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Evaluation of crop water stress index and leaf water potential for differentially irrigated quinoa with surface and subsurface drip systems

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Abstract

A 2-year field experiment was conducted with the objectives to evaluate the physiological and yield response of quinoa cv Titicaca to various deficit irrigation strategies applied with surface drip (SD) and subsurface drip systems (SSD) under the Mediterranean climatic conditions in 2016 and 2017. The treatments consisted of regulated deficit irrigation (RDI), partial root-zone drying (PRD_{50}), conventional deficit irrigations (DI_{50}, DI_{75}) and full irrigation (FI) under SD and SSD. A rainfed treatment was also included. The experimental design was split plots with four replications. 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 during vegetative stage until flowering, then received 100% of water requirement. The results indicated that RDI resulted in water saving of 23 and 21% for surface drip (SD) and SSD systems, respectively, and RDI produced statistically similar yield to FI treatment in both experimental years. 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. Thus, RDI and DI_{75} treatments appear to be good alternative to FI for sustainable quinoa production in the Mediterranean environmental conditions. Greater leaf water potential (LWP) and smaller crop water stress index (CWSI) values were measured in FI plots under both drip systems than deficit irrigation treatment plots. Significant second-order polynomial relations were determined between CWSI and LWP for the drip systems. Leaf area index (LAI), LWP decreased and CWSI increased as the drought increased. CWSI correlated significantly ($P < 0.01$) and negatively with grain yield, dry matter yield, LAI, and mean soil water content indicating that grain yield of quinoa declined with increasing CWSI values. All these relations are best described by significant second-order polynomial equations. The results revealed that quinoa should be irrigated at LWP values between -1.35 and -1.60 MPa, and average CWSI value of approximately 0.35 for high yields.

Introduction

In the Mediterranean and particularly semi-arid regions in the world, water scarcity is one of the most pressing constraints of plant production. The scarcity of fresh water resources and uneven distribution and irregularity of rainfall and climate change had significant effect on the sustainable agriculture in these regions. Therefore, efficient management of water and the cultivation of drought- and salt-tolerant crops such as quinoa and amaranth appear as major factors for a sustainable crop production in water scarce regions (Yazar and İncekaya 2014).

Quinoa (*Chenopodium quinoa Willd.*) is a highly nutritious seed crop (Repo-Carrasco et al. 2003; Jacobsen et al. 2007; Ruiz et al. 2014) and widely grown in the Andean region of South America and has earned special attention worldwide due to its nutritional and health benefits and its ability to adapt to unfavorable soil and climatic conditions (Garcia et al. 2003; Jacobsen et al. 2003, 2005; Hinojosa et al. 2018). Quinoa has the capacity to grow and adapt to marginal environments in many regions across the globe, and it exhibits notable tolerance to abiotic stressors such

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as drought and salinity (Garcia et al. 2003; Jacobsen et al. 2009; Razzaghi et al. 2011, 2012; Adolf et al. 2013; Ruiz et al. 2014; Pulvento et al. 2012; Yazar et al. 2015; Hinojosa et al. 2018). Quinoa has been recently introduced in Turkey through EU Project "Sustainable water use for securing food production in the Mediterranean region under changing climate (SWUP-MED)". The quinoa production could contribute to food security in the Mediterranean region as well as in other regions in the world (Hirich et al. 2012, 2014; Jacobsen et al. 2012).

Innovations for saving water in irrigated agriculture and thereby improving water use efficiency 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 deficit irrigation (DI), partial root-drying irrigation (PRD) and regulated deficit irrigation (RDI) that have been developed for limited irrigation managements. Conventional deficit irrigation (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). Partial root-zone drying (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 regulated deficit irrigation (RDI) has been identified as one of the key water-saving technologies in agriculture. RDI is another form of DI. 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).

Proper scheduling of irrigation with pressurized irrigation systems especially micro-irrigation methods such as surface and subsurface drip provides potential option to save water and increase yield, quality and water productivity. Irrigation application method is known to affect crop performance, including yield and crop water productivity (Bozkurt Çolak et al. 2018; Evett et al. 2019). Subsurface drip (SDI) has proven to be an efficient irrigation method with potential advantages of high water use efficiency, efficient fertilizer application, and lower labor costs than in a conventional drip irrigation system (Lamm and Camp 2007; Irmak et al. 2016). Placing the irrigation system underground coupled with an effective irrigation management program provide the oppotunity to supply proper amount of crop water and nutrient needs directly to crop root-zone and minimizes surface soil evaporation due to irrigation (Irmak 2005).

A quantitative estimate of impending plant water stress is a critical prerequisite for the efficient scheduling of irrigations. Ideally, the warning of stress should come from the crops themselves, obviating the need for precise information regarding available soil water, root distribution and evaporative demand of the atmosphere (Jones 2007). Sound knowledge of the soil water status, crop water requirements, crop water stress status, potential yield reduction under water-stressed conditions is required to optimize the use of water and energy and maximize profits (Zegbe et al. 2003; Kang et al. 2002). However, irrigation scheduling based upon crop water status can be more advantageous since crops respond to both the soil and aerial environment (Yazar et al. 1999). Therefore, use of plant-based irrigation scheduling techniques have increased more in recent years. In these techniques, timing of irrigation is determined by detecting the water stress status of the plant. Among the possible measures of plant water status include direct measurements of some aspect of such as leaf water potential (Wang et al. 2005; Shackel et al. 2010; Bozkurt Çolak et al. 2017), canopy temperatures (Idso et al. 1981; Jones 1999; Yazar et al. 1999, 2010; Alves and Pereira 2000; Payero et al. 2005; Chen et al. 2010; O'Shaughnessy et al. 2011; Taghvaeian et al. 2012; Sezen et al. 2014; Bozkurt Çolak et al. 2015; DeJonge et al. 2015; Argyrokastritis et al. 2015; Alghory and Yazar 2019) as well as measurements of a number of plant processes that are known to respond sensitively to water deficits. The use of leaf water potential (LWP) and crop water stress index (CWSI) are considered more practical at a commercial level (Naor 2006; Bonet et al. 2010; Moriana et al. 2010).

The crop water stress index is one of the most frequently used indices to quantify crop water stress based on canopy temperature. CWSI can be determined by the empirical approach proposed by Idso et al. (1981), which focuses on the relationship between the air and canopy temperature difference (Tc-Ta) and the vapor pressure deficit (VPD) under non-water-stressed and fully water-stressed conditions. Some research has evaluated the CWSI for quinoa in the Mediterranean region where crop water stress is frequent and pervasive (İnce Kaya 2015).

Plants respond directly to changes in water status in the plant tissues, whether in the roots or in other tissues, rather than to changes in the bulk soil water content (or potential). The actual tissue water potential at any time, therefore, depends both on the soil water status and on the rate of water flow through the plant and the corresponding hydraulic flow resistances between the bulk soil and the appropriate plant tissues (Jones 1999). Therefore, leaf water potential, which is a direct indicator of plant water status, can be used for irrigation scheduling in the crop production (Hsiao 1990). When leaf water potential is used with micro-irrigation techniques a significant amount of water can be saved and water productivity is maximized (Fereres and Evans 2006).

A number of studies 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. (2011) 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 (Galwey et al. 1989; Jensen et al. 2000; Jacobsen et al. 2009). Various studies reported that quinoa has responded positively to deficit irrigation in various experimental locations where grain yield was hardly affected by deficit irrigation (Costa et al. 2007; Geerts and Raes 2009; Pulvento et al. 2012; Razzaghi et al. 2012; Yazar et al. 2015). Quinoa's flowering and milk grain stages have been established as the most drought-sensitive (Geertz et al. 2008). However, studies on the physiological responses of quinoa to PRD and RDI irrigation management strategies under a specific condition are rather limited.

This study was carried out because not much information is available on quinoa's physiological response (such as crop water stress index (CWSI) and leaf water potential (LWP) along with yield response) to regulated deficit irrigation (RDI), partial root-zone drying (PRD) and conventional deficit irrigation applied with subsurface drip irrigation system. Therefore, the primary objective of this study is to evaluate the yield and physiological response such as CWSI and LWP of quinoa to RDI, PRD, and conventional deficit and full irrigation applied with surface drip and subsurface drip systems under the Mediterranean climatic conditions.

Materials and methods

Experimental site and soil

This research was conducted in the experimental field of the Irrigation and Agricultural Structures Department of the Cukurova University in Adana, Turkey. The site has a latitude of 36° 59′ N, longitude of $35^{\circ}18'$ E, and is 50 m above mean sea level. The soil of the experimental site is classified as the Mutlu soil series (Palexerollic Chromoxeret; FAO 2006), with clay texture throughout the soil profile, and has a pH range 7.61–7.87, electrical conductivity of the saturation extract (ECe) 0.12–0.19 dS m^{-1}, and volumetric soil water contents 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 60 cm soil depth.

Irrigation treatments and experimental design

In this study, two irrigation systems, namely surface drip (SD) and subsurface drip systems (SSD); and four 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 rainfed treatment RF were considered. Experiment was designed in split-plot with four replications. Irrigation systems (surface drip and subsurface drip are assigned to the main plots, irrigation strategies are assigned to the sub plots). Full irrigation (FI) in which soil water deficit was replenished to field capacity when 50% of available water at 60 cm was depleted. Deficit irrigation treatments (DI_{75} and DI_{50}) which received 75 and 50% of full irrigation, respectively. Partial root-zone drying (PRD_{50}) plots received 50% of FI, but from alternative laterals in each application. Regulated deficit irrigation (RDI) received 50% of FI until flowering growth stage, then received 100% of water requirement. Rainfed (RF), in which no irrigation was applied except during emergence and crop establishment period. Each subplot had a length of 10 m and 3.0 m (6 plant rows) in width.

Irrigation systems

In the surface drip irrigation plots, polyethelene (PE) laterals of 16 mm in diameter with in-line emitters (integral short tortuous path emitters) spaced 0.33 m apart, each delivering 2.0 L h^{-1} 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 water during one irrigation, the other lateral supplied water in the next irrigation. A locally produced surface drip irrigation system (Betaplast, Adana, Turkey) was used in the study.

Subsurface drip irrigation system laterals were buried under 15 cm of the soil surface by means of a chisel plow. In-line emitters with discharge rate of 2.0 l h^{-1} spaced at 40 cm intervals on the lateral line made of PE 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.

Agronomic practices

Quinoa (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: K, 20: 20: 0) was broadcast at a rate of 75 kg ha^{-1} of each of N and P_2O_5, and incorporated into the soil. The rest of the N was applied in Urea form at a rate of 25 kg ha^{-1}

with fertigation at each irrigation during the growing season using a bypass system. All treatment plots received a total of 150 kg N ha^{-1}.

Measurements and observations

Çukurova 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 for the experimental years. 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 Table 1.

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

Soil water content were monitored in traditional (gravimetric) in 0–60 cm and innovative manners (TDR) in 0–40 cm. Soil water content sensors (SM-150, Delta T) 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 actual crop water use or evapotranspiration (ETa) was calculated with the one dimensional water balance equation.

$$ETa = P + I + Cp \pm \Delta S - Dp - Ro, \qquad (1)$$

where ETa is actual evapotranspiration (mm); P, the precipitation (mm); I, the amount of irrigation water applied (mm); Cp is contribution through the capillary rise from ground water; ΔS, the change in the soil water content (mm) at planting and at harvest in 60 cm soil depth; Dp is deep drainage and Ro is runoff (mm). Rainfall amount over the soil water deficit in 60 cm effective root-zone depth is considered as deep percolation. Therefore, in this study, effective rainfall is considered as the part of rainfall equal to soil water deficit. Water table depth was about 5 m below the soil surface Cp was also neglected.

Canopy temperatures (Tc) were measured with a handheld infrared thermometer (IRT) (Everest Interscience model 100L DL, USA), which has a field of view of 3° and detects radiation in the 8–14 μ waveband. IRT readings were taken at a horizontal angle of 30–40° to have only crop canopy in view area. Data collection for Tc was initiated in the first week of May in the experimental years when the plant cover percentage was nearly 70%. Canopy temperatures were measured from four different corners

Table 1 Historical monthly mean and 2016–2017 growing seasons climatic data of the experimental area

Experimental years	Climatic parameters	March	April	May	June	July
2016	Tmax (°C)	22.3	27.9	28.3	33.7	35.3
	Tmin (°C)	8.7	11.0	15.1	20.5	24.0
	Tmean (°C)	14.9	18.6	21.4	27.2	29.6
	Rainfall (mm)	77.6	2.2	68.5	30.0	0.0
	Evaporation (mm)	82.9	114.0	163.0	207.2	233.3
	RH(%)	67.1	67.5	68.5	63.4	63.2
	Wind speed (m s^{-1})	1.3	1.5	1.6	1.7	1.8
2017	Tmax (°C)	21.4	29.1	28.7	32.4	36.5
	Tmin (°C)	8.9	11.4	15.0	19.6	23.4
	Tmean (°C)	14.9	20.3	21.8	26.0	30.1
	Rainfall (mm)	75.6	97.2	41.0	38.0	0.0
	Evaporation (mm)	81.7	112.0	156.0	201.2	230.6
	RH (%)	63.2	59.9	66.2	62.2	60.7
	Wind speed (m s^{-1})	1.4	1.6	1.8	1.7	1.8
Long-term (1950–2015)	Tmax (°C)	19.6	23.7	28.2	31.7	33.7
	Tmin (°C)	8.6	12.3	16.1	20.2	23.4
	Tmean (°C)	12.7	17.7	20.9	26.2	29.0
	Rainfall (mm)	67.6	55.8	46.6	20.1	7.3
	Evaporation (mm)	83.7	119.0	169.0	209.2	234.6
	RH(%)	67.0	62.5	65.8	62.3	61.6
	Wind speed (m s^{-1})	0.8	1.3	1.5	1.6	1.7

Tmax maximum air temperature, *Tmin* minimum air temperature, *Tmean* mean air temperature, *RH* relative humidity

of the plots at 1 m distance from the canopy and averaged to determine the plot's canopy temperature. Tc measurements were made between 12:00 and 14:00 h (local standard time) under clear skies when the sun was unobscured by clouds. Dry and wet bulb temperatures were measured with an aspirated psychrometer (Assmann Psychrometer, Sato Keiryoki MFG. Co., Ltd, Japan) at a height of 1.5 m in the open area adjacent to the experimental plots. The mean VPD was computed as the average of the calculated instantaneous wet and dry bulb temperatures and the standard psychrometer equation with a mean barometric pressure of 101.25 kPa. The CWSI was calculated based on empirical equation suggested by Idso et al. (1981)

$$CWSI = \frac{(Tc - Ta) - LL}{UL - LL}, \qquad (2)$$

where LL represents the non-water-stressed baseline (lower baseline) and UL represents the non-transpiring upper baseline; Tc = canopy temperature ($^{\circ}C$); Ta = air temperature ($^{\circ}C$). LL for the canopy–air temperature difference (Tc–Ta) versus the vapor pressure deficit (VPD) relationship was determined using data collected only from the unstressed treatments (FI). UL was computed according to the procedures explained by Idso et al. (1981). To verify the upper baseline, canopy temperatures of the heavy stressed plants were determined several times during the growing season of quinoa.

Midday leaf water potential (LWP) was measured with a pressure chamber (PMS Instrument Company, Model 615, Albany, USA) prior to irrigations once a week throughout the growing season (Scholander et al. 1965). All measurements were done between 12:00 and 14:00 h, and two leaves were measured per experimental unit. For this purpose, the two fully developed sunlit leaves of a plant in each plot and the average of two measurements made on the day was taken as mean the midday leaf water potential value for the plot.

Water use efficiency (WUE) and irrigation water use efficiency (IWUE) were calculated using the following equations (Yazar et al. 1999):

$$WUE = GY/ETa, \qquad (3)$$

$$IWUE = (GY_i - GY_d)/(Ii - Id), \qquad (4)$$

where WUE is water use efficiency (kg m^{-3}) in terms of yield per unit of water used; IWUE is irrigation water use efficiency (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 rainfed treatment (kg ha^{-1}); Ii is irrigation water applied (mm) in irrigated treatment; and Id is irrigation water applied in DRY treatment for plant establishment (mm).

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.

Leaf area index (LAI) measurements were made regularly throughout the growing season in the central two rows of quinoa plants in each treatment using the "LAI-2000 Plant Canopy Analyzer" (Li-Cor2000, Lincoln, NE). Four measurements below the canopy and one measurement above the canopy were made to account for the canopy light interception at five different angles, from which LAI was computed using a model of radiative transfer in vegetative canopies. The multiple below canopy readings and the fish-eye-field-of-view assure that LAI calculations are based on a large sample of the foliage canopy.

Phenological stages were monitored during the crop cycle in the field using the indications of Jacobsen and Stolen (1993) for quinoa. At physiological maturity yield was determined by hand harvesting all the plants in the 4 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.

Statistical analysis

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

Results

Irrigation and evapotranspiration

Evaluation of the climatic conditions during the experimental years indicated that mean temperatures were similar to long-term means. Monthly rainfalls fluctuated during and between the two growing seasons (2016 and 2017) when the experiments were conducted. In general, the 2017 growing season was relatively wet with a total rainfall of 182 mm compared to the 2016 growing season with a total rainfall of 98.5 mm. The monthly rainfall in April 2016 was only 2.2 mm, while it was 97.2 mm in April 2017. In addition, rainfall was more evenly distributed in 2017 than in 2016. In 2017, rainfall recived in May–June period was greater than the long-term means.

Irrigation quantity and crop water use (ETa) values for the different irrigation treatments and two irrigation

methods for the experimental years are summarized in Table 2. At the beginning of the 2016 growing season, all treatments received 49 mm of irrigation water in two applications in order for establishing good plant stand. In 2016 growing season, the amount of irrigation applied to surface drip (SD) irrigation plots varied from 99 mm in DI_{50} and PRD_{50} to 149 mm in FI treatment; the corresponding values for subsurface drip (SSD) plots varied from 95 to 140 mm. SD plots received slightly more water but the differences are not significant. In 2016 growing season, the RDI and DI_{75} plots in SD plots received 114 and 125 mm of irrigation water, respectively; while in SSD plots RDI and DI_{75} treatments received 110 and 118 mm of irrigation water, respectively. 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 were 46 to 92 mm. RDI plots received the same amount of irrigation water with FI in the second year due to rainy season until the crop reached the flowering stage. In general, less irrigation water was applied to all treatments in 2017 than in 2016

growing season due to higher rainfall amount received in 2017 than 2016.

In 2017, crop water use (ETa) 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. ETa values varied from 254 mm in RF to 350 mm in FI in SD plots; and 254 and 339 mm in SSD plots. Quinoa under surface drip plots used slightly more water than subsurface drip plots for the same treatments due to reduced surface evaporation from the SSD plots. In 2016, ETa 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. The ETa values were generally greater in the 2017 growing season than in 2016 growing season due to greater amounts of rainfall and slightly lower relative humidity during the 2017 growing season.

Variation of soil water content

Variation of soil water content at 20 and 40 cm soil depth in different irrigation treatments under surface and subsurface

Table 2 Quinoa irrigation, ETa, grain yield, WUE, LAI and dry matter yield values under different treatments in the experimental years

Years	Irrigation systems	Irrigation treatments	Seasonal irrigation (mm)	Eta (mm)	Grain yield (kg ha^{-1})	WUE (kg m^{-3})	IWUE (kg m^{-3})	LAI (m^2 m^{-2})	Dry matter yield (kg ha^{-1})
2016	SD	FI	149	282	3021	1.07	0.86 d	3.20 b	6081 b
		DI_{75}	125	246	2953	1.20	0.98 c	2.90 d	5893 d
		DI_{50}	99	217	2415	1.11	0.42 g	2.80 e	5265 g
		PRD_{50}	99	213	2844	1.34	1.12 a	2.70 f	5703f
		RDI	114	249	2801	1.12	0.92 c	2.80 e	5977 c
		RF	49	169	2205	1.30	-	2.45 g	4358 h
	SSD	FI	140	271	2891	1.07	0.75 e	3.40 a	6274 a
		DI_{75}	118	235	2662	1.13	0.66 f	3.10 c	5930 cd
		DI_{50}	95	212	2548	1.20	0.75 e	2.80 e	5280 g
		PRD_{50}	95	210	2625	1.25	0.91 c	2.70 f	5789 e
		RDI	110	239	2850	1.19	1.06 b	3.20 b	5960 c
		RF	49	169	2205	1.30	-	2.45 g	4358 h
2017	SD	FI	103	350	2454	0.71	0.58 ef	3.58 a	6445 b
		DI_{75}	77	315	2363	0.75	0.66 bc	3.30 c	6245 d
		DI_{50}	51	302	2050	0.69	0.38 h	2.85 e	5793 f
		PRD_{50}	51	299	2276	0.77	0.82 a	3.00 d	6045 e
		RDI	103	347	2442	0.71	0.57 f	3.45 b	6423 b
		RF	0	254	1856	0.73	-	2.58 f	5053 h
	SSD	FI	92	339	2482	0.71	0.68 b	3.62 a	6588 a
		DI_{75}	69	308	2279	0.75	0.61 de	3.43 b	6225 d
		DI_{50}	46	284	2098	0.75	0.53 g	2.94 d	5545 g
		PRD_{50}	46	289	2138	0.76	0.61 de	3.03 d	6288 c
		RDI	92	336	2435	0.72	0.63 cd	3.55 a	6558 a
		RF	0	250	1856	0.73	-	2.65 f	5053 h

**LSD grouping at 1% level, *LSD grouping at 5% level

drip irrigation systems are shown in Figs. 1a–d and 2a–d, for the 2016 and 2017 experimental years, respectively. As shown in Fig. 1a, in 2016, soil water content (SWC) at 20 cm soil depth in full (FI) and regulated deficit irrigation treatment (RDI) remained between 35 and 40% until June 22, 2016; then as the season progressed, SWC slightly decreased and remained between 32 and 35% during rest of the growing season. Thus, FI and RDI treatments did not cause any water stress throughout the quinoa growing season. SWC in the DI_{75} treatment was relatively higher as compared to DI_{50}, PRD_{50} and RF treatments, in which SWC variation were the greatest among the treatments, and water stress gradually built up towards the end of the growing season. SWC in RF treatment reached wilting point towards the end of the growing season. Similar trends were observed for the SWC variation at 40 cm soil depth for the treatments considered as shown in Fig. 1b. 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 more water from the 0–40 cm soil depth under the different treatments.

As shown in Fig. 1c–d, in 2016, the variation in soil water content at 20 and 40 cm depths for the different treatments

under the subsurface drip irrigation had similar trend to those under the surface drip irrigation. However, SWC in 20 cm depth under subsurface drip was greater than those under the surface drip irrigation, especially early in the season when the difference in SWC was larger. This difference can be attributed to elimination of surface evaporation losses that occur under surface drip irrigation. Therefore, greater SWC was retained in 20 cm soil layer under SSD as compared with SD, and SWC decreased in all treatments as the season progressed. Towards the end of the growing season, SWC reached below the wilting point in DI_{50}, PRD_{50} and RF treatments. SWC at 40 cm soil depth in different treatments under the subsurface drip irrigation posed a similar trend to those in surface drip irrigated treatments. SWC decreased in all treatments gradually as the season progressed, and reached their lowest values at the end of the growing season in 2016.

In 2017, the variation of SWC in experimental treatments under the SD and SSD systems followed similar trends as shown in Fig. 2a–d. FI and RDI treatments received the same amount of water in 2017 due to sufficient rainfall during the vegetative growth stage. FI and RDI treatments maintained higher SWC values in the root-zone depth than all other treatments considered throughout the growing seasons. The SWC values in the 20 and 40 cm soil depths
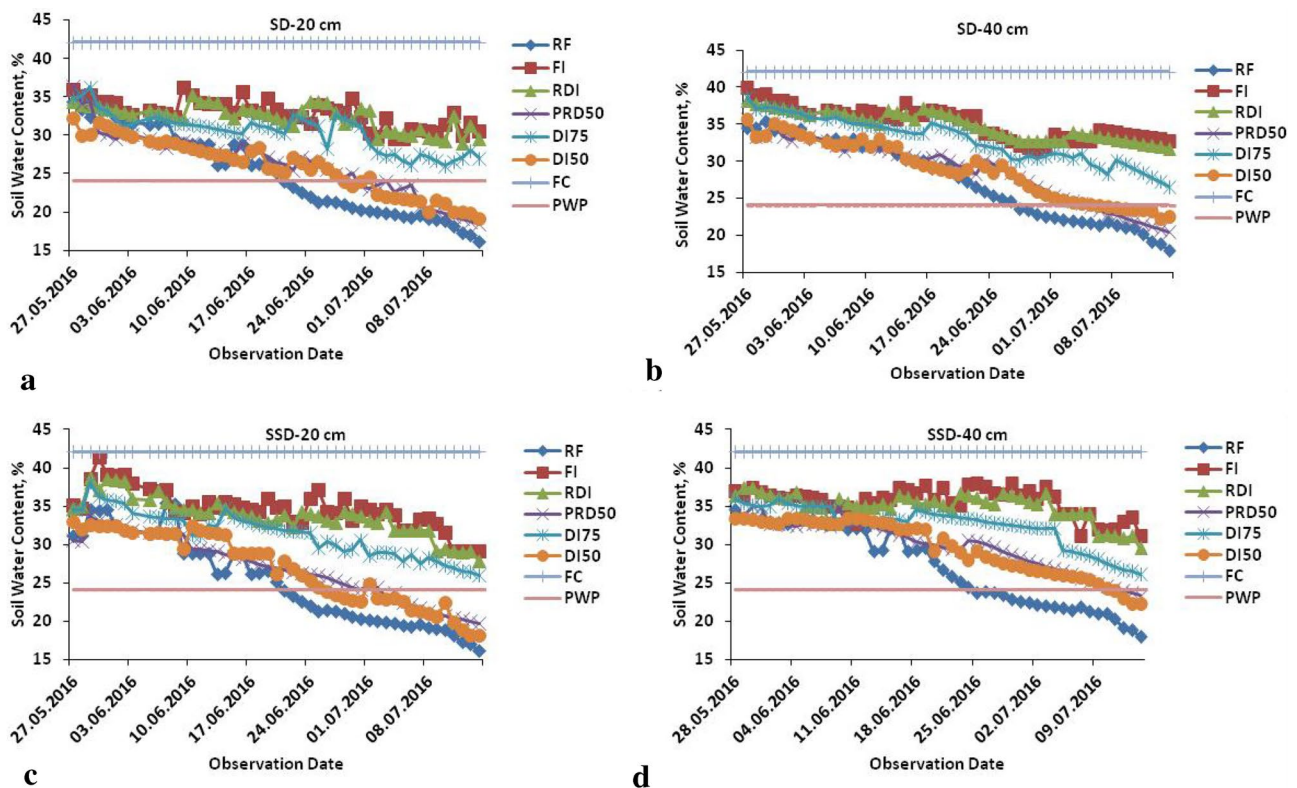

Fig. 1 Soil water storage variation under the different treatments in the 2016 growing season: **a** 20 cm in SD; **b** 40 cm in SD; **c** 20 cm in SSD; **d** 40 cm in SSD
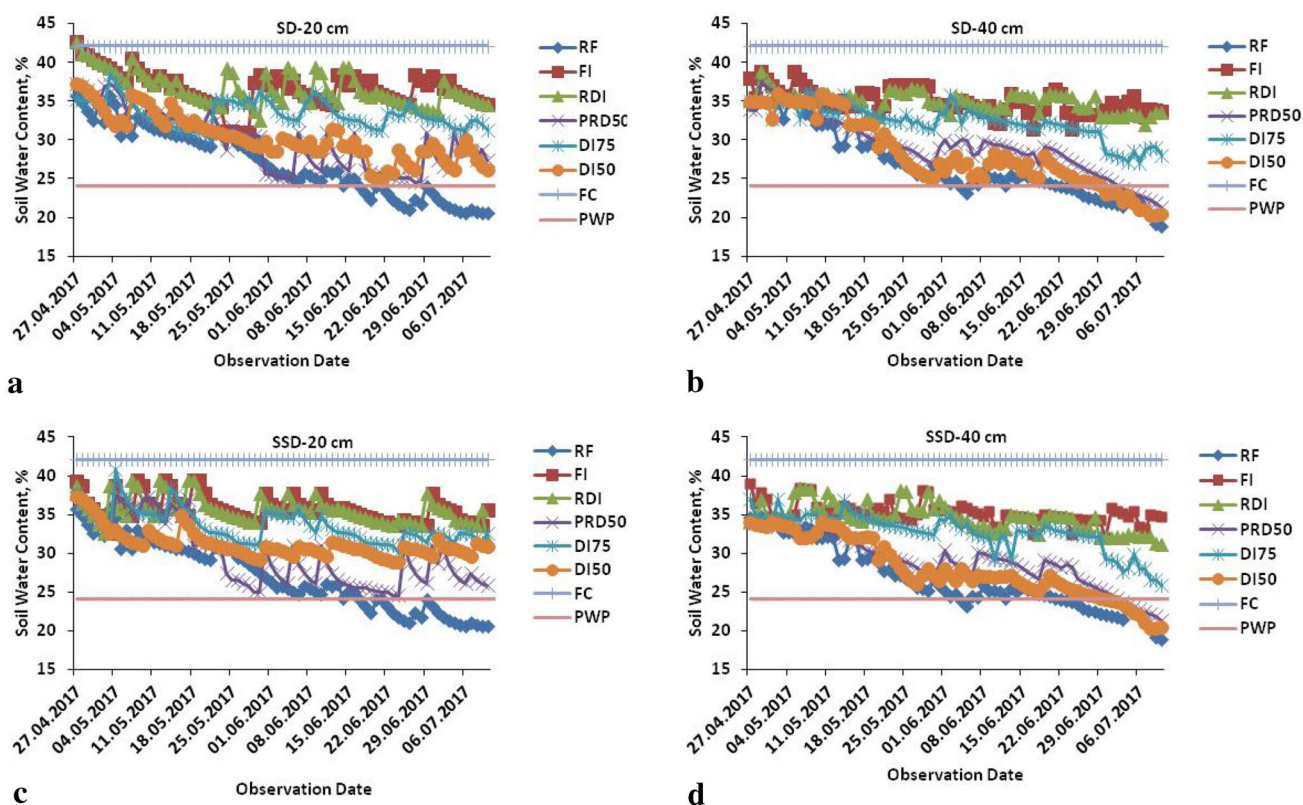
Fig. 2 Soil water storage variation under the different treatments in the 2017 growing season: **a** 20 cm in SD; **b** 40 cm in SD; **c** 20 cm in SSD; **d** 40 cm in SSD

remained slightly greater in 2017 than those in 2016. In DI_{50} and PRD_{50} treatments, SWC had slightly different SWC profiles throughout the 2017 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 values were below the FI and RDI throughout the growing season but SWC values in this treatment remained greater than PRD_{50} and DI_{50}.

Grain yield

The grain yield values for the different irrigation treatments and two drip irrigation methods for both experimental years (2016 and 2017) are given in Table 2. The statistical analysis results of the parameters considered in this study are summarized in Table 3. Grain yields varied from 2415 kg ha^{-1} in DI_{50} to 3021 kg ha^{-1} in FI in SD system; and changed between 2548 kg ha^{-1} in DI_{50} and 2891 kg ha^{-1} in FI under SSD system in 2016. In 2017, grain yields varied from 2050 kg ha^{-1} in DI_{50} to 2854 kg ha^{-1} in FI under SD system, and changed from 2098 kg ha^{-1} in DI_{50} to 2482 kg ha^{-1} in FI under SSD system. Both in 2016 and 2017 experimental years, RF produced the lowest yield as 2205 and

1856 kg ha^{-1}, repectively. As indicated in Table 3, there was no significant difference in grain yields between the surface drip and subsurface drip irrigation systems in the experimental years. However, irrigation treatments resulted in significantly different yields in 2016 and 2017 growing seasons ($P < 0.01$). 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 (Table 4). In the 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 also produced significantly higher yield than DI_{50} in the 2017.

Dry matter yield

In 2016, aboveground dry matter (DM) yields form the irrigated treatments varied from 5265 kg ha^{-1} in DI_{50} to 6081 kg ha^{-1} in FI under SD, and it changed between 5280 kg ha^{-1} in DI_{50} and 6274 kg ha^{-1} under SSD. In

Table 3 Statistical analysis results on grain yield, dry matter, WUE and IWUE of quinoa under different treatments in the experimental years

Years	Irrigation treatments	Grain yields (kg ha^{-1})	Dry matter (kg da^{-1})	WUE (kg m^{-3})	IWUE (kg m^{-3})
2016	Irrigation systems	ns	ns	ns	LSD = 0.016 P = 0.0018** Cv(%) = 6.12
	Irrigation treatments	LSD = 254.6 P = 0.0001** Cv(%) = 9.37	LSD = 26.4 P = 0.0001** Cv(%) = 0.46	LSD = 0.075 P = 0.0008** Cv(%) = 9.47	LSD = 0.030 P = 0.0001** Cv(%) = 6.12
	Int. of irr. syst. and irr treat	ns	LSD = 37.4 P = 0.0001** Cv(%) = 0.46	ns	LSD = 0.43 P = 0.0001** Cv(%) = 6.12
2017	Irrigation systems	ns	ns	ns	ns
	Irrigation treatments	LSD = 121.37 P = 0.0001** Cv(%) = 5.3	LSD = 21.55 P = 0.0001** Cv(%) = 0.4	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	LSD = 30.47 P = 0.0001** Cv(%) = 0.4	ns	LSD = 0.036 P = 0.0001** Cv(%) = 4.05

**LSD grouping at 1% level, *LSD grouping at 5% level

Table 4 Comparison of mean grain yield and mean WUE values averaged over two drip systems for the different treatments in the experimental years

Irrigation treatments	Grain yield kg ha^{-1}		WUE kg m^{-3}	
	2016	2017	2016	2107
FI	2906.3 a	2468.2 a	1.07 c	0.71 b
DI$_{75}$	2807.8 a	2320.5 bc	1.17 b	0.75 a
DI$_{50}$	2481.6 b	2074.0 d	1.15 b	0.72 b
PRD$_{50}$	2734.7 ab	2206.9 c	1.30 a	0.77 a
RDI	2825.6 a	2438.1 ab	1.15 b	0.72 b
RF	2204.1 c	1855.3 e	1.30 a	0.73 ab
LSD (0.05)	254.6	121.4	0.075	0.038
Probability	P = 0.0001**	P = 0.0001**	P = 0.0008**	P = 0.0453*

2017, DM yield values varied from 5793 kg ha^{-1} in DI$_{50}$ to 6445 kg ha^{-1} in FI under SD, and changed between 5445 kg ha^{-1} in DI$_{50}$ and 6588 kg ha^{-1} in FI under SSD. RF produced the least DM yield in both experimental years (Table 3). Irrigation method and irrigation treatment interaction was significantly different with regards to dry matter yields in both seasons. FI under SSD produced significantly greater dry matter yield than other treatments followed by FI under surface drip plots in the 2016 growing season. PRD$_{50}$ treatments under both drip systems produced significantly greater dry matter yield as compared to DI$_{50}$ treatments. RDI resulted in higher dry matter yield than DI$_{75}$ under both drip systems.

Leaf area index (LAI)

Maximum leaf area index values for different treatments under surface and subsurface drip systems for both experimental years are presented in Table 2. As seen in Table 3, there is no significant difference in LAI between the surface drip and subsurface drip irrigation systems in the experimental years. However, irrigation treatments resulted in significantly different LAI in 2016 and 2017 growing seasons ($P < 0.01$). Since there was no significant difference between the two drip systems regarding the LAI values, statistical comparisons of the maximum LAI values were made on yields averaged over the two drip systems (Table 4). FI treatments under both systems resulted in highest 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 senecenssence.

Leaf water potential (LWP)

The fluctuations in leaf water potential (LWP) values prior to irrigations for different irrigation treatments with time during the 2016 and 2017 growing seasons are shown in Fig. 3a–d. In general, the LWP values decreased with increasing water stress. In the surface drip treatment plots, LWP values ranged between − 1.54 MPa in FI and − 2.05 MPa in RF; varied between − 1.52 MPa in FI and − 2.06 MPa in RF under SSD in 2016. In the second year, LWP values varied form − 1.45 MPa in FI to − 1.99 MPa in RF under SD system and changed from − 1.42 MPa in FI and − 1.97 MPa in RF under SSD. Greater LWP values were observed in FI treatment plots than the deficit irrigation treatment plots under both drip systems. We observed slightly higher LWP values in SSD plots than in the SD plots, however, the difference between the two irrigation system was not significant. In 2017, again slightly higher LWP values were observed as compared to the 2016. The difference can be attributed to varying weather conditions between the two exprimental years. The lowest LWP values were observed in RF plots. Generally, LWP values decreased towards the end of season in comparison to the beginning of the season.

Crop water stress index (CWSI)

The upper limit (UL) and lower limit (LL) equations developed for quinoa following the Idso's empirical approach were as follows: $UL = − 0.0075\ VPD + 4.7506$; and $LL = − 1.4952\ VPD + 1.3851$. Since the intercept value in UL equation is small, UL is taken as 4.75 °C. During the study years, the vapor pressure deficit (VPD) of the air was calculated by using the psychrometric measurements, and the relationship between (Tc–Ta) and the plant water stress index (CWSI) was calculated by the empirical method.

The variations in CWSI prior to irrigations for the different treatments during the growing seasons are shown in Fig. 4a–d. Seasonal mean CWSI values for surface drip treatments in the first year varied from 0.32 in FI to 0.73 in RF; for subsurface drip treatments, CWSI varied from 0.30 in FI to 0.73 in RF under SSD in 2016. In the second year, seasonal mean CWSI values for SD treatments varied between 0.27 in FI and 0.67 in RF, for SSD treatments, CWSI varied from 0.28 in FI, 0.67 in RF. In the rainfed treatment, the decreasing SWC due to rainless period and no irrigation led to increased CWSI values. RDI and DI_{75} treatments under both drip systems had lower CWSI values than DI_{50} and PRD_{50}.
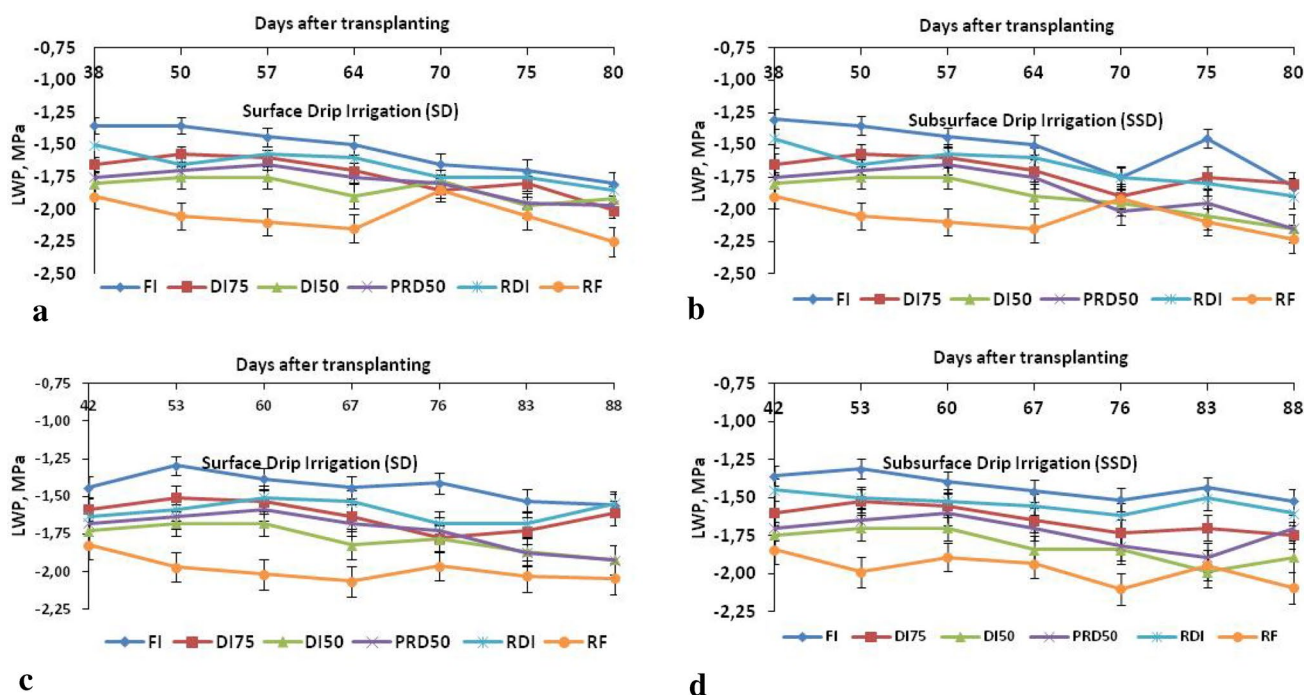

Fig. 3 Leaf water potential (LWP) variation for the different treatments under surface and subsurface drip irrigation systems; **a** LWP in SD in 2016; **b** LWP in SSD in 2016; **c** LWP in SD in 2017; **d** LWP in SSD in 2017
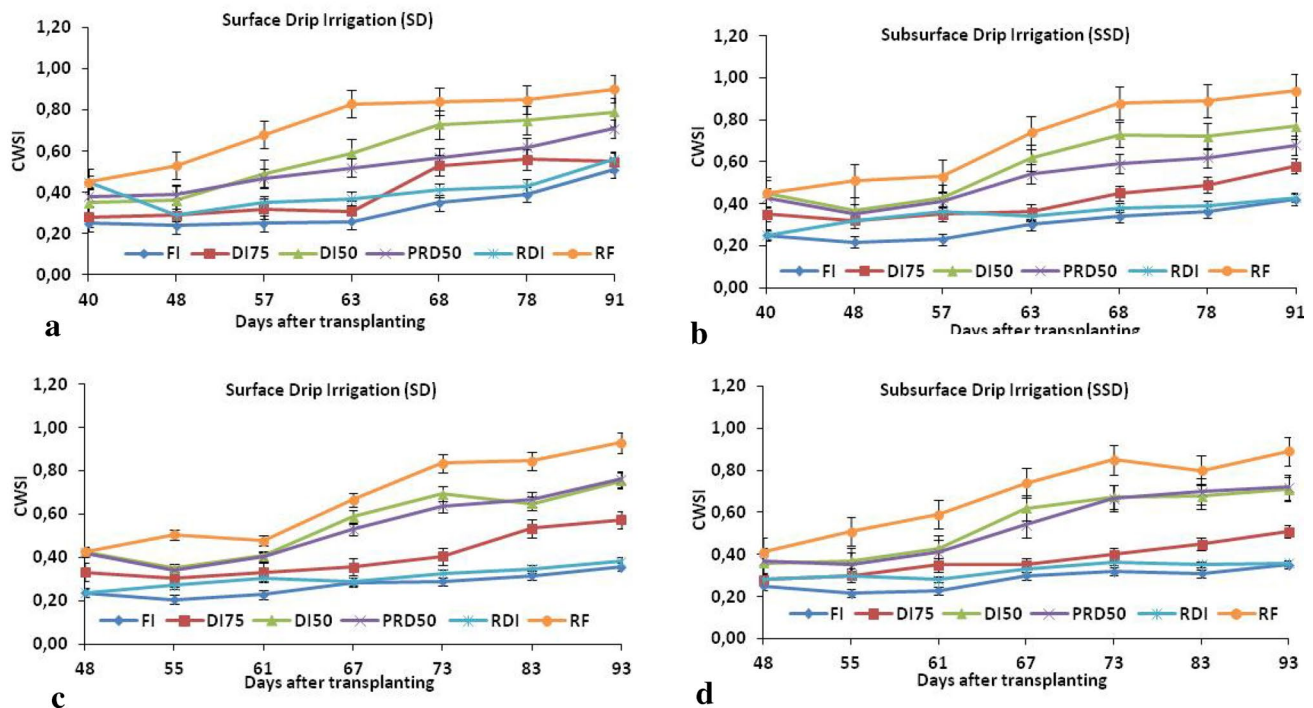
Fig. 4 Crop water stress index (CWSI) variation during the 2016 and 2017 quinoa growing seasons in all treatments under surface and subsurface drip irrigation: **a** CWSI in SD in 2016; **b** CWSI in SSD in 2016; **c** CWSI in SD in 2017; **d** CWSI in SSD in 2017

Relationships between LWP, grain yield, dry matter yield, LAI and mean soil water content

The curvilinear relationships between LWP (as the independent variable) and grain yield, dry matter yield, LAI, and soil water content (as the dependent variables) in the experimental years are presented in Figs. 5a–d and 6a–d, respectively. In general, the LWP correlated significantly ($P < 0.01$) and positively with grain yield, dry matter yield, LAI, and mean soil water content indicating that all four parameters declined with decreasing LWP values. All these relations are best described by significant second-order polynomial equations with high R^2 values. For the growing seasons, the relationship between LWP and grain yield had high determination coefficients that yielded $R^2 = 0.81$ for SD and 0.95 for SSD in first and second year, corresponding values were $R^2 = 0.92$ and 0.98, respectively.

Relationships between CWSI, grain yield, dry matter yield, LAI and mean soil water content

The relationships between CWSI (as the independent variable) and grain yield, dry matter yield, max. LAI, and soil water content (as the dependent variable) in the experimental years are presented in Figs. 7a–d and 8a–d, respectively. In general, the CWSI correlated significantly

($P < 0.01$) and negatively with grain yield, dry matter yield, LAI, and mean soil water content indicating that grain yield of quinoa declined with increasing CWSI values. All these relations are best described by significant second-order polynomial equations. For the growing seasons, the relationship between CWSI and grain yield had high determination coefficients that yielded $R^2 = 0.81$ for SD and 0.91 for SSD in first and second year, corresponding values were $R^2 = 0.93$ and 0.97, respectively. Determination coefficients for CWSI with dry matter, LAI and mean soil water content were all greater than 0.83 in both experimental years.

Relationships between CWSI and LWP

The relationships between CWSI and LWP for the different treatments under SD and SSD systems in the experimental years, respectively are shown in Fig. 9a, b. Significant second-order polynomial relations were determined between CWSI and LWP for the drip systems with high determination coefficients of $R^2 = 0.96$ for SD and 0.99 for SSD in 2016; and corresponding values were 0.94 and 0.91, respectively, for SD and SSD plots in 2017. These relations can be utilized for irrigation scheduling of quinoa.
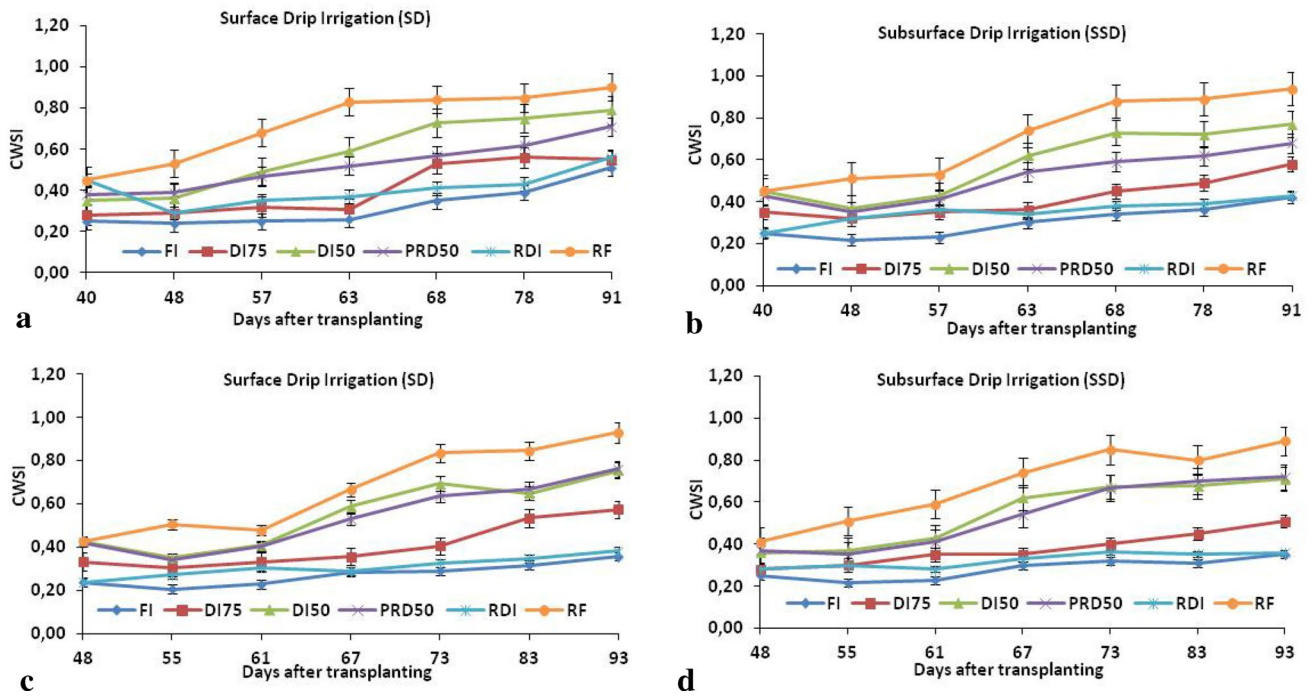
Fig. 5 The relationships between leaf water potential (LWP) and grain yield (**a**), dry matter yield (**b**), maximum leaf area index (LAI) (**c**) and mean soil water content (**d**) in the 2016 growing season
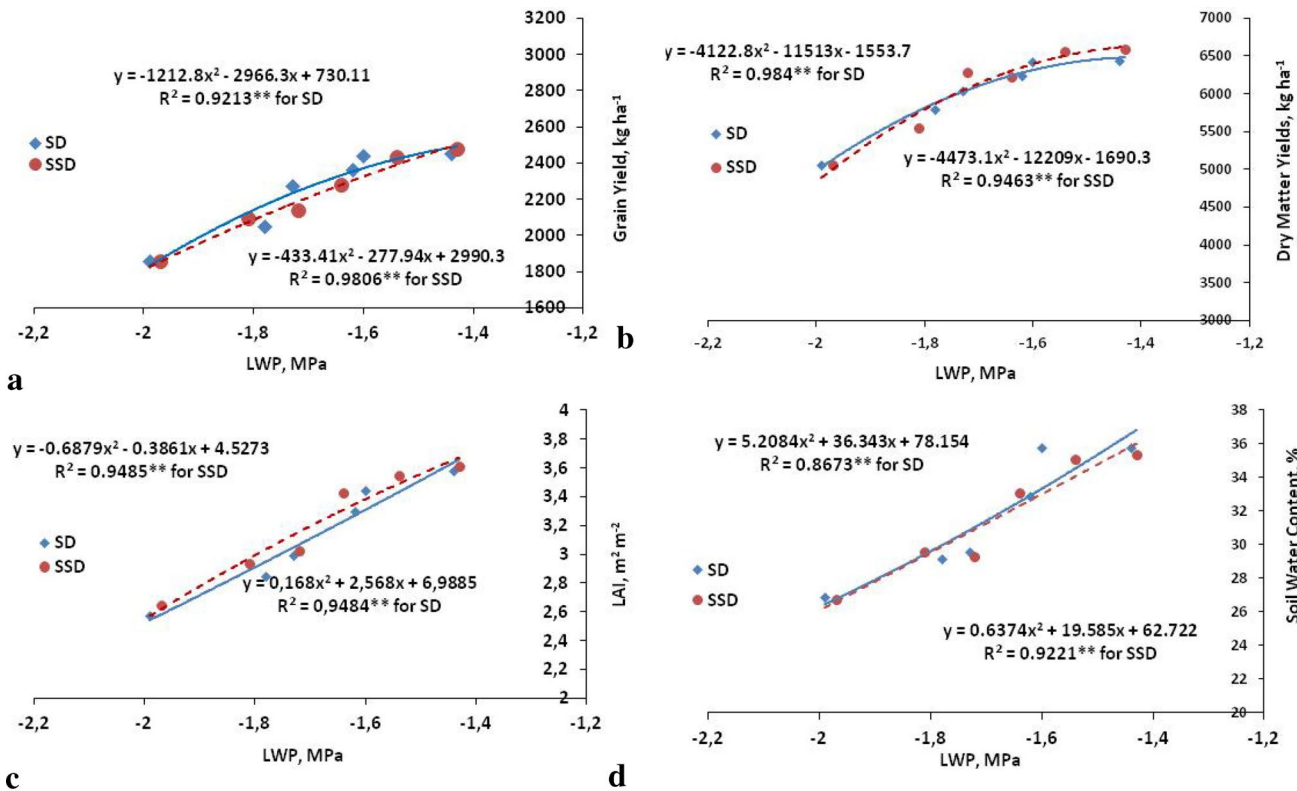

Fig. 6 The relationships between leaf water potential (LWP) and grain yield (**a**), dry matter yield (**b**), leaf area index (LAI) (**c**) and mean soil water content (**d**) in the 2017 growing season

Fig. 7 The relationships between crop water stress index (CWSI) and grain yield (**a**), dry matter yield (**b**), leaf area index (LAI) (**c**) and mean soil water content (**d**) in the 2016 growing season
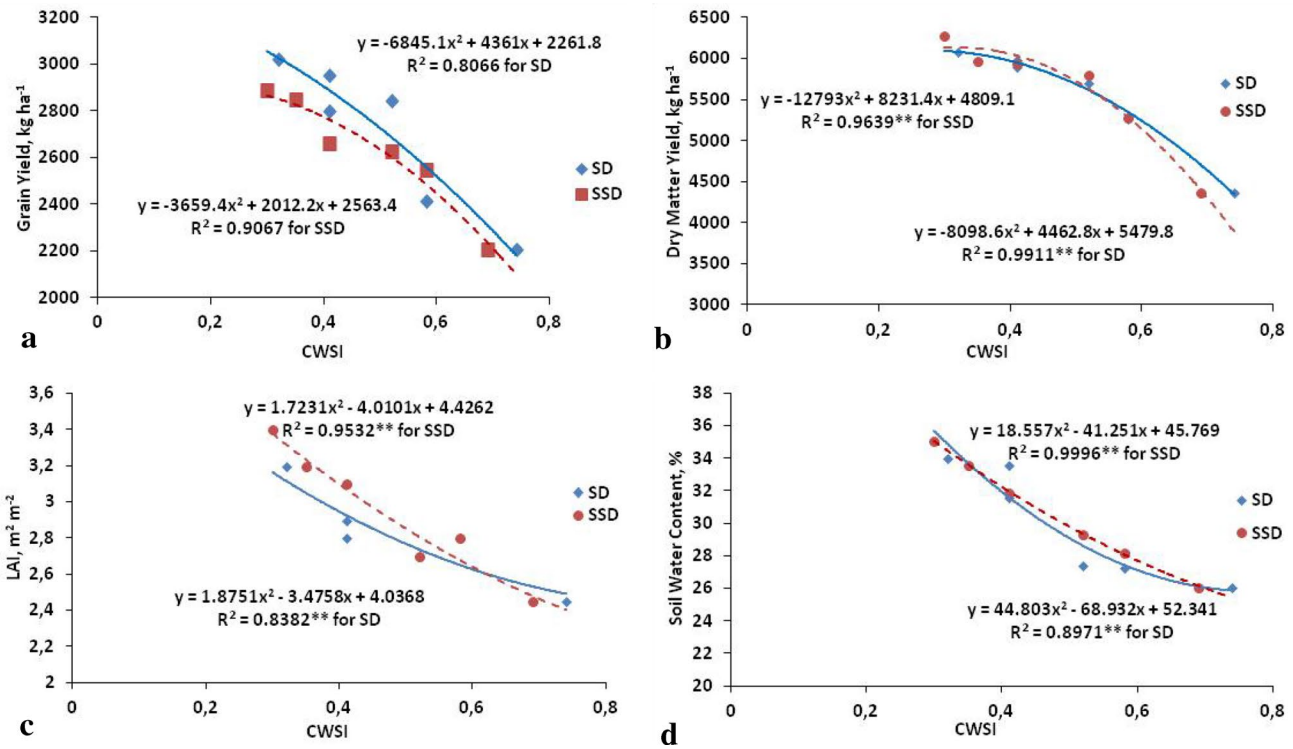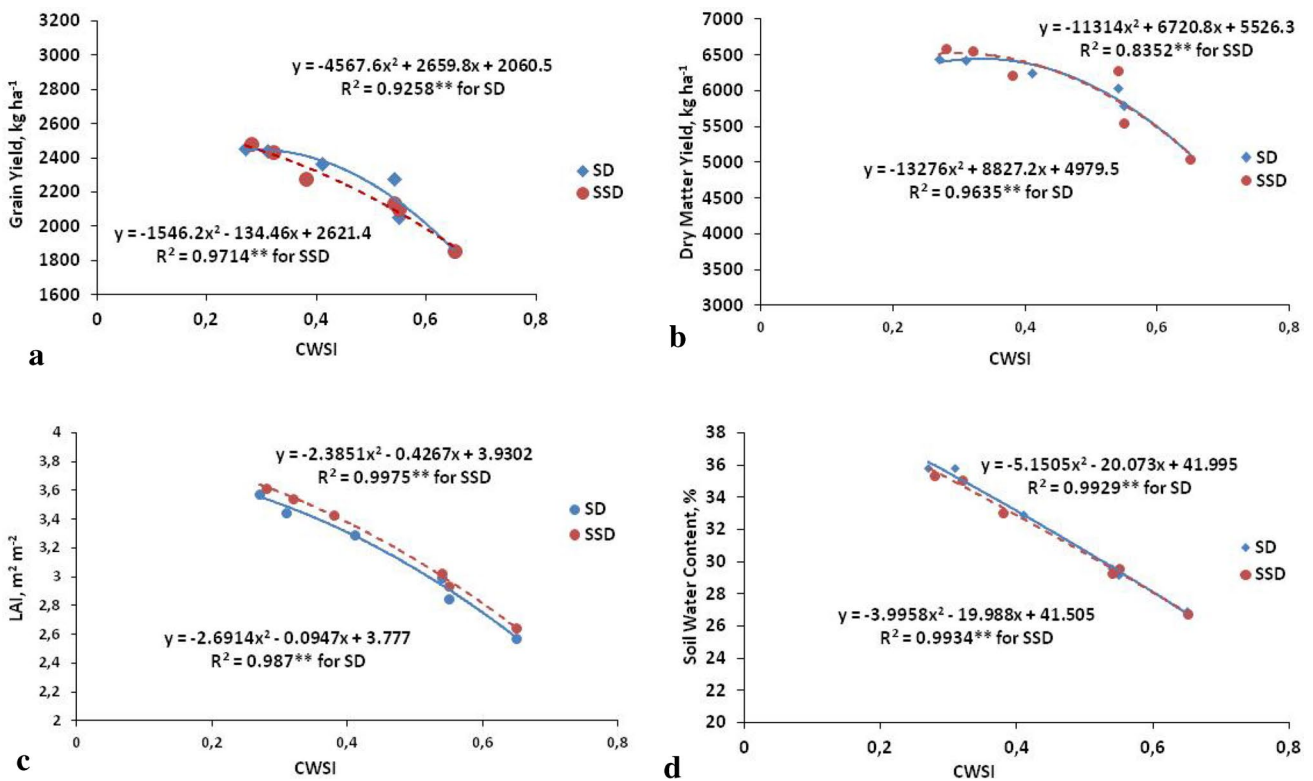

Fig. 8 The relationships between crop water stress index (CWSI) and grain yield (**a**), dry matter yield (**b**), leaf area index (LAI) (**c**) and mean soil water content (**d**) in the 2017 growing season
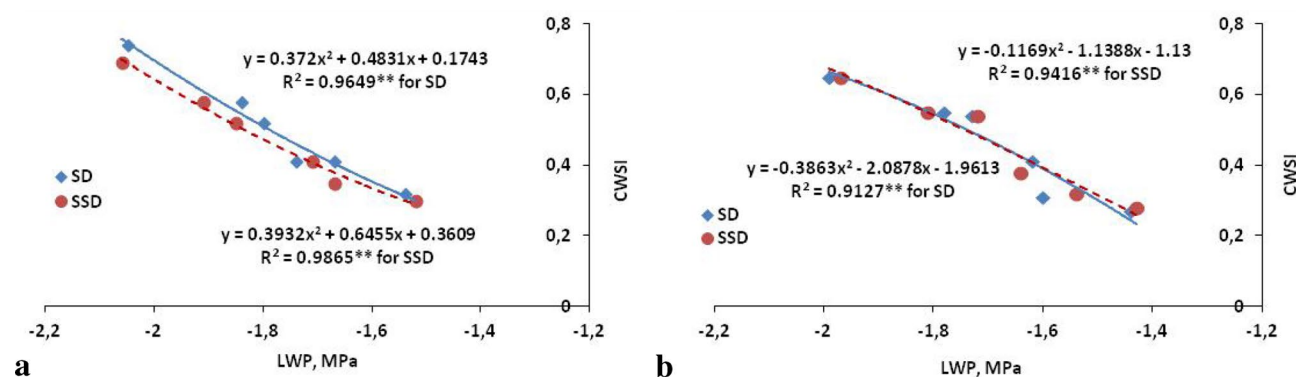
Fig. 9 The relationships between crop water stress index (CWSI) and leaf water potential (LWP) in the 2016–2017 growing season in all treatments: **a** 2016; **b** 2017

Water use efficiency and irrigation water use efficiency

RF and PRD_{50} treatments resulted in significantly greater WUE values than other treatments while the FI had the lowest WUE in the 2016 growing season. WUE 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 WUE changed between 0.69 kg m^{-3} in DI_{50} and 0.77 PRD_{50} in the SD system, and varied 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. WUE values were significantly greater in 2016 than those in 2017 due to higher ET and lower grain yield values observed in the second year. Since there was no significant difference between the two drip systems regarding the WUE values, statistical comparisons of the mean grain yields were made on yields averaged over the two drip systems (Table 4). PRD and RF treatments resulted in highest WUE values while FI had the lowest WUE in 2016. In 2017, PRD treatment had the highest WUE and FI resulted in the lowest WUE value.

Irrigation water use efficiency (IWUE) values ranged between 0.42 DI_{50} and 1.12 kg m^{-3} in RDI under SD treatments, and varied from 0.66 in DI_{75} and 1.06 kg m^{-3} in RDI in SSD in 2016. In the second year, IWUE values changed between 0.38 in DI_{50} and 0.82 in PRD_{50} in SD treatments; and varied from 0.53 in DI_{50} to 0.68 in FI in SSD. PRD_{50} resulted in the highest IWUE values, and lowest values were observed in DI_{50}. There was no significant difference between the tow drip systems regarding the IWUE values. Except PRD_{50}, FI and RDI treatments resulted in greater than other treatments in both drip systems. Yazar et al. (2015) found IWUE values varying between 0.88 and 1.0 kg m^{-3} for titicaca variety in Turkey.

Discussion

Quinoa grain yields in the first year (2016) were greater than those in the second year (2017) due to more favorable weather conditions prevailed in the first year. 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. A high temperature during flowering and seed set can significantly reduce the yield (Hinojosa et al. 2018). PRD treatment outperformed conventional deficit irrigation DI_{50}, although they received the same amount of water. This can be attributed to plants utilizing water more effectively under PRD than DI_{50}, and might be due to reduced evaporation loss since less area is wetted. RDI appeared to be a good alternative to full irrigation since it produced statistically similar yield to FI treatment in both experimental years. RDI resulted in water savings of 23 and 21% for SD and SSD systems, respectively, as compared with FI 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 stage in 2017 due to sufficient enough rainfalls received. DI_{75} treatment produced similar grain yield with FI in the first year but significantly lower yield in the second year. 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.

Rainfed treatment produced the lowest yield in both experimental years. The yield reductions varied between 31 and 37% for SSD and SD, respectively, under the rainfed (nonirrigated) conditions in 2016; and the corresponding

decreases were 32 and 34%, for SD and SSD in 2017. Geerts et al. (2007) found that drought stress during pre-flowering, flowering, and early grain filling had a strong negative effect on seed yield and water use efficiency when compared to drought stress in the vegetative stage or full irrigation. Geerts et al. (2009) concluded that deficit irrigation can stabilize yields at a level that is significantly higher than under rainfed cultivation. Several studies reported that drought stress during the vegetative stage of quinoa leads to deep root development, and no stress condition for the rest of the growing season allowing the quinoa plant to be able to optimize its photosynthesis (Geertz et al. 2008; Jacobsen et al. 2009; Hirich et al. 2014). Water stress during grain filling growth stage resulted in the lowest yields (Lavini et al. 2014). Razzaghi et al. (2012) referred that soil-drying during the 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 deficit irrigation. In this study, RDI treatment allowed water stress during the vegetative growth stage produced grain yield almost the same as that produced with full irrigation. Hirich et al. (2014) reported similar findings to RDI that for quinoa treatment receiving 50% of full irrigation during vegetative growth stage recorded the highest yield and water use efficiency in Morocco. There are few studies concluded that full irrigation increases quinoa grain yield and dry matter yield compared to deficit irrigation (Fghire et al. 2015; Yazar et al. 2015; Walters et al. 2016).

Yazar and İnce Kaya (2014) reported that the grain yield of quinoa cv. Titicaca ranged between 2.0 and 3.0 t ha^{-1} under non-stressed conditions in the Mediterranean region of Turkey. In Denmark, Razzaghi et al. (2011) obtained 3.3 t ha^{-1} yield from quinoa cv. Titicaca under non-stressed conditions, while it was reported that total grain yield of the same variety ranged from 1.9 to 3.3 t ha^{-1} in Italy (Lavini et al. 2014). Pulvento et al. (2012) found that quinoa grain yields for 'Titicaca' varied between 2.30 and 2.70 t ha^{-1} either under high irrigation (300–360 mm) or deficit irrigation (200–220 mm) in Italy. In Bolivia 3.7 t ha^{-1} (Garcia et al. 2003); in Chile 2.6 t ha^{-1} (Martinez et al. 2009) and in Morocco 3.3 t ha^{-1} (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^{-1}) from the November sown quinoa irrigated at 60% potential evapotranspiration and with 25 kg N ha^{-1} in Burkina Faso. Ahmadi et al. (2019) evaluated the plant density response of quinoa to full irrigation in Iran and reported the grain yields varied between 2.86 and 3.65 t ha^{-1}. Praveen Kadam et al. (2018) studied the effect of deficit irrigation applied with surface and subsurface drip 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. Our results are in agreement with most of the results from the studies mentioned above. 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.

FI and RDI under SSD produced significantly greater dry matter yield than other treatments and followed by FI and RDI under SD plots. Subsurface PRD$_{50}$ produced significantly greater dry matter yield as compared to surface PRD$_{50}$, DI$_{75}$ and DI$_{50}$ treatments. Subsurface RDI resulted in higher dry matter yield than surface RDI and DI$_{75}$. RF produced the least dry matter yield. In general, as the amount of irrigation water increased dry matter yield also increased except the PRD$_{50}$ under SSD. The deficit irrigation treatments caused a significant reduction in above ground plant dry matter yield. Thus, water stress resulted in lower dry matter yield in the RF, DI$_{50}$, PRD$_{50}$ treatments in comparison to RDI, DI$_{75}$ and FI treatments. A number of studies reported that deficit irrigation during vegetative growth stage induced root system development and growth for quinoa (Geerts et al. 2005; Jensen et al. 2000; Jacobsen et al. 2009). Issa Ali et al. (2019) explained that water stress in the vegetative growth stage can significantly increase the tolerance to drought stress during flowering and grain filling growth phases. Pulvento et al. (2012) observed that the deficit irrigation treatment of 25% of full irrigation caused an increase in WUE and a reduced dry matter accumulation in the leaves of quinoa in Italy. Yazar et al. (2015) evaluated the yield response of quinoa to fresh and saline water irrigations under Mediterranean climatic conditions, and reported dry matter yields ranging from 3809 kg ha^{-1} in RF to 6786 kg ha^{-1} in FI with fresh water. Hirich et al. (2014) observed he highest dry matter accumulation under FI conditions and the highest HI was recorded when quinoa was subjected to water stress during vegetative growth stage. Our findings are in line with above mentioned study results.

In general, LAI index values increased with increasing irrigation water. The increase in LAI of quinoa with irrigation has also been reported by Garcia et al. (2003). RF had the least LAI value among the treatments in the experimental years. LAI values in all treatments decreased towards the end of the season due to leaf senecenssence. The deficit irrigation treatments (DI$_{50}$, PRD$_{50}$) caused a significant reduction in leaf surface. 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 full irrigation and RDI. Slightly greater LAI values were observed in SSD plots than those in SD plots in the experimental years. Greater LAI values in 2017 growing season was due to higher rainfall received

during this season. 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. They concluded that water stress and salinity stress together reduced LAI considerably compared with full irrigations with fresh water. Lavini et al. (2014) found the highest LAI value of 2.8 for full irrigated treatment and the least LAI was observed in severe stress treatment in Southern Italy. İnce Kaya (2015) reported the maximum LAI value of 2.5 for full irrigation for Titicaca cultivar in Turkey. Fghire et al. (2017) evaluated the effect of water stress on LAI which increased significantly and a continuously and peaked at filling stage seed for all water treatments and thereafter the LAI started to decrease. The LAI exhibited an increase until the seed filling stage to reach maximum value of 5.26 under 100% ETc treatment. However, the LAI showed significant decreases in response to increased water stress, reaching minimum value of 1.9 in the the rainfed treatment in Morocco. Praveen Kadam et al. (2018) reported that LAI gradually increased with stage of the crop and 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, followed by non-stressed treatments at grain filling stages in India.

The different water supplies between treatments resulted in a different plant water status. It is noteworthy that plant water status, as evaluated by LWP, was significantly different compared to the control. Greater LWP values were observed in FI treatment plots than the deficit irrigation treatment plots under both drip systems. We observed slightly higher LWP values in SSD plots than in the SD plots, however the difference between the two irrigation system was not significant. In 2017, again slightly higher LWP values were observed as compared to the 2016. The difference can be attributed to varying weather conditions between the two exprimental years. The lowest LWP values were observed in RF plots. Generally, LWP values decreased towards the end of season in comparison to season beginning. This can be attributed to aging of leaves at the end of growing seasons. LWP values for RDI treatments under both drip system were very similar to values observed in FI plots in the second growing season since no irrigation was applied during the vegetative growth stage under this treatment. However, LWP values in FI plots under both drip systems were significantly greater than those observed in RDI, DI$_{75}$ and DI$_{50}$, PRD$_{50}$ treatments in the 2016 growing season. 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 plots in both experimental years.

A number of studies were conducted to determine the influence of water stress or drought on quinoa (Vacher 1998; Jensen et al. 2000; Razzaghi et al. 2011; İnce Kaya 2015; Fghire et al. 2015, 2017). Vacher (1998) analyzed the response to drought in two quinoa cultivars and found that at LWP of − 2.5 MPa and lower, stomatal closure was induced rapidly and associated with a 67% reduction in transpiration and photosynthetic rate. However, in a study of the effects of soil drying at various growth stages, Jensen et al. (2000) found that, in quinoa plants subjected to drought, stomatal closure began at LWP below − 1.2 to − 1.6 MPa and net photosysnthesis was reduced to 5–10 μmol m^2 s$^{−1}$ as a result of stomatal closure, when LWP decreased to − 1.5 to − 2.0 MPa. Razzaghi et al. (2011) in a greenhouse experiment observed that the LWP of full irrigated quinoa was remained almost constant at − 0.8 MPa throughout the drought period. In progressive drought treatment, the value was similar for the first 4 days of measurements, but on the last day of the drought period (day 10), LWP dropped abruptly to − 2.1 MPa. Our results show that the water status of the quinoa plant determined by the leaf water potential was significantly affected by irrigation; and the leaf water potential was closely affected by water stress treatments. Fghire et al. (2015) evaluated the physiogical response of quinoa to drought in Morocco and they reported that, LWP values for 100% ETc plants were maintained between − 0.4 and − 0.9 MPa throughout the experiment. LWP decreased slightly during the first 8 weeks after the beginning of the treatments, and then LWP values decreased substantially for all treatments, from − 1.0 to − 3.0 MPa for rainfed treatment. The results of this study for FI differed from the above mentioned study results for well-watered quinoa but in agreement with RF and PRD$_{50}$ and DI$_{50}$ treatments. İnce Kaya (2015) evaluated the LWP for drip irrigated quinoa in the Mediterranean region of Turkey, and reported LWP values of − 1.70 MPa for FI, and − 2.35 MPa for DI$_{33}$, and − 2.65 MPa for RF treatment. Yang et al. (2016) compared the effect of irrigation regimes on LWP, and reported significantly higher (less negative) LWP and reduced leaf area in FI plants than alternate root-zone drying and DI plants, respectively. Fghire et al. (2017) determined LWP under 100% ETc, the variation of LWP fluctuated between − 1.7 and − 2 MPa in Titicaca in Morocco. Our findings were in agreement with those reported by İnce Kaya (2015). Our results revealed that quinoa should be irrigated at LWP values around − 1.35 MPa in the early growing season and approximately − 1.50 MPa in the late season for high- and good-quality yields in the Mediterranean region.

The 2-year experimental results indicated that CWSI values increased with increasing water stress levels. The CWSI values in 2017 were relatively lower compared to the first season due to higher soil water content because of rains at the beginning of the second growing season. While the lowest CWSI values were observed in FI for both irrigation methods, higher values were determined in DI$_{50}$ and

PRD$_{50}$. In general, the variations of CWSI values prior to irrigations under the SSD and SD systems were very similar throughout the growing seasons. CWSI values early in the season were lower and increased as the season progressed. An average CWSI value of approximately 0.35 just before an irrigation can be used for irrigation scheduling of quinoa for high yields. There are very limited number of studies on CWSI for drip irrigated quinoa. İnce Kaya (2015) evaluated the CWSI for drip irrigated quinoa in the Mediterranean region of Turkey, and reported CWSI values of 0.26 for FI, and 0.75 for DI$_{33}$, and 0.96 for RF treatment. Our findings were very similar to those reported by İnce Kaya.

LWP correlated significantly ($P < 0.01$) and positively with grain yield, dry matter yield, LAI, and mean soil water content indicating that all four parameters declined with decreasing LWP values. All these relations are best described by significant second-order polynomial equations with high R^2 values. For the quinoa plant, Garcia et al. (1991) showed a linear relationship between LWP and the water content of the soil. İnce Kaya (2015) determined a significant linear relation between LWP and readily available soil water (RAW) for quinoa cv Titicaca as LWP = 16.804 RAW−29.183 with $R^2 = 0.92$. Cocozza et al. (2012) also obtained significant linear relation between LWP and RAW for quinoa in Italy as LWP = − 4.07 + 0.034 RAW with $R^2 = 0.60$. CWSI was correlated significantly ($P < 0.01$) and negatively with grain yield, dry matter yield, LAI, and mean soil water content indicating that grain yield of quinoa declined with increasing CWSI values. All these relations are best described by significant second-order polynomial equations. A similar negative relation was reported for wheat by Alghory and Yazar (2019). Significant second-order polynomial relations were determined between CWSI and LWP for the drip systems with high determination coefficients. Thus, a close relations between these two parameters reveals that both CWSI and LWP can be used for irrigation scheduling of quinoa in the Mediterranean climatic conditions.

There was no significant difference in WUE between SSD and SD in the experimental years. However, irrigation treatments had significantly different effect on WUE. WUE values were significantly higher in 2016 than those in 2017 due to higher ETa and lower grain yield values observed in the second year. PRD treatment resulted in highest WUE values under the two drip systems, followed by the RF in both experimental years. In general, higher the irrigation water lower the WUE. Quinoa develops response mechanisms to reduce water loss through rapid stomatal closure, cellular water deficit regulation, and root-to-shoot ratios that trigger a high water use efficiency (Miranda-Apodaca et al. 2018). As a C$_3$ crop, quinoa's water use efficiency (WUE) is generally low, 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; Riccardi et al.

2014; Lavini 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 WUE. Yazar et al. (2015) found WUE values varying between 0.48 and 1.39 kg m^{-3} for Titicaca variety in Turkey. Yazar et al. (2017) reported WUE values ranged from 1.00 kg m^{-3} in RF to 1.57 kg m^{-3} in DI$_{25}$ treatment under normal planting time and from 0.53 (RF) to 0.75 kg m^{-3} (DI$_{50}$) under the late planting treatments using drainage water applied with sprinkler line source system in Tarsus, Turkey. Patil et al. (2018) recorded the maximum water use efficiency of 0.96 kg m^{-3} under the treatment IW/E-Pan ratio of 0.6 in India. Ahmadi et al. (2019) reported WUE values for three planting densities varied between 0.25 and 0.39 kg m^{-3} in Iran. Alvar-Beltran et al. (2019) found WUE 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. The WUE values determined in our study presented here are in agreement with the abovementioned study results obtained under the Mediterranean climatic conditions, but differ from the results in other geographic locations.

Conclusions

The main focus of this study was to investigate physiological and yield response of quinoa to various deficit irrigation strategies such as regulated deficit, partial root-drying, and conventional deficit irrigation applied with surface drip and subsurface drip systems under the Mediterranean climatic conditions. The results revealed that irrigation treatments had significant effect on grain and dry matter yield as well as CWSI and LWP. The two drip systems performed similarly regarding the grain and dry matter yields. Quinoa under surface drip plots used slightly more water than subsurface drip plots for the same treatments due to reduced surface evaporation from the SSD plots. RDI appeared to be good alternative to full irrigation since it produced statistically similar yield to FI treatment in both experimental years. RDI resulted in water savings of 23 and 21% for SD and SSD systems, respectively. DI$_{75}$ treatment resulted in an average water saving of 17% for both drip methods. Thus, RDI and DI$_{75}$ treatments appear to be good alternatives to FI in the Mediterranean environmental conditions.

Our results show that the water status of the quinoa plant determined by the leaf water potential was significantly affected by irrigation treatments. We observed slightly higher LWP values in SSD plots than in the SD plots, however, the difference between the two irrigation system was not significant. Our results revealed that quinoa should be irrigated at LWP values around − 1.35 MPa in the early

growing season and approximately − 1.50 MPa in the late season for high- and good-quality yields in the Mediterranean region. Thus, the results indicated that LWP can be used for irrigation scheduling for quinoa. In general, the CWSI correlated significantly ($P < 0.01$) and negatively with grain yield, dry matter yield, maximum LAI, and mean soil water content indicating that grain yield of quinoa declined with increasing CWSI values. All these relations are best described by significant second-order polynomial equations.

The lowest CWSI values were observed in FI for both irrigation methods, higher values were determined in DI_{50} and PRD_{50}. In general, the variations of CWSI under the SSD and SD systems were very similar throughout the growing seasons. CWSI values early in the season were lower and increased as the season progressed. The amplitude of fluctuations increased by increasing levels of water deficit. An average CWSI value of approximately 0.35 just before an irrigation can be used for irrigation scheduling of quinoa to achieve high yields. Significant second-order polynomial relations were determined between CWSI and LWP for both drip systems. CWSI correlated significantly ($P < 0.01$) and negatively with grain yield, dry matter yield, maximum LAI, and mean soil water content indicating that grain yield of quinoa declined with increasing CWSI values. All these relations are best described by significant second-order polynomial equations.

Full irrigation to increase the quinoa yield in water-scarce regions is not an option; however, regulated deficit irrigation, partial root-zone drying and deficit irrigation are practices that reduce the amount of water used during the growing season without detriments to yield and might be useful alternatives. 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 at water-deficient areas without any loss on grain and dry matter yield is recommended along with conventional deficit irrigation (DI_{75}) in the semi-arid Mediterranean area.

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