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Yield and water productivity response of quinoa to various deficit irrigation regimes applied with surface and subsurface drip systems

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Abstract

This study evaluated the yield and water productiivty response of quinoa to regulated deficit irrigation (RDI), partial root-zone drying (PRD) and conventional deficit irrigation (DI) and full irrigation (FI) using surface (***SD***) and subsurface drip (***SSD***) systems in 2016 and 2017 in the eastern Mediterranean region of Turkey. The treatments consisted of RDI, PRD_{50}, DI_{50}, DI_{75} and FI. A rainfed treatment (RF) was also included in the study. The experimental design was split plots with four replications. DI_{75} and DI_{50} received 75 and 50% of FI, respectively. PRD_{50} received 50% of FI, but from alternative laterals. RDI received 50% of FI during vegetative stage until flowering, and then received 100% of water requirement. The results showed that quinoa under ***SD*** used slightly more water than ***SSD*** due to reduced surface evaporation. RDI resulted in water saving of 23 and 21% for ***SD*** and ***SSD***, respectively, compared to FI; and RDI produced statistically similar grain yields to FI. DI_{75} treatment resulted in water savings of 16% for both drip methods in the first year and 10 and 25% for ***SD*** and ***SSD*** systems, respectively, in the second year. PRD_{50} produced greater yield than DI_{50} eventhough they received the same amount of irrigation water. RF and PRD_{50} treatments resulted in significantly greater water productivity (WP) values than other treatments. There was no significant difference between ***SD*** and ***SSD*** regarding the grain and dry matter yields and WP values. Thus, RDI and DI_{75} appear to be good alternatives to FI for sustainable quinoa production in the Mediterranean region.

Introduction

Water scarcity is one of the major constraints of plant growth, productivity and adaptation in arid and semi-arid regions in the world. The lack of water resource and irregularity of precipitation had significantly impacted the sustainability of the crops production. In regions with scarce freshwater resources and increasing food demand for ever-growing populations, water management along with production of climate-proof crops become key factors for a sustainable agriculture (World Water Assessment Programme (WWAP) 2012). The cultivation of drought- and salt-tolerant crops such as quinoa has the potential to enhance farm-level productivity and livelihoods in drought- and salt-prone areas (Yazar and İncekaya, 2014).

Quinoa (*Chenopodium quinoa* Willd.) is a genetically diverse Andean crop that has earned special attention worldwide due to its nutritional and health benefits and its ability to adapt to contrasting environments, including nutrient-poor and saline soils and drought stressed marginal agro-ecosystems (Bazile *et al.*, 2016; Murphy *et al.*, 2016; Jacobsen, 2017; Maliro *et al.*, 2017; Hinojosa *et al.*, 2018). In view of its exceptional nutritional quality and ability to grow under marginal environments, the Food and Agriculture Organization of the United Nations has identified quinoa as one of the crops that will play an important role in ensuring future food security and designated the year 2013 as the 'Year of Quinoa' (Bazile *et al.*, 2015; Choukr-Allah *et al.*, 2016). Quinoa is well adapted to grow under unfavorable soil and climatic conditions. Its robust character is due to a high tolerance level of frost, soil salinity and drought (Adolf *et al.*, 2013; Ruiz *et al.*, 2014, 2016; Hinojosa *et al.*, 2018). The quinoa production could contribute to food security, and has a great potential to increase food security in the Mediterranean region and in other parts of the developing world (Hirich *et al.*, 2012, 2013; Jacobsen *et al.*, 2012; Hinojosa *et al.*, 2019).

Deficit irrigation (DI) is the most important irrigation strategy to increase water use efficiency and crop water productivity (WP) (Hirich *et al.*, 2014). Water management by proper scheduling of irrigation with improved crop water management techniques is a potential option to save water and increase WP. Therefore, the efficient utilization of limited available fresh water resources in irrigated agriculture necessitates the use pressurized irrigation systems such as surface and subsurface drip (***SSD***) systems for increasing yield and quality (Bozkurt Çolak *et al.*, 2018). ***SSD*** has proven to be an efficient irrigation method with potential advantages of high WP, fewer weed and disease problems, less soil erosion, efficient fertilizer application, maintenance of dry areas for tractor movement at any time, flexibility in design and lower labour costs than in a conventional drip irrigation system (Lamm and Camp, 2007; Irmak *et al.*, 2016).

Innovations for saving water in irrigated agriculture and thereby improving WP are of paramount importance in water-scarce regions. The increasing global shortage of water resources and high costs of irrigation have resulted in development of precise water-saving irrigation strategies that lead to minimize water use in crop production (Jones, 2004). Water-saving irrigation strategies reduce crop water consumptions and among these strategies are DI, partial root-zone drying (PRD) irrigation and regulated deficit irrigation (RDI) that have been developed for limited irrigation managements. Conventional DI is a well-accepted practice to optimize water use, thereby saving cost, by allowing crops to withstand mild water stress with no or only marginal decreases in yield and quality (English *et al.*, 1990). PRD is a further development of DI. PRD is an irrigation technique based on alternately wetting and drying opposite parts of the plant root system (Marsal *et al.*, 2008). Recently, RDI has been identified as one of the key water-saving technologies in agriculture. RDI is generally defined as an irrigation practice whereby a crop is irrigated with an amount of water below the full requirement for optimal plant growth in non-critical growth stages without causing significant yield reduction (Chai *et al.*, 2016). DI is a well-accepted practice to optimize increase water use, thereby saving cost, by allowing crops to withstand mild water stress with no or only marginal decreases in yield and quality. Quinoa has responded well to DI that was highly beneficial in various experimental locations where grain yield was hardly affected by DI (Costa *et al.*, 2007; Geerts and Raes, 2009; Pulvento *et al.*, 2012; Razzaghi *et al.*, 2012; Yazar *et al.*, 2015). RDI is generally defined as an irrigation practice whereby a crop is irrigated with an amount of water below the full requirement for optimum plant growth; this is to reduce the amount of water used for irrigating crops, improve the response of plants to the certain degree of water deficit in a positive manner, and reduce irrigation amounts or increase the crop's water use efficiency (WUE). The principle behind this approach is that the response of plants to RDI induced water stress varies with growth stages and that less irrigation applied to plants at non-critical stages may not cause significant negative impact on plant productivity even though it may reduce normal plant growth (Chai *et al.*, 2016). Quinoa's flowering and milk grain stages have been established as the most drought sensitive (Geertz *et al.*, 2008). Several studies have been conducted to understand the quinoa plant's physiology under drought stress (Jensen *et al.*, 2000; Jacobsen *et al.*, 2009; González *et al.*, 2011; Yang *et al.*, 2016).

A number of studies were carried out on the response of quinoa to drought and salinity in different geographic locations in the World: Garcia *et al.* (2003) and Geertz *et al.* (2008) in Bolivia; Martinez *et al.* (2009) in Chile; Razzaghi *et al.* (2012) in Denmark; Pulvento *et al.* (2012) and Lavini *et al.* (2014) in Italy; Yazar and İnce Kaya (2014), Yazar *et al.* (2015) in Turkey; Hirich *et al.* (2014) in Morocco; Alvar-Beltran *et al.* (2019) in Burkina-Faso. Quinoa has an exceptional capacity to grow in water-deficient soil due to its inherent low water requirement and the ability to resume its photosynthetic rate and maintain its leaf area after a period of drought (Jensen *et al.*, 2000; Jacobsen *et al.*, 2009).

Few studies concluded that full irrigation (FI) increases quinoa grain yield and biomass compared to DI (Fghire *et al.*, 2015; Yazar *et al.*, 2015; Walters *et al.*, 2016). However, very little information is available about quinoa response to RDI, PRD and conventional DI applied with ***SSD*** irrigation system. Therefore, the primary objective of this study is to evaluate the yield and water use efficiency response of quinoa to RDI, PRD and conventional deficit and FI applied with surface drip (***SD***) and ***SSD*** systems under the Mediterranean climatic conditions.

Materials and methods

Experimental site and soil

This research was conducted in the experimental farm of Cukurova University in Adana, Turkey. The site has a latitude of 36°59′N, longitude of 35°18′E and is 50 m above mean sea level. The soil of the experimental site is classified as the Mutlu soil series (Palexerollic Chromoxeret; Jahn *et al.*, 2006), with clay texture throughout the soil profile, and has a pH range 7.61–7.87, electrical conductivity of the saturation extract (ECe) 0.32–0.35 dS/m, organic matter content of 1.23% and volumetric soil-water contents (SWCs) at field capacity and permanent wilting point of the root zone 37–41% and 24–26%, respectively. Mean bulk density varies from 1.14 to 1.30 g/cm^3. Available water-holding capacity of the soil is 110 mm in the top 60 cm soil depth.

Irrigation treatments and experimental design

In this study two irrigation systems, namely ***SD*** and ***SSD*** systems; and five irrigation regimes (full irrigation, FI; deficit irrigation, DI_{50}; deficit irrigation, DI_{75}; partial root-zone drying, PRD_{50} and regulated deficit irrigation, RDI) and a rainfed treatment (RF) were considered. Experiment was designed in split plot with four replications. Irrigation systems (***SD*** and ***SSD***) are assigned to the main plots, irrigation strategies (FI, RDI, DI_{75}, DI_{50}, PRD_{50} and RF) are assigned to the sub-plots. FI in which soil-water deficit was replenished to field capacity when 50% of available water at effective root-zone depth of 60 cm was depleted. DI treatments (DI_{75} and DI_{50}) received 75 and 50% of FI, respectively. PRD_{50} plots received 50% of FI, but from alternative laterals in each application. RDI received 50% of FI until flowering growth stage, and then received 100% of water requirement. Rainfed (RF), in which no irrigation was applied except during emergence and crop establishment period. Irrigation duration for FI treatment was estimated using average emitter flow rate and number of emitters and then duration for DI_{50} and DI_{75} was determined. Each subplot had a length of 10 and 3.0 m (six plant rows) in width.

Irrigation systems

In the ***SD*** irrigation plots, laterals of 16 mm in diameter with in-line emitters spaced 0.33 m apart, each delivering 2.0 l/h at an operating pressure of 100 kPa. One drip lateral was placed at the centre of adjacent crop rows 0.50 m apart in the experimental plots. In PRD_{50} plots, two drip laterals were placed on both sides of the crop row at 25 cm from the crop row. One lateral provided

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water during one irrigation, the other lateral supplied water in the next irrigation. A locally produced drip-irrigation system (Betaplast, Adana, Turkey) was used in the study.

SSD irrigation system laterals were buried under 25 cm of the soil surface by means of a chisel plow. In-line emitters with discharge rate of 2.0 l/h spaced at 0.33 m intervals on the lateral line were used in ***SSD*** treatment plots except in PRD_{50} (Geoflow Corte Madera, CA, USA). A totalizing flow meter was installed at the control unit to measure total flow distributed to all replications in each treatment. Water was supplied from an open-channel irrigation network in the vicinity experimental site with a pump. Electrical conductivity of water, sodium absorption ratio and pH was 0.67 dS/m, 0.82 and 7.1, respectively.

Agronomic practices

Quinoa (*Chenopodium quinoa* Willd cv. Titicaca) seeds were sown by hand 3–4 cm apart in the row and at 50 cm row spacing on 25 March 2016 and 21 March 2017. At planting, a composite fertilizer ($N : P_2O_5 : K_2O$, 20 : 20 : 0) was broadcast at a rate of 75 kg/ha of each of N and P_2O_5, and incorporated into the soil. The additional of the N was applied in urea form at a rate of 25 kg/ha with fertigation at three consecutive irrigations on 12, 19 and 26 May 2016; and 1, 12, 23 May 2017 during vegetative growth stage using a bypass system. All treatment plots received a total of 150 kg/ha N.

Measurements and observations

The experimental area is located in a semi-arid climate. Weather data were collected from an automatic recording meteorological station located about 60 m from the experimental site. Precipitation, maximum and minimum air temperatures, air humidity, wind speed and solar radiation measured on a daily basis, and summarized for each growing season along with long-term mean climatic data from 1950 to 2015 are shown in Fig. 1.

Plant and soil-water measurements were started after plant establishment, and terminated on the harvest date. Measurements of SWC were made from one day before irrigations until harvest in four replications for all treatments.

Soil moisture content were monitored in traditional (gravimetric) in 0–60 cm and innovative manners (TDR) in 0–40 cm. SWC sensors (SM-150, Delta T Devices, UK) were placed between the two plants in the crop row at 20 and 40 cm depth at one replication for each irrigation treatment with data loggers.

Seasonal crop water use or evapotranspiration (ET) was calculated with the water balance equation:

$$\mathrm{ET} = P + I + \mathrm{Cp} \pm \Delta S - \mathrm{Roff} \qquad (1)$$

where ET is evapotranspiration (mm); P is the precipitation (mm); I is the amount of irrigation water applied (mm); Cp is the contribution through the capillary rise from ground water; ΔS is the change in the SWC (mm) at planting and at harvest in 60 cm soil depth; Dp is deep drainage and Roff is run off (mm). Since the amount of irrigation water was controlled Dp and Roff were assumed to be negligible. Water table depth was about 5 m below the soil surface Cp was also neglected.

WP and IWP were calculated using the following equations:

$$\mathrm{WP} = \mathrm{GY}/\mathrm{ET} \qquad (2)$$

$$\mathrm{IWP} = \frac{(\mathrm{GY_i}\text{-}\mathrm{GY_d})}{I} \qquad (3)$$

where WP is water productivity (kg/m^{-3}) in terms of yield per unit of water used; GY is grain yield (kg/ha); IWP is irrigation water productivity (kg/m^3) in terms of yield per unit of irrigation water applied; GY_i is grain yield of irrigated treatment and GY_d grain yield of RF (kg/ha); ET is evapotranspiration (mm); I is irrigation water applied (mm).

The water use–yield relationship was determined by Eqn (4) using the Stewart model in which dimensionless parameters in relative yield reduction and relative water ET are used (Doorenbos and Kassam, 1979);

$$1 - \mathrm{Ya/Ym} = \mathrm{ky}(1 - \mathrm{ETa/ETm}) \qquad (4)$$

where Ya is the actual yield (kg/ha), Ym the maximum yield (kg/ha), Ya/Ym the relative yield, 1 − (Ya/Ym) the decrease in relative yield, ky yield response factor, ETa the actual crop evapotranspiration (mm), ETm the maximum crop evapotranspiration (mm), ETa/ETm the relative evapotranspiration, 1 − (ETa/ETm) the decrease in relative evapotranspiration.

In order to determine dry matter (DM) yield, all plants within a 0.5 m row section in each plot were cut at ground level at 14-day intervals until harvest. Plant samples were dried at 65°C until constant weight was achieved. Harvest index (HI) was calculated as the ratio of grain yield to above ground biomass yield. Leaf area was measured with an optical leaf area meter at 2-week intervals throughout the growing season (LI-2000 Canopy Analyzer; LICOR Biosciences, Lincoln, NE, USA).

Phenological stages were monitored during the crop cycle in the field using the indications of Jacobsen and Stolen (1993) for quinoa. Yield was determined by hand harvesting all the plants in the 8 m long sections of the four center rows in each plot to avoid border effects. The harvest was carried out on 14 July 2016 and 12 July 2017 in the experimental years. The panicles, separated from the rest of the plant, were dried in the sun, and then, the cleaned seeds were removed. The 1000 grain weights were determined on ten plants per plot.

Statistical analysis

Analysis of variance was performed to evaluate the statistical effect of irrigation treatments on yield and yield components, WP and ET using the JMP Statistical software developed by SAS (SAS Institute, Inc., Cary, NC, USA). Treatment means were compared using Least standard deviation (LSD) test (Steel and Torrie, 1980).

Results

Irrigation and ET

The climatic conditions during the experimental years indicated that mean temperatures were similar to long-term means as depicted in Fig. 1. Monthly rainfalls fluctuated during and between the growing seasons. In general, the 2017 growing season was relatively wet during April (97.2 mm) compared to previous year (2.2 mm), which was the drier experimental year. Rainfall was more evenly distributed in 2017 than in 2016. In 2016, less rainfall was received (98.5 mm) compared with 2017 (182 mm), in which rainfall recived in May–June period was greater than

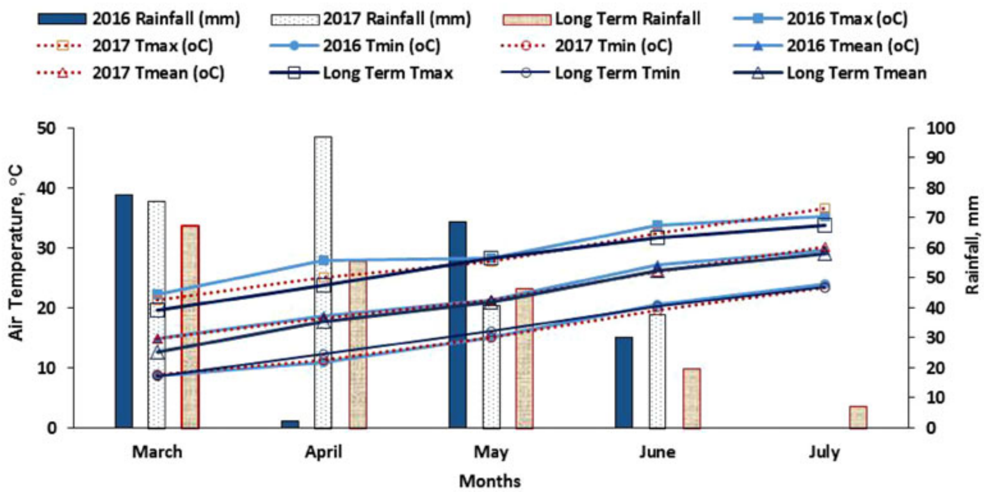

Fig. 1. Colour online. Mean monthly weather data in the experimental years along with long-term historical means (1950–2015).

the long-term means. The length of growing periods of quinoa was 111 days in 2016 and 113 days in 2017 growing season.

Irrigation quantity and ET values for the different irrigation treatments and two irrigation methods for the experimental years are summarized in Table 1. In 2016 growing season, the amount of irrigation applied to ***SD*** irrigation plots varied from 99 mm in DI_{50} and PRD_{50} to 149 mm in FI treatment; the corresponding values for ***SSD*** plots varied from 95 to 140 mm. ***SD*** plots received slightly more water but the difference was not significant. The RDI and DI_{75} plots in ***SD*** plots received 114 and 125 mm, respectively; in ***SSD*** plots, RDI and DI_{75} treatments received 110 and 118 mm, respectively, in 2016. In the 2017 growing season, the amount of irrigation water in ***SD*** plots varied from 51.5 mm in DI_{50} and PRD_{50} to 103 mm in FI treatment; the corresponding values for the ***SSD*** plots 46–92 mm. RDI plots received the same amount of water with FI in the second year due to rainy season until flowering. In general, less amount of irrigation water was applied to all treatments in 2017 than in 2016 growing season due to greater quantity of rainfall received in the second year.

Crop ET values ranged from 169 mm in RF to 282 mm in FI in ***SD***, and varied between 169 mm in RF and 271 mm in FI in ***SSD*** plots in 2016 growing season. ET values varied from 254 mm in RF to 350 mm in FI in ***SD*** plots; and 254 and 339 mm in ***SSD*** plots in 2017. Quinoa under ***SD*** plots used slightly more water than ***SSD*** plots for the same treatments due to reduced surface evaporation from the ***SSD*** plots. In the first experimental year, ET values in DI_{75} and RDI treatments in ***SD*** system were 246 and 217 mm, respectively. The corresponding values for the ***SSD*** were 235 and 212 mm, respectively. In the 2017 growing season, ET values were generally greater than those in 2016 due to greater amounts and favorable distribution of rainfall during the second season.

Variation of SWC

SWC at 20 cm soil depth in FI and RDI treatment remained between 35 and 40% until 22 June 2016 then as the season advanced SWC slightly decreased and remained between 32–35% during rest of the growing season. Thus, these two treatments did not cause any water stress throughout the quinoa growing season. SWC in the DI_{75} treatment also is maintained relatively high as compared to DI_{50}, PRD_{50} and RF treatments, in which SWC variation were the greatest among the treatments, and water stress gradually build up towards the end of growing season. SWC in RF treatment reached wilting point towards the end of growing season. Similar trends were observed for the SWC variation at 40 cm soil depth for the treatments considered. Again SWC values in FI, RDI and DI_{75} treatments remained relatively higher as compared to DI_{50}, PRD_{50} and RF. SWC in the 40 cm soil depth was greater than SWC values in the 20 cm depth in the corresponding treatments. It can be concluded that quinoa consumed most water from the top 40 cm soil depth under different treatments.

Variation SWC at 20 and 40 cm depths under the different treatments under the ***SSD*** had similar trend to those under the ***SD*** system in 2016. However, SWC in 20 cm depth under ***SSD*** was greater than those under the ***SD*** system, especially early in the season the difference was larger. This difference can be attributed to elimination of surface evaporation losses that occur under ***SD*** irrigation. Thus, more water was remained at 20 cm soil depth under ***SSD***, and SWC decreased in all treatments as the season progressed. SWC towards the end of growing season reached below the wilting point in DI_{50}, PRD_{50} and RF treatments. SWC at 40 cm soil depth in different treatments under the ***SSD*** irrigation posed a similar trend those in ***SD*** irrigated treatments. SWC decreased in all treatments gradually as the season progressed, and reached their lowest values at the end of growing season.

Fluctuations in SWC in experimental treatments under the ***SD*** and ***SSD*** systems followed similar trends in the second experimental year. FI and RDI treatments received the same amount of water in 2017 due to sufficient rainfall during the vegetative growth stage. These two treatments maintained higher SWC values than all other treatments considered. The SWC values in the 20 and 40 cm soil depths remained slightly greater in 2017 than those in 2016. In DI_{50} and PRD_{50} treatments, SWC had slightly different SWC profiles throughout the growing season. In FI and RDI treatments, SWC values remained above 32% in most of the growing season except towards the late grain filling stage during which SWC values decreased considerably. In DI_{75}, SWC curves took place below the FI and RDI throughout the

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Table 1. Quinoa irrigation, actual crop evpotranspiration (ET), grain yield, water productivity (WP), irrigation water productivity (IWP), 1000 grain weight, dry matter yield and harvest index (HI) values under different treatments in the experimental years

Years	Irrigation systems	Irrigation treatments	Seasonal irrigation (mm)	ET (mm)	Grain yield (kg/ha)	WP (kg/ m^3)	IWP** (kg/ m^3)	1000-grain weight (g)	Dry matter yield** (kg/ha)	HI (%)
2016	SD	FI	149	282	3021	1.07	0.55 cd	3.63	6081 b	49.7
		DI_{75}	125	246	2953	1.20	0.60 b	3.27	5893 d	50.1
		DI_{50}	99	217	2415	1.11	0.21 h	2.91	5265 g	45.9
		PRD_{50}	99	213	2844	1.34	0.65 a	3.09	5703f	49.9
		RDI	114	249	2801	1.12	0.52 de	3.54	5977 c	48.5
		RF	49	169	2205	1.30	–	2.83	4358 h	50.6
	SSD	FI	140	271	2891	1.07	0.49 e	3.54	6274 a	46.1
		DI_{75}	118	235	2662	1.13	0.39 g	3.19	5930 cd	44.9
		DI_{50}	95	212	2548	1.20	0.36 g	2.83	5280 g	48.3
		PRD_{50}	95	210	2625	1.25	0.44 f	3.01	5789 e	43.8
		RDI	110	239	2850	1.19	0.59 bc	3.45	5960 c	47.8
		RF	49	169	2205	1.30	–	2.76	4358 h	50.6
2017	SD	FI	103	350	2454	0.71	0.58 ef	3.45	6445 b	38.1
		DI_{75}	77	315	2363	0.75	0.66 bc	3.10	6245 d	37.8
		DI_{50}	51	302	2050	0.69	0.38 h	2.76	5793 f	35.4
		PRD_{50}	51	299	2276	0.77	0.82 a	2.93	6045 e	37.6
		RDI	103	347	2442	0.71	0.57 f	3.36	6423 b	39.9
		RF	0	254	1856	0.73	–	2.69	5053 h	36.7
	SSD	FI	92	339	2482	0.71	0.68 b	3.36	6588 a	37.6
		DI_{75}	69	308	2279	0.75	0.61 de	3.03	6225 d	36.6
		DI_{50}	46	284	2098	0.75	0.53 g	2.69	5545 g	37.8
		PRD_{50}	46	289	2138	0.76	0.61 de	2.86	6288 c	34.0
		RDI	92	336	2435	0.72	0.63 cd	3.28	6558 a	38.9
		RF	0	254	1856	0.73	–	2.62	5053 h	36.7

Values followed by different small letters (a, b and c) indicate significant differences at $P < 0.05$; **LSD grouping at 1% level.

growing season but SWC values in this treatment remained greater than PRD_{50} and DI_{50}. More information regarding SWC variations in the different treatments in the experimental years have been given in previous publication by Bozkurt Çolak *et al.* (2020).

Grain yield

Grain yield values for the different irrigation treatments and two irrigation methods in the experimental years are summarized in Table 1. Statistical analysis results are given in Table 2. There was no significant difference in grain yields between the two drip irrigation systems in the experimental years. However, irrigation treatments resulted in significantly different yields ($P < 0.01$) as shown in Table 3. Since there was no significant difference between the two drip systems regarding the grain yield values, statistical comparisons of the mean grain yields were made on yields averaged over the two drip systems. Quinoa grain yield values in the first year were greater than those in the second year due to more favorable weather conditions prevailed in the first year. In 2016 growing season, FI, DI_{75}, and RDI treatments resulted in similar yields and significantly greater yields than DI_{50} and RF. Although PRD_{50} and DI_{50} treatments received the same amount of irrigation water, PRD_{50} resulted in higher yields than DI_{50}. In the 2017 growing season, FI and RDI treatments resulted in significantly greater yields than other treatments followed by DI_{75}. PRD_{50} treatment produced significantly higher yield than DI_{50} in the 2017.

DM yield

DM yield values for the different irrigation treatments and two irrigation methods in the experimental years are summarized in Table 1. Statistical analysis results are given in Table 2. Irrigation method and irrigation treatment interaction was significantly different with regard to DM yields ($P < 0.05$). FI under the ***SSD*** produced significantly greater DM yield than other treatments followed by FI under ***SD*** plots in the 2016 growing season. PRD_{50} treatments under both drip systems produced significantly greater biomass yield as compared to DI_{50} treatments. RDI resulted in higher DM yield than DI_{75} under both drip systems.

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Table 2. Statistical analysis results on grain yield, 1000-grain weight, dry matter yield, harvest index (HI), water productivity (WP) and irrigation water productivity (IWP) of quinoa under different treatments in the experimental years

Years	Irrigation treatments	Grain yield (kg/ha)	1000-grain weight (g)	Dry matter (kg/ha)	HI (%)	WP (kg/m^3)	IWP (kg/m^3)
2016	Irrigation systems	ns	ns	ns	ns	ns	LSD = 0.016 P = 0.0018** Cv(%) = 6.12
	Irrigation treatments	LSD = 254.6 P = 0.0001** Cv(%) = 9.37	LSD = 0.013 P = 0.0001** Cv(%) = 9.41	LSD = 264.0 P = 0.0001** Cv(%) = 0.46	ns	LSD = 1.15 P = 0.0008** Cv(%) = 9.47	LSD = 0.030 P = 0.0001** Cv(%) = 6.12
	Int. of irr. syst. and irr treat.	ns	ns	LSD = 374.0 P = 0.0001** Cv(%) = 0.46	ns	ns	LSD = 0.43 P = 0.0001** Cv(%) = 6.12
2017	Irrigation systems	ns	ns	ns	ns	ns	ns
	Irrigation treatments	LSD = 121.37 P = 0.0001** Cv(%) = 5.3	LSD = 0.0124 P = 0.0001** Cv(%) = 0.4	LSD = 215.5 P = 0.0001** Cv(%) = 0.4	ns	LSD = 0.038 P = 0.0453* Cv(%) = 5.1	LSD = 0.025 P = 0.0001** Cv(%) = 4.05
	Int. of irr. syst. and irr treat.	ns	ns	LSD = 304.7 P = 0.0001** Cv(%) = 0.4	ns	ns	LSD = 0.036 P = 0.0001** Cv(%) = 4.05

Values followed by different small letters (a, b and c) indicate significant differences at $P < 0.05$; **LSD grouping at 1% level, *LSD grouping at 5% level.

Irrigation method and irrigation treatment interaction was significantly different with regard to DM yield in 2017 ($P < 0.05$). FI and RDI under ***SSD*** produced significantly greater DM yield than other treatments and followed by FI and RDI under ***SD*** plots. Subsurface PRD_{50} produced significantly greater DM yield as compared to surface PRD_{50}, DI_{75} and DI_{50} treatments. Subsurface RDI resulted in higher DM yield than surface RDI and DI_{75}. RF produced the least DM yield.

Leaf area index

Variation of leaf area index (LAI) for different treatments under ***SD*** and ***SSD*** systems in the experimental years are depicted in Figs 2(*a*)–(*d*). As shown in Figs 2(*a*)–(*d*), LAI values under the ***SD*** and ***SSD*** systems had similar trends throughout the growing seasons. FI treatments under both systems resulted in greatest LAI values followed by RDI and DI_{75} treatments. FI treatment under ***SSD*** reached the maximum LAI value of 3.4 and FI under ***SD*** system had maximum LAI of 3.1 during flowering stage in the first year. In the second year, the corresponding values were 3.55 and 3.52 for ***SSD*** and ***SD***, respectively. RF had the least LAI value among the treatments in the experimental years. LAI values in all treatments decreased towards the end of season due to leaf senecensence.

1000 grain weight

1000 grain weight values for the different irrigation treatments and two irrigation methods in the experimental years are summarized in Table 1. Statistical analysis results are given in Table 2. There was no significant difference in 1000 grain weight between the two drip irrigation systems in the experimental years. However, irrigation treatments resulted in significantly different yields ($P < 0.01$) as shown in Table 3. Irrigation systems resulted in similar 1000 grain weight values in both experimental years. However, irrigation treatments produced significanly different 1000 grain weight values in the study years. The 1000 grain weight values were slightly greater in the first year than those in the second year. In 2016, the greatest 1000 grain weight value was observed in FI treatments followed by RDI and DI_{75}. As the amount of irrigation water applied increased 1000 grain weight values also increased. RF produced the least 1000 grain weight value. In 2017, again FI treatment produced the greatest 1000 grain weight value than all other treatments followed by RDI and DI_{75}. PRD_{50} resulted in significantly greater 1000 grain weight value than DI_{50} in the experimental years.

Harvest index

SD treatments produced slightly greater HI values than ***SSD*** treatments in the 2016 growing season, however, HI values were similar between the two drip systems in 2017. HI values under the different treatments varied from 45.9% in DI_{50} to 50.6% RF in ***SD*** treatments; and changed between 43.8% in PRD_{50} and 50.6% in RF in ***SSD*** in 2016. In the second year, HI values varied between 35.4% in DI_{50} and 39.9% in RDI in ***SD*** treatments; and varied from 34.0% in PRD_{50} to 38.9% in RDI in ***SSD***. Greater DM yield and lower grain yield values in the second year resulted in lower HI values than those in 2016.

WP and IWP

WP and IWP values for the different irrigation treatments and two irrigation methods in the experimental years are summarized in Table 1. RF and PRD_{50} treatments resulted in significantly greater WP values than other treatments while the FI had the least WP in the 2016 growing season. The WP values ranged between 1.07 kg/m^3 in FI and 1.34 kg/m^3 in PRD_{50} under ***SD***, and varied from 1.07 in FI and 1.30 kg/m^3 in RF under ***SSD*** in the first year, and WP varied between 0.69 kg/m^3 in DI_{50} and 0.77 PRD_{50} in ***SD*** system, and from 0.71 kg/m^3 in FI to 0.76 kg/m^3 in PRD_{50} under ***SSD***. There was no significant difference between ***SSD*** and ***SD*** in the experimental years. WP values were significantly greater in 2016 than those in 2017 due to higher ET and lower grain yield values observed in the second year.

Table 3. Comparison of mean grain yield, 1000-grain weight and mean water productivity (WP) values averaged over two drip systems for the different treatments in the experimental years

Irrigation treatments	Grain yield (kg/ha)		1000-grain weight (g)		WP (kg/m^3)	
	2016	2017	2016	2017	2016	2017
FI	2906.3 a	2468.2 a	3.59 a	3.41 a	1.07 c	0.71 b
DI_{75}	2807.8 a	2320.5 bc	3.23 c	3.06 c	1.17 b	0.75 a
DI_{50}	2481.6 b	2074.0 d	2.87 e	2.73 e	1.15 b	0.72 b
PRD_{50}	2734.7 ab	2206.9 c	3.05 d	2.90 d	1.30 a	0.77 a
RDI	2825.6 a	2438.1 ab	3.49 b	3.32 b	1.15 b	0.72 b
RF	2204.1 c	1855.3 e	2.80 f	2.66 f	1.30 a	0.73 ab
LSD (0.05)	254.6	121.4	0.013	0.0124	0.075	0.038
Probability	$P = 0.0001$**	$P = 0.0001$**	$P = 0.0001$**	$P = 0.0001$**	$P = 0.0008$**	$P = 0.0453$*

Values followed by different small letters (a, b and c) indicate significant differences at $P < 0.05$; **LSD grouping at 1% level, *LSD grouping at 5% level.

IWP values ranged between 0.21 DI_{50} and 0.65 kg/m^3 in PRD_{50} under ***SD*** treatments, and varied from 0.36 in DI_{50} and 0.59 kg/m^3 in RDI in ***SSD*** in 2016. In the second year, IWP values changed between 0.38 in DI_{50} and 0.82 kg/m^3 in PRD_{50} in ***SD*** treatments; and varied from 0.53 in DI_{50} to 0.68 kg/m^3 in FI in ***SSD***. PRD_{50} resulted in the highest irrigation water use efficiency (IWUE) values, and lowest values were observed in DI_{50}. There is no significant difference between the two drip systems regarding the IWP values. Except PRD_{50}, FI and RDI treatments resulted in greater than other treatments in both drip systems.

The relationships between yield and ET and irrigation water

The relationships between grain yield and ET for different treatments under the two drip systems for the experimental years are shown in Figs 3(*a*) and (*b*). Significant second-order polynomial relations were found between yield and ET ($P < 0.01$). The equation for the yield–ET relations for ***SD*** and ***SSD*** systems in 2016 is as follows:

$$GY = -0.0327ET^2 + 21.903ET + 558.38(R^2 = 0.77**) \text{ for } \textbf{\textit{SD}} \quad (5)$$

$$GY = -0.0382ET^2 + 23.574ET - 689.53(R^2 = 0.94**) \text{ for } \textbf{\textit{SSD}} \quad (6)$$

Significant linear relationships were obtained between yield and ET for drip systems in the 2017 growing season ($P < 0.01$). The following equations were developed for these relations:

$$GY = 6.2275ET + 302.37(R^2 = 0.85**) \text{ for } \textbf{\textit{SD}} \quad (7)$$

$$GY = 6.87ET + 146.81(R^2 = 0.997**) \text{ for } \textbf{\textit{SSD}} \quad (8)$$

Significant second-order polynomial relations were developed between grain yield and irrigation water for experimental years as shown in Figs 4(*a*) and (*b*).

Yield response factor (ky)

The slope of the relationship between relative yield reduction and relative ET deficit is called yield response factor (ky). The yield response factor for ***SD*** and ***SSD*** treatments are depicted in Figs 5(*a*) and –(*b*), and ky values for ***SD*** and ***SSD*** systems for quinoa are found to be 0.54 and 0.66 in 2016 growing season. The corresponding values for the 2017 growing seasons are 0.89 and 0.80 for ***SD*** and ***SSD*** systems, respectively.

Discussion

In arid and semi-arid agroecosystems, drought is the main abiotic stress damaging the potential yield and causing yield instability in quinoa (Fuentes and Bhargava, 2011 and Razzaghi *et al.*, 2011). The findings of the current research revealed that quinoa under ***SD*** plots used slightly more water than ***SSD*** plots for the same treatments most probably due to reduced surface evaporation from the ***SSD*** plots. SWC was similar for the FI, RDI and DI75 treatments, and was relatively higher compared to the DI50, PRD50 and RF treatments. SWC in the 40 cm soil depth was greater than SWC values in the 20 cm depth in the corresponding treatments. Application of water balance equation to 0–20 cm, 0–40 cm and 0–60 cm soil depth indicated that quinoa consumed most water from 0–20 cm soil depth followed by 20–40 cm depth under different treatments.

There was no significant difference in grain yields between the two drip irrigation systems in the experimental years. However, irrigation treatments resulted in significantly different yields ($P < 0.01$). Quinoa grain yield values in the first year were greater than those in the second year, due to more favorable weather conditions that prevailed in the first year. Maximum air temperatures in 2016 were (22.3, 27.9, 28.3, 33.7 and 35.3°C in March, April, May, June and July, respectively) several degrees higher than those in 2017. Especially, occurrence of high air temperatures (over 35°C) for several days in a row during the flowering period in late April 2017 could be the reason for relatively lower yields in the second year. Other parameters were similar, therefore this is probably the reason for greater yield in 2016 then in 2017. A high temperature during flowering and seed set can significantly reduce the yield (Hinojosa *et al.*, 2018).

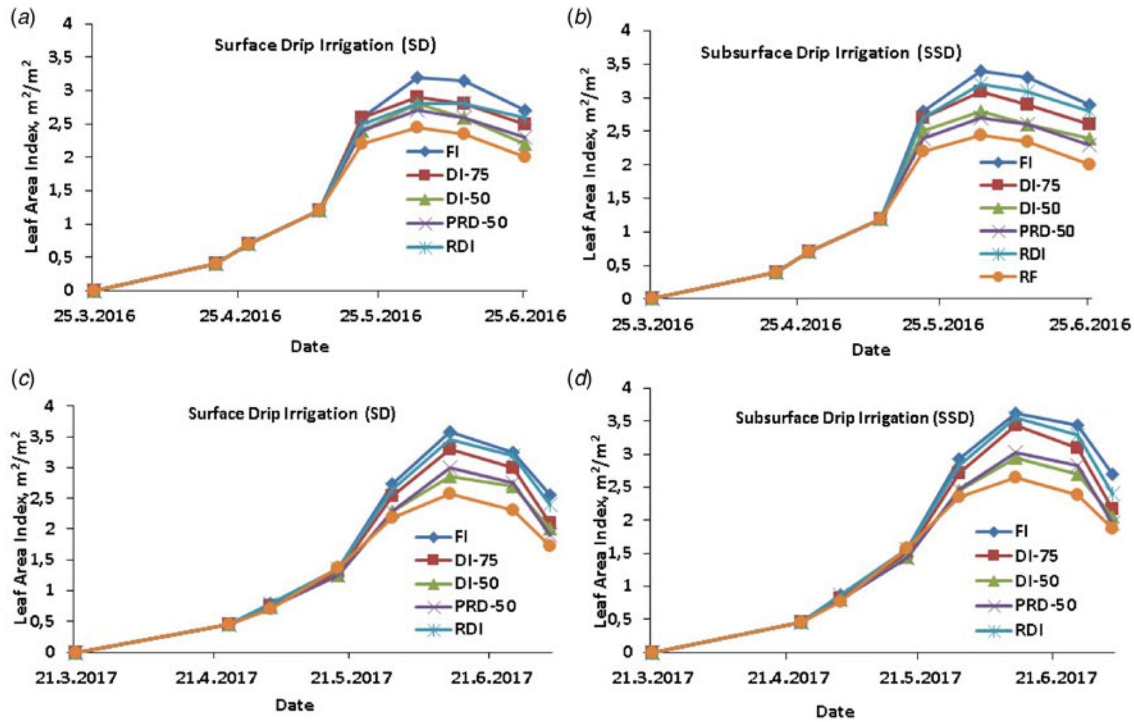

Fig. 2. Colour online. Leaf area index (LAI) variation during the 2016–17 quinoa growing season in all treatments under surface and subsurface drip irrigation: (*a*) SD-2016; (*b*) SSD-2016; (*c*) SD-2017; (*d*) SSD-2017 (vertical bars represent standard errors).

Although not evaluated in the current study, the genetic ability of quinoa might be another cause for lower yields in 2017.

RDI appeared to be good alternative to FI since it produced statistically similar yield to FI treatment in both experimental years. RDI resulted in water saving of 23 and 21% for ***SD*** and ***SSD*** systems, respectively, in the first year and no saving occurred in the second year since FI and RDI received same amount of irrigation water, and no irrigation was applied during the vegetative growing stage in 2017 due to sufficient enough rainfall received. DI_{75} treatment produced similar grain yield with FI in the first year but significantly lower yield in the second year due to differences in amount and distribution of rainfall between the two growing seasons. DI_{75} treatment resulted in water savings of 16% for both drip methods in the first year and 10 and 25% for ***SD*** and ***SSD*** systems, respectively, in the second year. Average grain yield reductions of 3 and 8% occurred in DI_{75} in comparison to FI were determined for the first and second experimental year, respectively. Therefore, DI_{75} can be considered as an alternative to FI in water scarce regions.

The yield reductions changed between 24 and 27%, respectively, for ***SSD*** and ***SD*** under the rainfed (nonirrigated) conditions in 2016; and the corresponding decreases were 24 and 25%, for ***SD*** and ***SSD*** in 2017. Quinoa is highly resistant to a number of abiotic stresses (Jacobsen *et al*., 2003). Several drought resistant mechanisms are present in quinoa. Drought in early vegetative stages may prolong its life cycle, allowing the plant to make up for growth lost during the early drought if water becomes available later. Drought stress during the vegetative growth stage leads to deep root development, and without stress conditions for the rest of the growing season allowed the plant to be able to optimize its photosynthesis and carbon translocation (Geertz *et al*., 2008; Jacobsen *et al*., 2009; Hirich *et al*., 2014). Greater midday leaf water potential (LWP) values were observed in FI treatment plots than the DI treatment plots under both drip systems (data are not shown, details can be found in Bozkurt Çolak *et al*., 2020). RDI and DI_{75} treatments had greater LWP values than DI_{50} and PRD_{50} treatments since RDI and DI_{75} received more irrigation water than DI_{50} and PRD_{50} treatment. We also observed slightly higher LWP values in SSD plots than in the SD plots, however, the difference between the two irrigation systems was not significant. Generally, LWP values decreased towards the end of season in comparison to the beginning of the season (Bozkurt Çolak *et al*., 2020). Towards the end of the growing season, SWC reached closer to the wilting point in DI_{50}, PRD_{50} and RF treatments. Gradual build up of water stress as indicated by lower SWC and lower LWP, resulted in reduced grain yields in DI_{50}, PRD_{50} and RF treatments in the experimental years. These findings are in line with the results reported by Lavini *et al*. (2014), and Razzaghi *et al*. (2012) who stated that water stress during grain filling stage significantly decreased the seed yields of quinoa Titicaca. Cocozza *et al*. (2012) suggested that a certain amount of water supplied during flowering and grain filling is enough to stabilize quinoa yield even for severe DI. Geerts *et al*. (2007) found that drought stress during preflowering, flowering and early grain filling had a strong negative effect on grain yield and WP when compared to drought stress in the vegetative stage or FI. DI can stabilize yields at a level that is significantly higher than under rainfed cultivation (Geerts *et al*., 2009). In this study, RDI treatment allowed water stress during the vegetative growth stage, produced grain yield almost the same as that produced with FI. Hirich *et al*., (2014) reported similar findings to RDI that for quinoa treatment receiving 50% of FI during vegetative growth stage recorded the highest yield and WP in Morocco.

The grain yield of quinoa cv. Titicaca ranged between 2.0 and 3.0 t/ha under non-stressed conditions in the Mediterranean

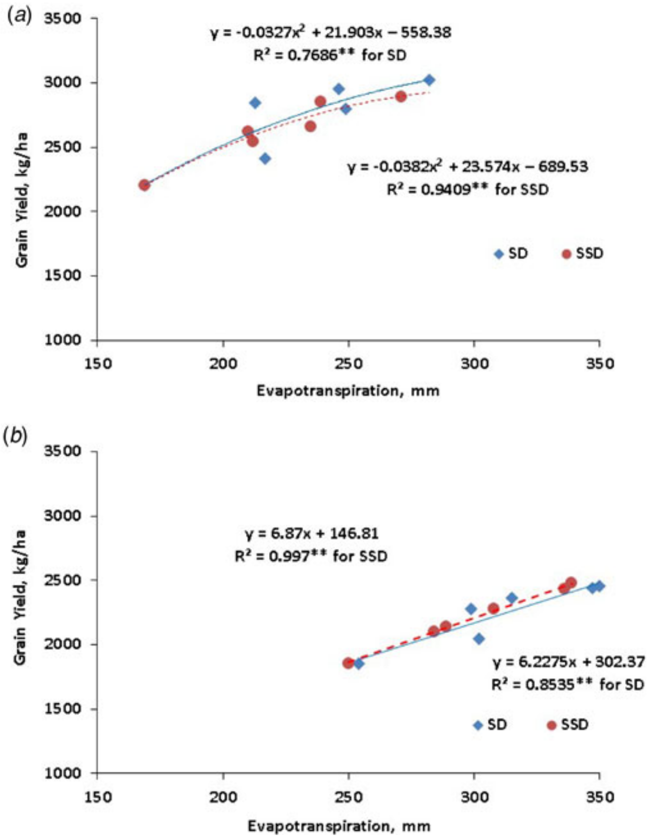

Fig. 3. Colour online. The relationships between grain yield and crop evapotranspiration (ET) (*a*) 2016 and (*b*) 2017.

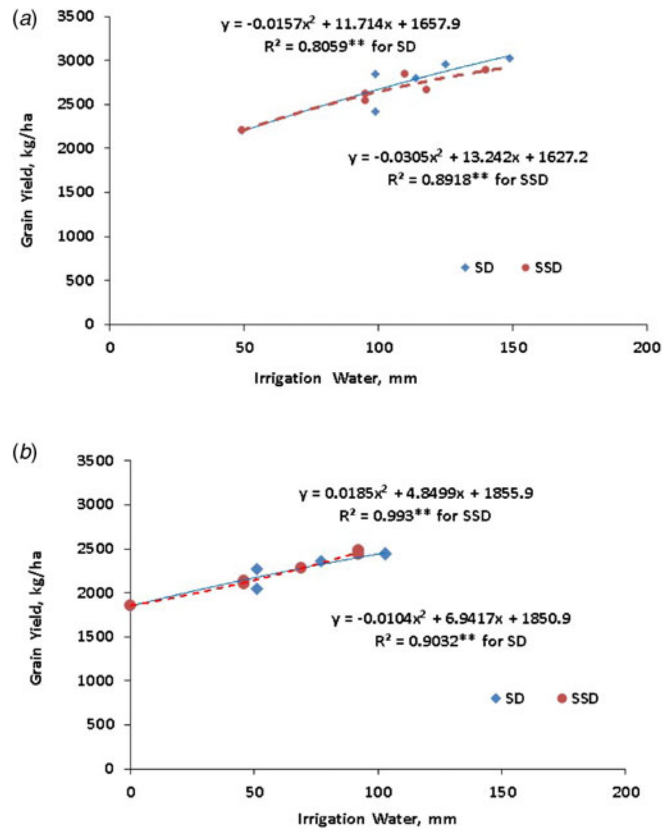

Fig. 4. Colour online. The relationships between grain yield and irrigation water (*a*) 2016 and (*b*) 2017.

region of Turkey (Yazar and İnce Kaya, 2014). Pulvento *et al.* (2012) found that yields for 'Titicaca' ranged between 2.30 and 2.70 t/ha whether grown under high irrigation (300–360 mm) or DI (200–220 mm) in Italy. In Denmark, Razzaghi *et al.* (2011) obtained 3.3 t/ha yield from quinoa cv. Titicaca under non-stressed conditions while it was reported that total grain yield of same variety ranged from 1.9 to 3.3 t/ha in Italy (Lavini *et al.*, 2014). In Bolivia 3.7 t/ha (Garcia *et al.*, 2003); in Chile 2.6 t/ha (Martinez *et al.*, 2009) and in Morocco 3.3 t/ha (Hirich *et al.*, 2014) grain yields have been obtained from different quinoa varieties.

Alvar-Beltran *et al.* (2019) obtained the highest yield of Titicaca (1.9 t/ha) from the November sown quinoa irrigated at 60% potential ET and with 25 kg N/ha in Burkina Faso. Ahmadi *et al.* (2019) evaluated the plant density response of quinoa to FI in Iran and reported the grain yields varied between 2.86 and 3.65 t/ha. Praveen Kadam *et al.* (2018) studied the effect of DI applied with ***SD*** and ***SSD*** systems in India and they found that the highest grain yield and stalk yield was recorded with 1.0 Epan (Class A pan evaporation) throughout cropping period in India. According to these results, grain yields of quinoa under non-stressed conditions vary depending on plant cultivars, sowing date and environmental conditions such as soil and climate. The results of this study revealed that both RDI and DI_{75} treatments appeared to be suitable irrigation strategies under the Mediterranean climatic conditions.

In general, as the amount of irrigation water increased DM yield also increased, except for PRD_{50} under ***SSD***. The DI treatments caused a significant reduction in above ground plant DM yield. Thus, water stress resulted in lower DM yield in the RF, DI_{50}, PRD_{50} treatments in comparison to RDI, DI_{75} and FI treatments. Several researches showed that DI application during vegetative growth stage induced root system growth and development for quinoa (Jensen *et al.*, 2000; Geerts *et al.*, 2005; Jacobsen *et al.*, 2009). Pulvento *et al.* (2012) reported that the treatment with a reduction in the irrigation water to 25% of full irrigated treatment caused an increase in WP and a reduced DM accumulation in the leaves in Italy. Hirich *et al.* (2014) observed the highest DM accumulation under FI conditions and the highest HI was recorded when quinoa was subjected to water stress during vegetative growth stage.

In general, LAI index values increased with increasing irrigation water. FI treatments under both systems resulted in greatest LAI values followed by RDI and DI_{75} treatments. RF had the least LAI value among the treatments in the experimental years. LAI values increased continuously until grain filling stage in all treatments, and then decreased towards the end of season due to leaf senecensence. Since the leaf area of plants is reduced under stress, the water used for transpiration is reduced; efficiency of water use is remarkably higher in these plants compared to FI and RDI. The increase in LAI of quinoa with irrigation has also been reported by Garcia *et al.* (2003). The deficit treatments (DI_{50}, PRD_{50}) caused a significant reduction in leaf surface. Yazar *et al.* (2015) determined LAI values for fresh and saline irrigation water treatments varying from 1.4 in RF and DI_{25} to 2.9 in FI with fresh water for drip-irrigated Titicaca variety in Turkey. Ince Kaya (2015) reported the maximum LAI value of 2.5 for FI for Titicaca cultivar in Turkey. They concluded that water

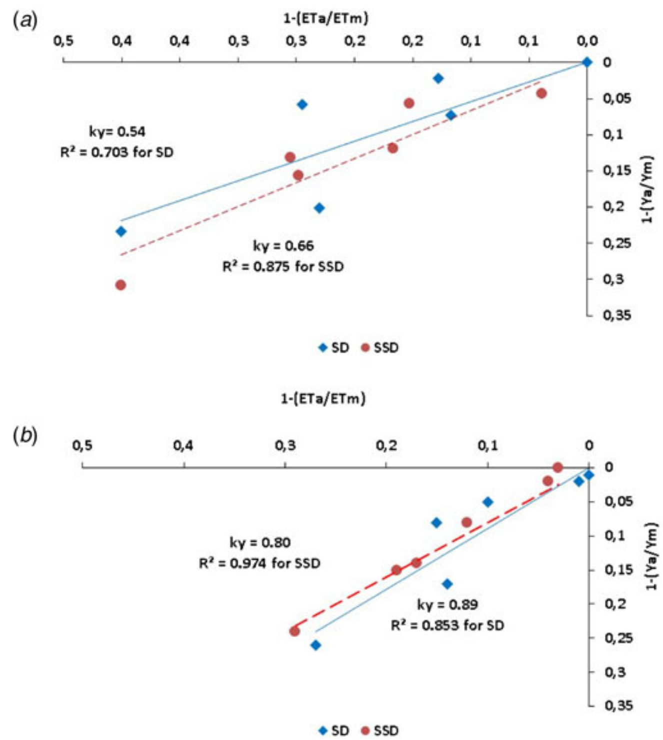

Fig. 5. Colour online. The yield response factor (ky) for surface and subsurface drip treatments (*a*) 2016 and (*b*) 2017.

and salinity stress together reduced LAI considerably compared with FIs with fresh water. Lavini *et al*. (2014) found the highest LAI value of 2.8 for full irrigated treatment and the least LAI in severe stress treatment in Southern Italy. Fghire *et al*. (2017) evaluated the effect of water stress on LAI which increased significantly and a continuously and peaked at grain filling stage for all water treatments and there after the LAI started to decrease in Morocco. Similar results are reported by Praveen Kadam *et al*. (2018) that LAI reached peak at grain filling stage and declined at maturity due to drying and senescence of foliage. The non-stressed treatment reported significantly higher LAI at all stages of the crop, it is followed by non-stressed treatments at grain filling stages in India.

As the amount of irrigation water applied increased 1000 grain weight values also increased. RF produced the least 1000 grain weight value while FI treatment had the greatest 1000 grain weight value than all other treatments followed by RDI and DI_{75}. PRD_{50} resulted in significantly greater 1000 grain weight value than DI_{50} in the experimental years. The research findings indicated that water stress caused a decrease in 1000 grain weight in RF and DI_{50} treatments in comparison to FI, RDI and DI_{75} treatments. Razzaghi *et al*. (2012) determined the 1000-grain weight values for titicaca varying from 3.1 and 3.2 g for different soil textures in Denmark. Pulvento *et al*. (2012) found 1000-grain weight values changing between 2.44 and 2.67 g for Titicaca in Italy. Yazar *et al*. (2017) reported 1000-grain weight values ranging from 3.03 g in FI to 3.29 g in RF under normal planting time; and varied from 2.62 g in FI to 2.79 g in RF in late planting in Turkey. The findings in the present study are contradictory to findings reported by Yazar *et al*. (2017). Alvar-Beltran *et al*. (2019) determined the 1000-grain weight values varying between 1.75 and 2.41 g for Titicaca variety in Burkina-Faso under different irrigation treatments.

There was no significant difference among the irrigation treatments regarding the HI. Greater DM yield and lower grain yield values in the second year resulted in lower HI values than those in 2016. The DI treatments caused a significant reduction in above ground plant DM and grain yields. Thus, water stress resulted in lower DM yield and grain yield in the RF, DI_{50}, PRD_{50} treatments in comparison to RDI, DI_{75} and FI treatments. Razzaghi *et al*. (2012) found HI values for sandy-loam, sandy and clay loam soils, respectively, as 46, 47 and 43% for titicaca variety in Denmark. Pulvento *et al*. (2012) reported HI values for titicaca ranging from 40 and 41% in Italy. Yazar *et al*. (2015) found HI values varying between 44 and 47% for titicaca variety in Turkey. Yazar *et al*. (2017) reported HI values ranging from 30.9% in FI to 36.6% DI_{25} under normal planting time; and varied from 28.7% in FI to 30.1% in RF in late planting in Turkey. Alvar-Beltran *et al*. (2019) found HI values varying between 35 and 40% for titicaca variety under different irrigation treatments in Burkina Faso.

Regarding the WP, there was no significant difference between ***SSD*** and ***SD*** in the experimental years. WP values were significantly greater in 2016 than those in 2017 due to higher ET and lower grain yield values observed in the second year. RF and PRD_{50} treatments resulted in significantly greater WP values than other treatments while the FI had the least WP. As a C_3 crop, quinoa's WP is generally low, lying between 0.3 and 0.6 kg/m^3 in the Bolivian Altiplano while exceeding 1 kg/m^3 in Morocco and Italy (Geerts *et al*., 2009; Hirich *et al*., 2014; Lavini *et al*., 2014; Riccardi *et al*., 2014). Geerts *et al*. (2008) reported that drought stress conditions at key phenological stages (pre-flowering, flowering and pasty grain formation) had a negative effect both on grain yield per plant and WP. Yazar *et al*. (2015) found WP values varying between 0.48 and 1.39 kg/m^3 for Titicaca variety in Turkey. Yazar *et al*. (2017) reported WP values ranged from 1.00 kg/m^3 in RF to 1.57 kg/m^3 in DI_{25} treatment under normal planting time (early April) and from 0.53 (RF) to 0.75 kg/m^3 (DI_{50}) under the late planting (late April) treatments using drainage water applied with sprinkler line source system in Tarsus, Turkey. Patil *et al*. (2018) recorded the maximum WP as 0.96 kg/m^3 under the treatment IW/E-Pan ratio of 0.6 in India. Ahmadi *et al*. (2019) reported WP values for three planting densities varied between 0.25 and 0.39 kg/m^3 in Iran. Alvar-Beltran *et al*. (2019) found WP values for different planting times and different irrigation in Burkina-Faso changing from 0.17 to 1.69 kg/m^3 for November planting; and varying from 0.23 to 0.81 kg/m^3 for December planting. Yazar *et al*. (2015) found IWP values varying between 0.88 and 1.0 kg/m^3 for titicaca variety in Turkey. It can be concluded that higher WP should be associated with greater yield in order to recommend a suitable irrigation strategy for producers. In this study, RDI and DI_{75} treatments were recommended for farmers producing quinoa under semi-arid conditions.

Significant second-order polynomial relations were found between grain yield and crop ET in the first year but significant linear relationships were obtained in the second year. Yazar *et al*. (2017) determined significant linear relationship for normal planting time (April 11), and second-order polynomial relations were found between the seed yield and ET under the normal and late planting times (April 30) in Tarsus, Turkey ($R^2 = 0.912$ and 0.899 for normal and late planting, respectively). Patil *et al*. (2018) derived second degree polynomial relationship between grain yield and total water applied with correlation coefficient of 0.89 in India. Our findings are in agreement with the above-

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mentioned studies. The high correlation between grain yield and ET in this study indicates that grain yield is strongly influenced by the pattern of water use during the course of the season and emphasizes the importance of adequate water supply during all growing season for higher yield and WP.

The yield response factor for ***SD*** and ***SSD*** treatments were <1.0 in both experimental years that means that quinoa is drought resistant crop. ky values were greater in the second year due to higher yields compared to the first year. Ince Kaya (2015) developed yield response factor (ky) for differentially irrigated quinoa cv. titicaca as 0.96 in the Mediterranean region of Turkey. Garcia *et al.* (2003) found ky of 0.67 for quinoa in Bolivia. Our findings are inline with these study results.

Conclusions

The results of the current study demonstrated that various DI strategies such as regulated deficit, PRD, and conventional DI applied with ***SD*** and ***SSD*** systems had significant effect on grain and DM yields of quinoa, and WP under the Mediterranean climatic conditions. However, the two drip systems performed similary regarding the grain and DM yields. RDI resulted in water saving of 23 and 21% for ***SD*** and ***SSD*** systems, respectively, but produced similar yield as I_{100}. DI_{75} treatment resulted in water savings of 16% for both drip methods in the first year and 10 and 25% for ***SD*** and ***SSD*** systems, respectively, in the second year. Average grain yield reductions of 3 and 8% occurred in DI_{75} in comparison to FI. Thus, RDI and DI_{75} treatments appear to be good alternative to FI in the Mediterranean environmental conditions. RF and PRD_{50} treatments resulted in significantly greater WP values than other treatments while the FI had the least WP.

Therefore, RDI, in which applying irrigation water by reducing the crop water requirement by 50% at the vegetative growth stage has a significant contribution for sustainable and efficient irrigation water utilization in water stress areas without any loss of grain and DM yield is recommended along with conventional DI (DI_{75}) in the semi-arid Mediterranean area.

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Conflict of interest. None.

Ethical standards. Not applicable.

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