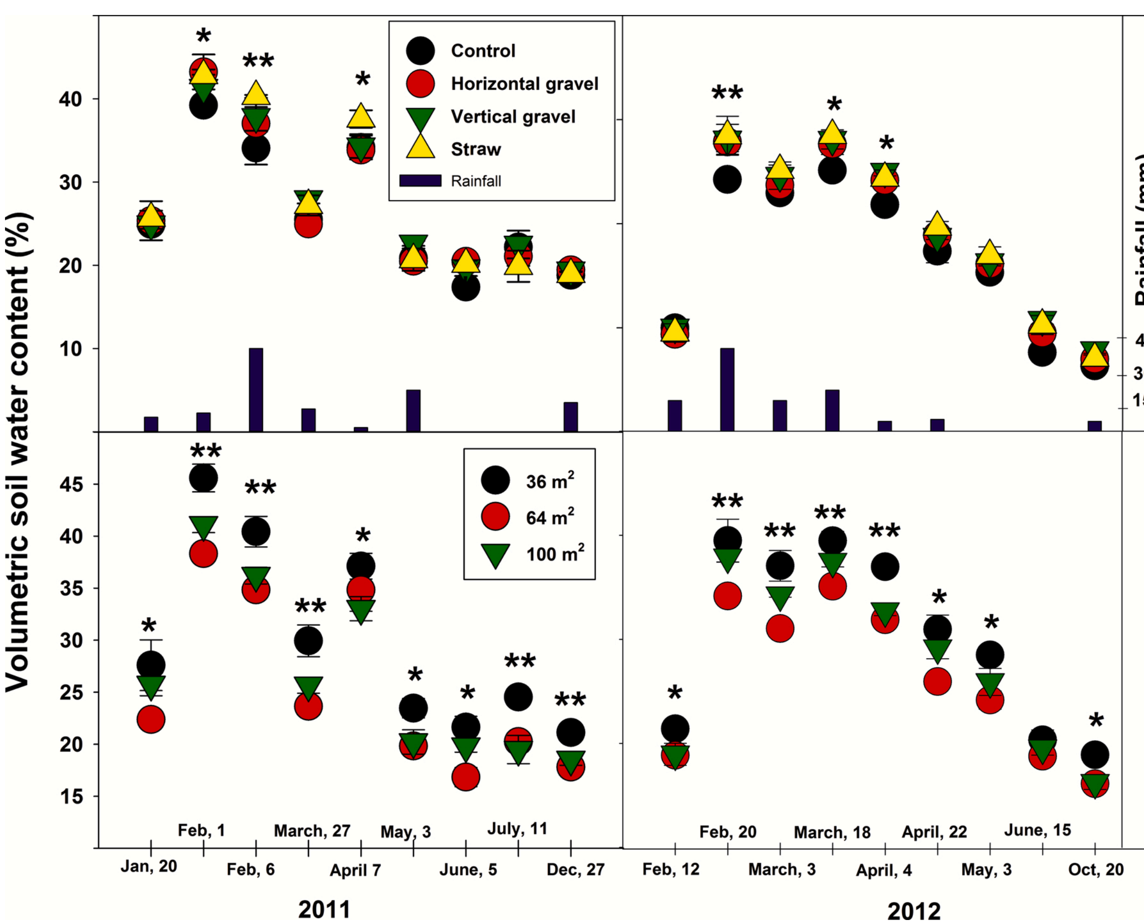

Fig. 2. Volumetric soil water content (%) of pistachio transplants grown in the field under different water harvesting micro-catchments area (36, 64 and 100 m^2) and mulching techniques (horizontal and vertical gravel, straw and control, no mulching) for two growing seasons. *, **, show significant difference at $P < 0.05$ and $P < 0.01$, respectively. Mulching × micro-catchment area interactions were not significant. The error bars represent mean ± standard error.

Table 2
Percentage increase (2012 compared with 2011) in height and number of leaves of pistachio trees grown in the field under different water harvesting micro-catchment area (36, 64 and 100 m^2) and mulching techniques (horizontal and vertical gravel, straw and control, no mulching) for two growing seasons.

Mulching (M)	Micro-catchment area (A)	Percentage increase	
		Plant height (cm)	Number of leaves per plant
Control		43.4 b	21.9 c
Vertical gravel		57.0 a	41.7 a
Horizontal gravel		56.9 a	28.8 b
Straw		46.1 b	29.7 b
	36 m^2	56.6 a	38.9 a
	64 m^2	47.7 b	28.5 b
	100 m^2	48.3 b	24.1 b
ANOVA	M	***	***
	A	**	***
	M × A	*	***

*, **, *** Show significant difference at P < 0.1, 0.05, 0.01 and 0.001, respectively. Means in columns followed by different letters are significantly different at P < 0.05.

mulching had higher *Pn* and *gs* than control only in August. Although 36 and 64 m^2 micro-catchments were similar for *Pn* and *gs* in June, July and August, the overall means of *Pn* and *gs* for the 36 m^2 was higher than 64 m^2 treatment (Table 3). Interestingly, *Pn* and *gs* from 36 m^2 were consistently and significantly higher than the 100 m^2 micro-catchment across the study period. In this study, water harvesting treatments (mulching and micro-catchment) significantly improved Ψsmd (Table 3). For example, gravel mulching (vertical and horizontal) significantly increased Ψsmd (less negative) compared with control and straw mulching in May and overall mean. In addition, Ψsmd values from 36 m^2 micro-catchment were higher (less negative) than 64 and 100 m^2 micro-catchments across the growing season (May, June, July, August) and overall mean.

The mulching × micro-catchment interaction showed that gravel (horizontal and vertical) and 36 m^2 interaction had higher *Pn* than other treatment in May (Fig. 4). In addition, mulching (horizontal and vertical gravels, straw) and 36 m^2 interaction as well as control and micro-catchments (64 and 100 m^2) had the highest *gs* in May. In August, mulching (horizontal and vertical gravels, straw) and micro-catchments (36 and 64 m^2) interaction had higher *Pn* compared with control and 64 m^2. The mulching × micro-catchment area results for *E* and Ψsmd were inconsistent or not significant across the study period (Fig. 4).

3.3. Rainfall - runoff volume

A separate experiment was designed to determine the total runoff volume from micro-catchments plots in the first year, 2011. During the experimental period (2011), nine storms were recorded and the total rainfall was 174 mm (Fig. 5). The minimum rainfall record was 2 mm (April, 7) and the maximum rainfall depth was 40 mm (February, 6). The runoff volume differed significantly between the micro-catchment plots over the experimental period. While 100 m^2 micro-catchment had the highest runoff volume in February 1, March 27 and April 7,

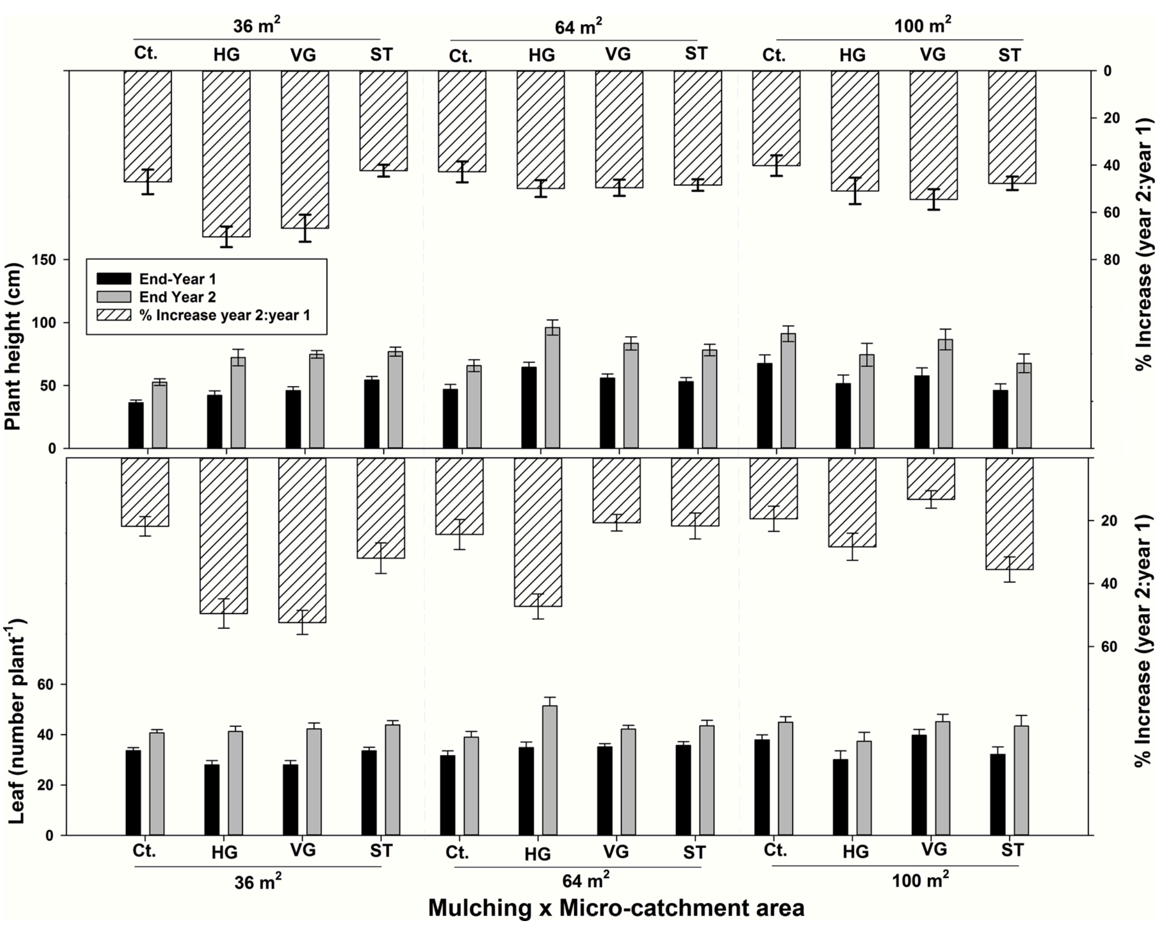

Fig. 3. Plant height, leaf number per plant and percentage increase (2012 compared with 2011) of height and leaf number for pistachio trees grown in the field under different water harvesting micro-catchment area (36, 64 and 100 m^2) and mulching techniques [horizontal gravel (HG) and vertical gravel (VG), straw (ST) and control (Ct., no mulching)] for two growing seasons. The error bars represent mean ± standard error.

Table 3
Photosynthesis, stomatal conductance, transpiration and midday stem water potential of pistachio trees grown in the field under different water harvesting micro-catchment area (36, 64 and 100 m^2) and mulching techniques (horizontal and vertical gravel, straw and control, no mulching) for two growing seasons. Measurements were collected during the 2012 growing season.

Variable	Treatment		Measurement date				Overall mean
			May	June	July	August	
Photosynthesis ($\mu mol\ m^{-2}\ s^{-1}$)	Mulching (M)	Control	10.9 b	15.6	16.1	11.3 b	13.5
		Vertical gravel	12.2 ab	16.5	16.5	13.5 a	14.7
		Horizontal gravel	13.9 a	15.2	15.6	13.4 a	14.6
		Straw	11.5 ab	14.8	14.8	13.5 a	13.6
	Micro-catchment area (A)	36 m^2	15.3 a	16.6 a	18.2 a	15.3 a	16.4 a
		64 m^2	11.8 b	16.3 a	15.3 ab	13.7 a	14.3 b
		100 m^2	9.4 c	13.7 b	13.7 b	9.8 b	11.7 c
	ANOVA	M	*	NS	NS	*	NS
		A	***	*	*	***	**
		M×A	*	NS	NS	*	NS
Stomatal conductance ($mol\ m^{-2}\ s^{-1}$)	Mulching	Control	0.17	0.27	0.28	0.16 b	0.22
		Vertical gravel	0.18	0.29	0.29	0.21 a	0.24
		Horizontal gravel	0.22	0.26	0.27	0.20 a	0.24
		Straw	0.19	0.24	0.24	0.21 a	0.22
	Micro-catchment area	36 m^2	0.26 a	0.29 a	0.33 a	0.26 a	0.29 a
		64 m^2	0.17 b	0.28 a	0.26 ab	0.22 a	0.23 b
		100 m^2	0.14 b	0.22 b	0.22 b	0.12 b	0.17 c
	ANOVA	M	NS	NS	NS	*	NS
		A	***	*	*	***	*
		M×A	***	NS	NS	*	NS
Transpiration ($mmol\ m^{-2}\ s^{-1}$)	Mulching	Control	2.5	1.6 b	1.2	1.5	1.7
		Vertical gravel	2.1	1.7 b	1.1	1.9	1.7
		Horizontal gravel	2.6	2.6 a	1.8	1.6	2.2
		Straw	2.4	2.1 ab	0.9	1.4	1.7
	Micro-catchment area	36 m^2	2.3 b	2.0	1.7 a	1.6 b	1.9 ab
		64 m^2	3.5 a	2.1	0.8 b	1.9 a	2.1 a
		100 m^2	1.4 b	1.9	1.3 ab	1.3 c	1.5 b
	ANOVA	M	NS	*	NS	NS	NS
		A	***	NS	*	*	*
		M×A	NS	***	NS	NS	*
Midday stem water potential (MPa)	Mulching	Control	−0.52 b	−0.88 c	−1.02 b	−1.12 c	−0.88 b
		Vertical gravel	−0.41 a	−0.75 a	−0.92 b	−1.00 a	−0.77 a
		Horizontal gravel	−0.44 a	−0.80 ab	−0.94 a	−1.04 ab	−0.80 a
		Straw	−050 b	−0.86 bc	−1.01 a	−1.08 bc	−0.86 b
	Micro-catchments area	36 m^2	−0.38 a	−0.69 a	−0.87 a	−0.93 a	−0.72 a
		64 m^2	−0.46 ab	−0.80 b	−0.97 b	−1.07 b	−0.82 b
		100 m^2	−0.55 c	−0.97 c	−1.08 c	−1.18 bc	−0.95 c
	ANOVA	M	***	**	*	**	***
		A	***	***	***	***	***
		M×A	NS	NS	NS	NS	NS

*, **, *** Show significant difference at $P < 0.1$, 0.05, 0.01 and 0.001 respectively. NS, not significant at $P < 0.1$.
Means in columns followed by different letters are significantly different at $P < 0.05$.

the 36 m^2 collected more runoff water than the other micro-catchments in February 20, November 20 and December 27 (Fig. 5). The total runoff volume for the 36 m^2 micro-catchment was 53.4 L, for 64 m^2 was 30.6 L and for 100 m^2 was 41.7 L.

4. Discussion

4.1. Soil water content

Rainfall, the main source of water in arid and semi-arid regions is limited and highly variable. Water harvesting can be an applicable approach to assist agriculture and secure yields under those highly variable water availability regions (Vettera and Rieger, 2019). In situ rain water harvesting is a promising practice to support sustainable development in arid regions because it improves infiltration and groundwater recharge, soil nutrients enrichment as well as biomass production (Vohland and Barry, 2009). In fact, water harvesting approach has the potential to improve the availability of water for an extended period (Mandal et al., 2020). Several water harvesting techniques has been suggested such as mulching (gravels, straw and plastic) and micro/macro-catchments with different area and shape. However, the efficiency of those techniques to maintain adequate soil water content for plant is not similar.

In dry lands, hortonian runoff is a scale process that associated with

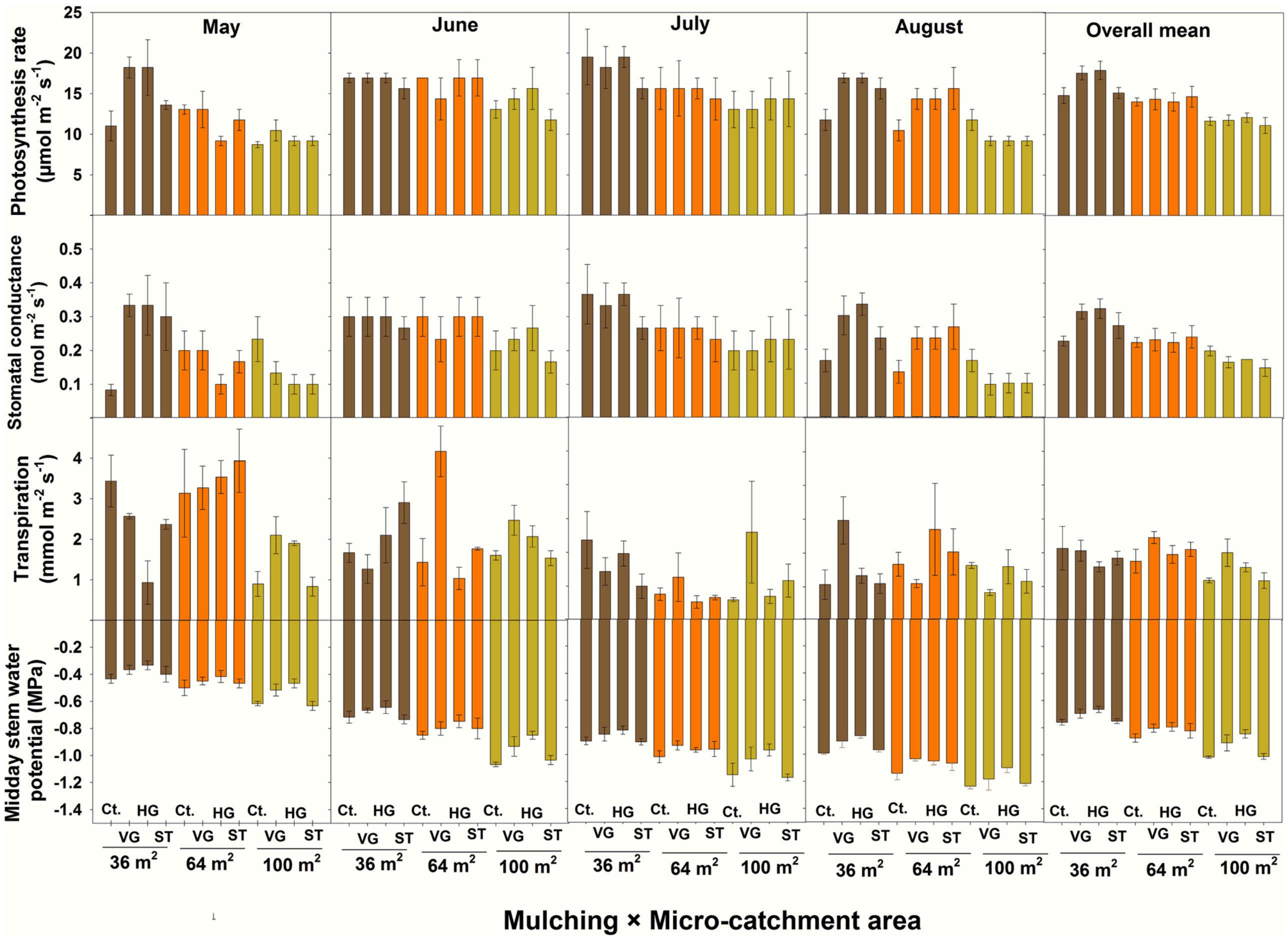

Fig. 4. Photosynthesis, stomatal conductance, transpiration and midday stem water potential of pistachio trees grown in the field under different water harvesting micro-catchments area (36, 64 and 100 m^2) and mulching techniques [horizontal gravel (HG) and vertical gravel (VG), straw (ST) and control (Ct., no mulching)] for 2012 growing season. The error bars represent mean ± standard error.

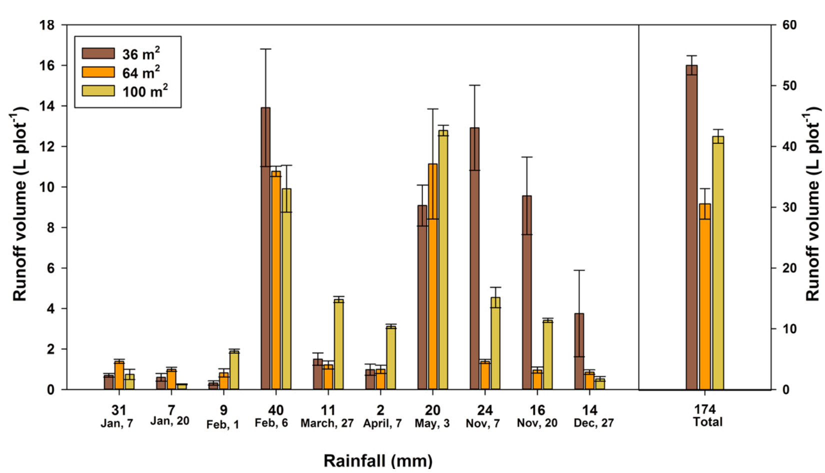

Fig. 5. Rainfall and runoff of water harvesting micro-catchment area treatment (36, 64 and 100 m^2) for 2011 growing season.

rainfall, infiltration and runoff routing (Chen et al., 2016). That soil water content decreased in parallel with increased micro-catchment area (36 to 100 m^2) is consistent with the results of Bagarello et al. (2018) and (Chen et al., 2016). In fact, scale effect exists on conditions of stationary heterogeneous land surface and results in a decrease of runoff depth as spatial scales increase (Chen et al., 2016). For mulching effect, higher soil water content under soil-mulching treatments (straw or gravels) could partially attributed to mulching effect which reduced evaporation from the soil compared with bare soil (control) (Fig. 2).

4.2. Pistachio morphology and physiology

Recent studies has linked gas exchange component (*Pn*, *E*, and *gs*) to shoot and root growth as well as yield (A'saf et al., 2020; Ayad et al., 2018; Leskovar and Othman, 2019; Marino et al., 2018). In this study, the combined water harvesting, gravel mulching (vertical and horizontal) and 36 m^2 micro-catchment were the best candidate to improve the morphology (plant height and number of leaves per tree) of young pistachio trees (Tables 2 and 3). Our results, like those of Ojasvi et al. (1999), concluded that gravel mulching and shallow conical micro-catchments of 1.0 m radius constructed around the trunk significantly increased the jujube height by 40–48 % over the control.

Information about the amount of water available in the root zone is essential as a basis for calculating water balances and plant water status (Landsberg and Waring, 2017; Othman et al., 2014b). In this study, the better morpho-physiological responses of pistachio trees in mulching (vertical and horizontal) × 36 m^2 micro-catchment plots can be due to higher soil moisture content (Fig. 2). Soil moisture content is significantly and positively correlated with plant morpho-physiology (Othman et al., 2014b). Landsberg and Waring (2017) looked back over 50 years of research into the water relations of trees and concluded that hydraulic redistribution of water in the soil can play a key role in facilitating root growth, especially in dry soils.

Pistachio is a drought tolerance species; able to survive under drought conditions with as little as 100 mm of rainfall (Goldhamer and Beede, 2004). During the study period, pistachio trees were grown under rain-fed conditions. No supplemental irrigation was applied. A three-year study on pistachio tree suggested that Ψsmd of –1.5 MPa is the water deficit threshold, as it did not reduce the yield. Conversely, Ψsmd of −2.0 MPa resulted in a significant negative effect on *gs* and pistachio production (Memmi et al., 2016). In pecan, the reduction in *Pn* and *gs* exceeded 50 % when Ψsmd ranged from –1.5 to –2.0 MPa (Othman et al., 2014b). Interestingly, in our study, Ψsmd never exceeded (more negative) –1.2 MPa across the water harvesting treatments and over the study period (Table 3, Fig. 4). In fact, the Ψsmd for the 36 m^2 micro-catchment never exceeded –1.0 MPa. Considering the Ψsmd values across the experimental period, we believe that young pistachio trees can be grown under rain-fed regime (rainfall 150–200 mm), specifically when micro-catchment-water-harvesting (MCWH) is applied.

Nature-based solutions enhance the sustainability of catchment systems by promoting desirable soil and landscape functions (Keesstra et al., 2018b). The concentration of nature-based solutions on the concept of connectivity (making the landscape less connected) enabling less rainfall to be transformed into runoff and increasing soil moisture (Keesstra et al., 2018b). Although water harvesting approach results is remarkable, farmer perception for adopting this approach is quite negative, especially for using mulching. In fact, farmers claim for subsidies to adopt mulching approach because the cost of mulch (e.g. straw) is higher than traditional tillage practices (Cerdà et al., 2017). A socioeconomic survey on soil mulching showed that the use of straw mulching in olive (*Olea europaea* L.) plantation would cost €174.7 ha^{-1}, which account for 22.5 % of the total income of the farmers (Rodrigo-Comino et al., 2019). Overall, to convince farmers to adopt water harvesting strategy, it needs to be subsidized (Rodrigo-Comino et al., 2019).

4.3. *Runoff efficiency*

Micro-catchment water harvesting consists of a closed diamond, square or rectangular basin levees on gently sloping land. This technique is simple and cheap in construction, and consequently easy to build and adopt (Oweis and Taimeh, 1996). The efficiency of the water harvesting system depends on amount of water consume by the crop and the amount of rainfall receive in the catchment area (runoff efficiency). In fact, the overall efficiency of the system can differ significantly by altering the area of the catchment and the root zone capacity (Oweis and Taimeh, 1996). In this study, the runoff volume of 36 m^2 was 75 % and 28 % higher than those from 64 and 100 m^2, respectively (Fig. 5). Bagarello et al. (2018) assessed the influence of plot scale (plot length and area) on runoff and sediment concentration in bare ploughed plots ranging from 1 to 48 m^2. They found that both runoff and soil loss significantly decreased in the passage from the reference area (1 m^2) to the largest one (48 m^2). The investigation of plot-scale effects on event runoff per unit area (Qe), sediment concentration (Ce), and soil loss per unit area (SLe) revealed that when scale effects were detected, the longer plot lengths yielded smaller Qe and SLe values and larger Ce values (Bagarello and Ferro, 2017).

The slope degree and the minimum rainfall amount for effective water harvesting are controversial. Malesu et al. (2007) found that the successful and sustainable water harvesting system (specifically, for ponds and pans) had a site slope of less than 8 % (slopes <2 % are the best), seasonal rainfall above 200 mm and low permeability soil. Ali et al. (2010) assessed the MCWH potential in Mediterranean arid environment for three consecutive years. During the study period, the annual rain was 158 mm in the first year, 45 mm in second year and 127 mm in third. They found that runoff yield varied between 5 and 187 m^3 ha^{-1} which account for 5 and 85 % of the incidental rainfall. Interestingly, the rainfall threshold for runoff development was estimated about 4 mm. A water catchment area of 4.5 km^2 and a landscape slope of 1 %–1.5 % were associated with runoff volume exceeding 1000 m^3 when total rainfall during the day was about 20 mm (Carter and Miller, 1991). However, two year study investigated the effect of slope degree (8 % and 15 %) and micro-catchment area (50 and 70 m^2) on the amount of water harvested in tree basin for young olive showed that the 15 % slope resulted in greater harvested volume for small storms when compared with 8 %, but the two were comparable when storms were large. Interestingly, the 70 m^2 catchment area resulted in greater volume of harvested water only when storm was higher than 26 mm. In this study, the slope degree was 12 % and the rainfall during the day (storm) ranged from 2 to 40 mm. The number of storms with total rainfall ≥20 mm during the growing season was 4 storms per year. The gas exchange and Ψsmd values were within the proper ranges though the trees were under rain-fed conditions. Overall, we believe that the construction of MCWH with 12 % slope degree is appropriate for growth and development of young pistachio trees, specifically when annual rainfall is greater than 150 mm. However, further studies are needed to evaluate the influence of these combined water harvesting techniques (mulching × micro-catchment) on pistachio fruit production and quality.

5. Conclusions

Water harvesting can provide a supplementary amount of water for the cultivation of pistachio crop especially during drought periods. In this study, combined water harvesting techniques (mulching × micro-catchment) significantly improved soil water content, plant morphology (plant height and leaf number per tree) and physiology of pistachio trees. Soil water content from the 36 m^2 micro-catchment was higher than 64 and 100 m^2. Mulching and micro-catchment interaction revealed that, vertical and horizontal mulching and 36 m^2 had the highest percentage increase in tree height compared with other treatments. Higher soil water content in the 36 m^2 micro-catchment resulted in higher gas exchange (*Pn*, *gs*, and *E*) and Ψsmd. Consequently, trees grown in the 36 m^2 micro-catchment had better tree morphology (plant height and number of leaves per tree) than pistachio trees grown in 64 and 100 m^2 micro-catchment area treatments. Interestingly, The 36 m^2 micro-catchment collected 75 % higher runoff water than 64 m^2 and 28 % than 100 m^2. Therefore, the 36 m^2 is the best micro-catchment area in term of runoff efficiency. Overall, the gravel mulching (vertical and horizontal) and 36 m^2 micro-catchment is the potential water harvesting techniques for improving the morphology and physiology of young pistachio trees which grown in rain-fed regime.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106464.

References

A'saf, T., Al-Ajlouni, M., Ayad, J., Othman, Y., St. Hilaire, R., 2020. Performance of six different soilless green roof substrates for the Mediterranean region. Sci. Total Environ. 730, 139182 https://doi.org/10.1016/j.scitotenv.2020.139182.

Ali, A., Yazar, A., Aal, A.A., Oweis, T., Hayek, P., 2010. Micro-catchment water harvesting potential of an arid environment. Agric. Water Manage. 98, 96–104. https://doi.org/10.1016/j.agwat.2010.08.002.

Ayad, J., Othman, Y., Al-Ajlouni, M., Alsmairat, N., 2018. Photosynthesis, gas exchange and yield of two strawberry (*Fragaria × ananassa* duch.) cultivars in response to gibberellic acid. Fresenius Environ. Bull. 27 (12), 9127–9134.

Bagarello, V., Ferro, V., 2017. Scale effects on plot runoff and soil erosion in a Mediterranean environment. Vadose Zone J. 16 (12), 1–14. https://doi.org/10.2136/vzj2017.03.0059.

Bagarello, V., Ferro, V., Keesstra, S., Comino, J.R., Pulido, M., Cerdà, A., 2018. Testing simple scaling in soil erosion processes at plot scale. Catena 167, 171–180. https://doi.org/10.1016/j.catena.2018.04.035.

Carter, D.C., Miller, S., 1991. Three years experience with an on-farm macrocatchment water harvesting system in Botswana. Agric. Water Manage. 19, 191–203. https://doi.org/10.1016/0378-3774(91)90041-G.

Cerdà, A., Rodrigo-Comino, J., Giménez-Morera, A., Keesstra, S.D., 2017. An economic, perception and biophysical approach to the use of oat straw as mulch in Mediterranean rainfed agriculture land. Ecol. Eng. 108, 162–171. https://doi.org/10.1016/j.ecoleng.2017.08.028.

Chakraborty, D., Nagarajan, S., Aggarwal, P., Gupta, V.K., Tomar, R.K., Garg, R.N., Sahoo, R.N., Sarkar, A., Chopra, U.K., Sarma, K.S.S., Kalra, N., 2008. Effect ofmulching on soil and plant water status, and the growth and yield of wheat (*Triticum aestivum* L.) in a semi-arid environment. Agric. Water Manage. 95, 1323–1334. https://doi.org/10.1016/j.agwat.2008.06.001.

Chen, L., Sela, S., Svoray, T., Assouline, S., 2016. Scale dependence of Hortonian rainfall runoff processes in a semiarid environment. Water Resour. Res. 52, 5149–5166. https://doi.org/10.1002/2015WR018315.

Critchley, W., Siege, K., 1991. Water Harvesting. A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production, FAO Paper No. AGUmisc. /17/91. FAO, Rome.

Denny, E., Donnelly, K., McKay, R., Ponte, G., Uetake, T., 2008. Sustainable Water Strategies for Jordan. International Economic Development Program. Gerald R. Ford School of Public Policy, University of Michigan, Ann Arbor.

Dile, Y., Karlberg, L., Temesgen, M., Rockström, J., 2013. The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa. Agric. Ecosyst. Environ. 181, 69–79. https://doi.org/10.1016/j.agee.2013.09.014.

Fantino, M., Bichard, C., Mistretta, F., Bellisle, F., 2020. Daily consumption of pistachios over 12 weeks improves dietary profile without increasing body weight in healthy women: a randomized controlled intervention. Appetite 144, 104483. https://doi.org/10.1016/j.appet.2019.104483.

Gao, X.D., Li, H.C., Zhao, X.N., 2020. Impact of land management practices on tree water use strategy and responses to drought in a dryland plantation. Land Degrad. Dev. https://doi.org/10.1002/ldr.3687.

Goldhamer, D.A., Beede, B.H., 2004. Regulated deficit irrigation effects on yield, nut quality and water-use efficiency of mature pistachio trees. J. Hortic. Sci. Biotechnol. 79 (4), 538–545. https://doi.org/10.1080/14620316.2004.11511802.

Grum, B., Assefa, D., Hessel, R., Woldearegay, K., Ritsema, C.J., Aregawi, B., Geissen, V., 2017. Improving on-site water availability by combining in-situ water harvesting techniques in semi-arid Northern Ethiopia. Agric. Water Manage. 193, 153–162. https://doi.org/10.1016/j.agwat.2017.08.009.

Kanber, R., Yazar, A., Önder, S., Köksal, H., 1993. Irrigation response of pistachio (*Pistacia vera* L.). Irrig. Sci. 14, 1–14. https://doi.org/10.1007/BF00195000.

Keesstra, S., Mol, G., de Leeuw, J., Okx, J., de Cleen, M., Visser, S., 2018a. Soil-related sustainable development goals: four concepts to make land degradation neutrality and restoration work. Land 7 (4), 133. https://doi.org/10.3390/land7040133.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018b. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. Total Environ. 610, 997–1009. https://doi.org/10.1016/j.scitotenv.2017.08.077.

Keesstra, S.D., Rodrigo-Comino, J., Novara, A., Giménez-Morera, A., Pulido, M., Di Prima, S., Cerdà, A., 2019. Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated clementine plantations in Eastern Spain. An assessment using rainfall simulation experiments. Catena 174, 95–103. https://doi.org/10.1016/j.catena.2018.11.007.

Landsberg, J., Waring, R., 2017. Water relations in tree physiology: where to from here? Tree Physiol. 37 (1), 18–32. https://doi.org/10.1093/treephys/tpw102.

Leskovar, D., Othman, Y., 2019. Nitrogen management for improving root and shoot components of young 'Arbequina' olives. HortSci 54 (1), 175–180.

Li, X., 2003. Gravel–sand mulch for soil and water conservation in the semiarid loess region of northwest China. Catena 52, 105–127. https://doi.org/10.1016/S0341-8162(02)00181-9.

Li, X.Y., Gong, J.D., Wei, X.H., 2000. In-situ rainwater harvesting and gravel mulch combination for corn production in the dry semi-arid region of China. J. Arid Environ. 46, 371–382. https://doi.org/10.1006/jare.2000.0705.

Li, H.C., Gao, X.D., Zhao, X.N., Wu, P., Li, L., Ling, Q., Sun, W., 2016. Integrating a mini catchment with mulching for soil water management in a sloping jujube orchard on the semiarid Loess Plateau of China. Solid Earth 7, 167–175.

Li, H.C., Zhao, X., Gao, X., Ren, K., Wu, P., 2018. Effects of water collection and mulching combinations on water infiltration and consumption in a semiarid rainfed orchard. J. Hydrol. 558, 432–441. https://doi.org/10.1016/j.jhydrol.2018.01.052.

Malesu, M., Khaka, E., Odour, A., De Bock, T., Nyabenge, M., Odour, V., 2007. Mapping the Potential of Rainwater Harvesting Technologies in Africa: a GIS Overview and Atlas of Development Domains for the Continent and None Selected Countries. World Agroforestry Centre (ICRAF) ICRAF Technical Manual No. 7, Nairobi, Kenya.

Mandal, S., Vema, V., Kurian, C., Sudheer, K., 2020. Improving the crop productivity in rainfed areas with water harvesting structures and deficit irrigation strategies. J. Hydrol. 586, 124818 https://doi.org/10.1016/j.jhydrol.2020.124818.

Marino, G., Di Martino, S., Roxas, A.A., Caruso, T., Ferguson, L., Barone, E., Marra, F.P., 2018. Sustainability of pistachio production (*Pistacia vera* L.) under supplemental irrigation in a Mediterranean climate. Sci. Hortic. 241, 260–266. https://doi.org/10.1016/j.scienta.2018.06.032.

Mark, A., Tomar, C.S., Sharma, D.D., Vikas, G., Khachi, B., Kachawaya, D., 2014. Studies on effect of mulches and herbicides on growth, yield and quality of pecan nut (Koch.). Green Farming 4, 604–609.

Memmi, H., Gijón, M., Couceiro, J., Pérez-López, D., 2016. Water stress thresholds for regulated deficit irrigation in pistachiotrees: Rootstock influence and effects on yield quality. Agric. Water Manage. 164, 58–72. https://doi.org/10.1016/j.agwat.2015.08.006.

Muriu-Ng'ang'a, F.W., Mucheru-Muna, M., Waswa, F., Mairura, F.S., 2017. Socio-economic factors influencing utilisation of rain water harvesting and saving technologies in Tharaka South, Eastern Kenya. Agric. Water Manage. 194, 150–159. https://doi.org/10.1016/j.agwat.2017.09.005.

Ojasvi, P., Goyal, R.K., Gupta, J.P., 1999. The micro-catchment water harvesting technique for the plantation of jujube (*Zizyphus mauritiana*) in an agroforestry system under arid conditions. Agric. Water Manage. 41 (3), 139–147. https://doi.org/10.1016/S0378-3774(99)00023-2.

Othman, Y.A., Steele, C., Van Leeuwen, D., Heerema, R., Bawazir, S., St. Hilaire, R., 2014a. Remote sensing used to detect moisture status of pecan orchards grown in a desert environment. Int. J. Remote Sens. 35 (3), 949–966. https://doi.org/10.1080/01431161.2013.873834.

Othman, Y.A., VanLeeuwen, D., Heerema, R., St. Hilaire, R., 2014b. Midday stem water potential values needed to maintain photosynthesis and gas exchange established for pecans. J. Am. Soc. Hortic. Sci. 139 (5), 537–546. https://doi.org/10.21273/JASHS.139.5.537.

Oweis, T.Y., Taimeh, A.Y., 1996. Evaluation of a small basin water-harvesting system in the arid region of Jordan. Water Resour. Manage. 10, 21–34. https://doi.org/10.1007/BF00698809.

Pourmohammadali, B., Hosseinifard, S.J., Salehi, M.H., Shirani, H., Boroujeni, I.E., 2019. Effects of soil properties, water quality and management practices on pistachio yield in Rafsanjan region, southeast of Iran. Agric. Water Manage. 213, 894–902. https://doi.org/10.1016/j.agwat.2018.12.005.

Rodrigo-Comino, J., Giménez-Morera, A., Panagos, P., Pourghasemi, H.R., Pulido, M., Cerdà, A., 2019. The potential of straw mulch as a nature-based solution for soil erosion in olive plantation treated with glyphosate: a biophysical and socioeconomic assessment. Land Degrad. Dev. https://doi.org/10.1002/ldr.3305.

Sawalhah, M., Al-Kofahi, S., Othman, Y.A., Cibils, A., 2018. Assessing rangeland cover conversion in Jordan after the Arab spring using a remote sensing approach. J. Arid Environ. 157, 97–102. https://doi.org/10.1016/j.jaridenv.2018.07.003.

Vettera, T., Rieger, A., 2019. Ancient water harvesting in the Old World Dry Belt synopsis and outlook. J. Arid Environ. 169, 42–53. https://doi.org/10.1016/j.jaridenv.2019.103996.

Visser, S., Keesstra, S., Maas, G., De Cleen, M., 2019. Soil as a basis to create enabling conditions for transitions towards sustainable land management as a key to achieve the SDGs by 2030. Sustainability 11 (23), 6792. https://doi.org/10.3390/su11236792.

Vohland, K., Barry, B., 2009. A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. Agric. Ecosyst. Environ. 131, 119–127. https://doi.org/10.1016/j.agee.2009.01.010.