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Assessment of growth, seed yield, and water productivity of two *Chenopodium quinoa* cultivars under different irrigation levels in semiarid conditions

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Abstract

Drought management requires information on water productivity, crop water consumption, and relevant crop cultivars. Water productivity is important in determining the relationship between crop yield and evapotranspiration, especially in areas with limited irrigation and low rainfall. During the experiment, the seed yield, yield components, and water-yield relationships of two quinoa (*Chenopodium quinoa* Willd.) cultivars 'Titicaca' and 'Carmen' under conditions of decreasing irrigation water were determined. It was conducted as a field experiment in three replications and two years (2018–2019). In the experiment, four different irrigation water treatments: I_{100} – full irrigation (control), I_{75} – 25% deficit, I_{50} – 50% deficit, and I_0 – 100% deficit (no irrigation), were used. According to the average of two-year experimental data, the seed yield, plant height, 1000-grain weight, and harvest index were 2754 kg ha^{-1}, 75.4 cm, 2.81 g, and 37.7% for the 'Carmen' and 3335 kg ha^{-1}, 108.3 cm, 2.93 g, and 40.5% for the 'Titicaca', respectively. Yield component values decreased due to irrigation water restriction for both cultivars. The water productivity value was similar in the I_{100} and I_{75} treatments of both cultivars. The yield response factor (ky) for 'Carmen' and 'Titicaca' was determined to be 1.37 and 1.39 in 2018, and 1.23 and 1.20 in 2019, respectively. At the end of the experiment, it was determined that irrigation had an increasing effect on the seed yield, plant height, 1000-grain weight, and harvest index values in quinoa plants under semiarid conditions. In addition, recommendations were made for the use of the I_{75} irrigation, which saves water, and for the 'Titicaca', which is more suitable for the climate of semi -arid region.

Keywords: quinoa, drought, water-yield relationships, yield response factor (ky), seed yield.

Introduction

In the 21st century, more severe droughts are expected in many parts of the world (Schwalm et al., 2017). Similarly, in the Mediterranean basin, where Turkey is located, regular rainfall is predicted to decrease and drought to increase (IPCC, 2014). Agriculture uses about 70% of the world's freshwater resources (Almuktar et al., 2018; Phasinam et al., 2022). To cope with the growing population and its resulting increasing demand for food, it is necessary to use existing water resources more economically and efficiently. Due to the inadequacy of existing water resources, it has become necessary to use different strategies to maximise the benefits of irrigation water.

Deficit irrigation practices are promising irrigation strategies to save water in agricultural irrigation (Geerts et al., 2008). With deficit irrigation, water is delivered to more areas using less water. Water productivity is the most important parameter to be considered in deficit irrigation strategies (Molden, 2003). Crop water productivity is valuable means to study the cumulative effect of water stress tolerance mechanisms in quinoa. Water productivity, whose unit is kg m^{-3}, is defined as the ratio of actual yield (Ya) to the actual evapotranspiration (ETa), i.e., soil evaporation, or crop transpiration (Geerts et al., 2009). Fghire et al. (2022) reported higher water productivity under deficit irrigation conditions.

Quinoa (*Chenopodium quinoa* Willd.) is a plant originating from the Andean region (Colombia, Peru, Ecuador, Argentina, Chile, and Bolivia) that stands out due to its high nutritional value (Präger et al., 2018; Alandia et al., 2020). Quinoa seeds contain high amounts

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of protein, vitamins, and minerals, which are important in human and animal nutrition (Bilalis et al., 2019). Worldwide, an average seed yield of 9275 kg ha^{-1} was obtained on 188 878 ha (FAOSTAT, https://www.fao.org/faostat/en/#data/QCL). Due to the increased market value of quinoa and insufficient production in relation to demand, it has been suggested that quinoa can be grown under irrigated conditions (Garcia et al., 2003). Ali et al. (2020) and Saddiq et al. (2021) reported that grain yield, dry matter yield, and plant height of quinoa increased under irrigated conditions. In the research conducted in Bolivia, it was reported that a seed yield of 2040 kg ha^{-1} was obtained under irrigation, while it remained at 1680 kg ha^{-1} under dry farming (Geerts et al., 2008).

It is obvious that food and water requirements will increase in the future due to population growth and water shortage in agriculture. Water productivity is considered a determining component of yield under water deficit conditions. Therefore, it is necessary to know the water components of plants with a high protein content. In addition, to obtain a high yield in agricultural production and to ensure an efficient use of water, it is an important factor to select cultivars suitable for the climatic conditions of the region.

The objectives of the experiment were (i) to determine deficit irrigation practices that could compete in terms of water productivity with full irrigation, and (ii) to identify the appropriate cultivars for the semi-arid region by studying the seed yield and yield parameters of the plant and water-yield relationships under water deficit conditions.

Material and methods

Experimental area, climate, and soil properties. Field experiment was conducted during two consecutive growing seasons, 2018 and 2019, in the experiment area (38°34′36″ N, 43°17′25″ E, 1680 m a. s. l.) of Agriculture Faculty, Van Yuzuncu Yil University in Turkey. The long-term average total precipitation in the experimental area is 385 mm (Turkish State Meteorological Service, https://www.mgm.gov.tr/eng/forecast-cities.aspx).

Monthly total precipitation and mean air temperatures during the vegetation periods were obtained from the meteorological station i-METOS located in the experimental area. The total precipitation during the growing periods was 71.2 and 35.6 mm in 2018 and 2019, respectively (Figure 1).

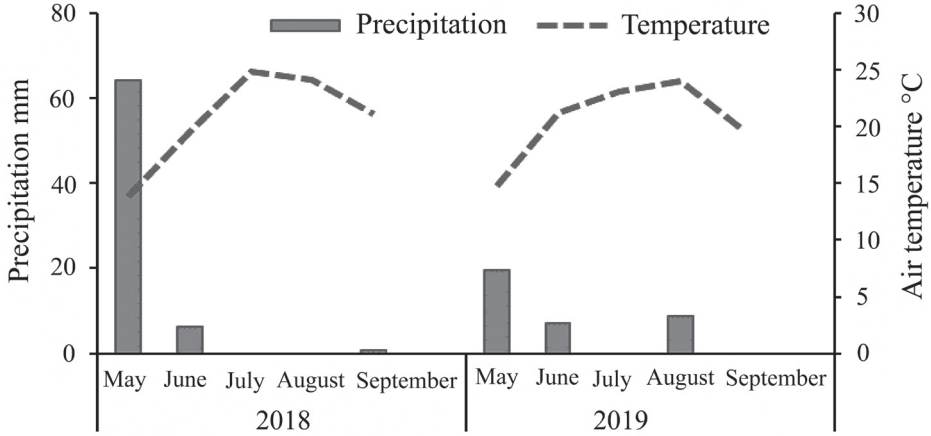


Figure 1. Monthly mean air temperature and precipitation values in 2018 (1 May – 20 September) and 2019 (6 May – 30 September) during growing periods

In the 0–90 cm layer, the soil was classified as a clay loam texture with a bulk density of 1.37 g cm^{-3}. The soil was slightly alkaline and moderately calcareous, the organic matter percentage was low, and the phosphorus and potassium contents were sufficient (Table 1).

Table 1. Characteristics of the soil of the experimental area

Physical and chemical properties	Soil layer depth cm		
	0–30	30–60	60–90
Sand %	41.8	42.2	44.1
Silt %	26.2	25.5	25.7
Clay %	32.0	32.3	30.2
Texture	clay loam	clay loam	clay loam
Field capacity vol%	30.8	31.4	30.2
Permanent wilting point vol%	17.6	16.9	17.5
Bulk density g cm^{-3}	1.37	1.34	1.40
pH	7.95	8.04	8.11
$CaCO_3$ %	8.6	9.8	12.3
Organic matter %	1.02	0.88	0.83
P_2O_5 kg ha^{-1}	75	84	89
K_2O_5 kg ha^{-1}	1012	954	983

Agricultural practice. The plots were tilled with the conventional tillage practice: mould-board plough + rotary tiller + leveller. Quinoa (*Chenopodium quinoa* Willd.) cultivars 'Titicaca' and 'Carmen' obtained from a commercial company and widespread in the country were used in the experiment. The seeds were sown manually on 1 May 2018 in the 1st year, and on 6 May 2019 in the 2nd year of the experiment, in the rows where the marker was drawn. The distance between two rows was 35 cm, and the distance between two plants above the row was 20 cm (Geren et al., 2015). Quinoa plants were harvested on 20 September 2018 in the 1st year, and on 30 September 2019 in the 2nd year of the experiment, when the seeds had matured and dried. Against weeds, mechanical and chemical control was applied. As fertiliser, 125 kg ha^{-1} N and 80 kg ha^{-1} P were applied. Half of the nitrogen fertiliser was applied at sowing, the other half when the plants were 40–50 cm tall; all of the phosphorus fertiliser was applied during sowing (Geren et al., 2015; Yazar et al., 2017). Phosphorus is an important macronutrient, most of which is retained in soil in the form of iron and aluminum oxides and calcium phosphates, which cannot be used by plants (Alam, Ladha, 2004). Furthermore, although plant-available phosphorus was found in the soil, according to Jacobsen et al. (1994), quinoa plants responded better to phosphorus doses of 100 kg or more per hectare.

Irrigation systems and irrigation treatments. The drip irrigation method was used. For irrigation systems, non-pressure compensating emitters with a flow rate of 2.3 L s^{-1} in an operation pressure of 0.1 MPa and a distance of 33 cm were used. The experiment was planned considering four different irrigation (I) water levels: 1) I_{100} – full, or non-deficit irrigation (control), 2) I_{75} – 25% deficit irrigation, 3) I_{50} – 50% deficit irrigation, and 4) I_0 – 100% deficit, or no irrigation (Figure 2).

1	T-I_{100}	C-I_0	C-I_{50}	C-I_{75}	T-I_{50}	C-I_{100}	T-I_{75}	T-I_0
2	T-I_{75}	C-I_{100}	T-I_{50}	C-I_0	C-I_{75}	T-I_{100}	T-I_0	C-I_{50}
3	C-I_{50}	T-I_{75}	T-I_{100}	T-I_0	C-I_{100}	C-I_0	T-I_{50}	C-I_{75}

Cultivar: T – Titicaca, C – Carmen; irrigation regime: I_{100} – full (control), I_{75} – 25% deficit, I_{50} – 50% deficit, I_0 – 100% deficit (no irrigation); 1, 2, 3 – blocks

Figure 2. Experimental design

The irrigation schedule was based on the reference evapotranspiration (ET) method. ET values were calculated according to the FAO-56 Penman-Monteith method with the software CROPWAT, version 8.0 (Allen et al., 1998). For calculations, daily weather data: air temperature, relative humidity, wind speed, and hours sunshine, were collected from the meteorological station METOS® (Pessl Instruments, Austria) in the experimental area. When the sum of daily reference plant water consumption values was 50 ± 5 mm, the available soil moisture content in the fully irrigated plot was measured by the gravimetric method, and the differences between the field capacity and available moisture were applied for irrigation amounts. The soil moisture content was measured at a horizontal distance of approximately 10 cm from the dripper between two plants in the row. To determine the amount of irrigation water, soil samples from the 0–90 cm (0–30, 30–60, and 60–90 cm) layer were taken before each irrigation from the full irrigation (control) treatment and the moisture content was determined. The soil moisture content was measured in all treatments before each irrigation at planting and harvest and used to calculate actual evapotranspiration (ETa) values.

The total water content calculated according to equations 1 and 2 was applied in the I_{100} treatment, while 25% and 50% reductions were applied in the I_{75} and I_{50} treatments, respectively.

$$I = \frac{[(FC - CM) \times \gamma s \times D \times W]}{10} \quad (1),$$

$$V = I \times A \quad (2),$$

where I is the irrigation water quantity (mm), FC is the soil moisture content at field capacity (%Pw), CMC is the available moisture content (%Pw), γs is the soil bulk density (g cm^{-3}), D is the effective root depth (cm), and W is the wetted percentage area (0.65); V is the irrigation water volume (litres), and A is the plot area (m^2). The length of each plot was 5 m, and the width was 1.75 m. The experimental area was 8.75 m^2.

Water components. During the experiment, evapotranspiration (ET) for quinoa plants was determined according to equation 3 (Allen et al., 1998):

$$ETa = I + P + C - Dp - R \pm \Delta S \quad (3),$$

where ETa is the actual evapotranspiration (mm), I is the irrigation water quantity (mm), P is the precipitation (mm), C is the capillary rise (mm), Dp is the deep percolation (mm), R is the surface runoff (mm), and ΔS is the soil water moisture change (mm). The capillary rise was not taken into account due to the deep-

water level (>10 m) in the experiment area. The amounts of precipitation exceeding the field capacity were considered as deep percolation. During the experiment, no surface runoff was realised due to the controlled drip irrigation. Soil moisture measurement was determined gravimetrically during the growing period and harvest.

WP and IWP were calculated according to equations 4 and 5 (Howell, 2001):

$$WP = \frac{Yi}{10 \times ETa} \quad (4),$$

$$IWP = \frac{Yi - Y0}{10 \times I} \quad (5),$$

where WP is the water productivity (kg m^{-3}), IWP is the irrigation water productivity (kg m^{-3}), Yi is the yield obtained from the irrigation treatment (kg ha^{-1}), Y0 is the yield obtained from the non-irrigation treatment (kg ha^{-1}), ETa is the actual evapotranspiration (mm), and I is the irrigation water quantity (mm).

The yield response factor (ky) value was determined using Stewart's equation (6) (Doorenbos, Kassam, 1986):

$$[1 - \frac{Ya}{Ym}] = ky\ [1 - \frac{ETa}{ETm}] \quad (6),$$

where Ya is the actual yield (kg ha^{-1}), Ym is the maximum yield (kg ha^{-1}), ky is the yield response factor, ETa is the actual evapotranspiration (mm), and ETm is the maximum evapotranspiration (mm).

Measurements of yield and yield components. The seeds of the selected plants in the experimental area were separated and weighed with a balance for seed yield (SY) calculation. For the determination of dry matter yield, they were dried in an oven at 70°C temperature to constant weight and converted to t ha^{-1}. The harvest index (HI) was calculated as SY divided by total plant biomass. The 1000-grain weight (TGW) was determined by weighing and calculating 100 seeds in four replicates.

Statistical analysis. The experiment was conducted as a randomised complete block design with three replications. To determine the significance of factors and their respective interactions, all data were subjected to analysis of variance (ANOVA) using the General Linear Model with SPSS, version 21 (IBM Inc., USA). The data of both experinetal years were statistically evaluated separately. When significant, mean comparisons between the treatments were conducted using the Duncan multiple comparison test. The classifications in the ANOVA tables were made according to the significance of the interaction.

Results

Irrigation water and evapotranspiration. Irrigation water was applied 17 and 19 times in 2018 and 2019, respectively. In 2018, the abundant rainfall in May, when planting was done, was effective in reducing the number of irrigations. The amount of irrigation water in the I_{100}, I_{75}, I_{50}, and I_0 treatments was 408.1, 309.5, 210.8, and 13.5 mm in 2018, and 436.4, 329.7, 223.0, and 9.6 mm in 2019, respectively. In 2019, 6.9%, 6.5%, and 5.8% more irrigation water was used in the I_{100}, I_{75}, I_{50}, and I_0 treatments, respectively, compared to 2018 (Table 2). Plant water consumption values are given in Table 2. The highest and the lowest values of plant water consumption were found in the I_{100} and I_0 treatments, respectively. Plant water consumption values decreased with the decrease in the amount of irrigation water. The difference between years was determined more in the I_{50} and I_0 treatments, compared to the I_{100} and I_{75} ones.

Table 2. Effect of the irrigation water (I), actual evapotranspiration (ETa), seed yield (SY), water productivity (WP), and irrigation water productivity (IWP) of quinoa cultivars during the experimental years

Year	Irrigation regime	Cultivar	I mm	ETa mm	SY kg ha^{-1}	WP kg m^{-3}	IWP kg m^{-3}
2018	I_{100}	Carmen	408.1	469.4	2914	0.62	0.56
	I_{75}		309.5	418.7	2339	0.56	0.55
	I_{50}		210.8	354.6	1333	0.38	0.34
	I_0		13.5	202.3	622	0.31	
	I_{100}	Titicaca	408.1	470.8	3430	0.73	0.63
	I_{75}		309.5	410.0	2938	0.72	0.68
	I_{50}		210.8	369.1	1840	0.50	0.47
	I_0		13.5	212.6	844	0.40	
2019	I_{100}	Carmen	436.4	475.0	2597	0.55	0.45
	I_{75}		329.7	399.4	2106	0.53	0.44
	I_{50}		223.0	342.5	1161	0.34	0.23
	I_0		9.6	180.9	654	0.36	
	I_{100}	Titicaca	436.4	466.1	3239	0.69	0.55
	I_{75}		329.7	408.2	2865	0.70	0.62
	I_{50}		223.0	346.3	1628	0.47	0.36
	I_0		9.6	169.7	818	0.48	

Irrigation regime: I_{100} – full (control), I_{75} – 25% deficit, I_{50} – 50% deficit, I_0 – 100% deficit (no irrigation)

Seed yield (SY). Both cultivar and the irrigation regime had a significant effect on the plant SY in both experimental years. In 2018, SY was insignificant in the cultivar and irrigation regime treatments, while the difference between SY was significant in 2019 (Table 3).

The lowest seed yield of both cultivars was obtained in 2019 (Table 2). In 2019, the seed yield of the 'Carmen' and 'Titicaca' decreased by 9.6% and 5.5%, respectively, compared to 2018. The 'Titicaca' yielded more than the 'Carmen' in both years. The seed yield decreased with decreasing irrigation water in both years. In the I_{75} treatment, the seed yield decreased by 16.80% in 2018 and 14.78% in 2019, compared to I_{100}; in the 50% treatment, the seed yield decreased by 50.03% in 2018 and by 52.18% in 2019. While the difference between the I_{100} and I_{75} treatments was small, the difference between the I_{100} and I_{50} ones was much higher.

Table 3. Effect of the cultivar and irrigation regime (IR) on the seed yield (SY) (kg ha^{-1}) (± standard error) of quinoa plants during the experimental years

Year	Cultivar	Irrigation regime				Mean
		I_{100}	I_{75}	I_{50}	I_0	
2018	Carmen	2914 ± 72	2339 ± 91	1333 ± 64	622 ± 43	1802 B
	Titicaca	3430 ± 57	2938 ± 45	1840 ± 95	844 ± 53	2263 A
	Mean	3172 A	2639 B	1587 C	733 D	
2019	Carmen	2594 ± 47 c	2106 ± 63 d	1161 ± 47 f	654 ± 38 g	1629 B
	Titicaca	3239 ± 49 a	2865 ± 89 b	1628 ± 63 e	818 ± 55 g	2138 A
	Mean	2917 A	2486 B	1395 C	736 D	
2018ns		2033				
2019		1884				
P_{2018}	SY	0.000	P_{2019}	SY	0.000	
	IR	0.000		IR	0.000	
	SY × IR	0.064		SY × IR	0.001	

Note. Irrigation regimes: I_{100} – full (control), I_{75} – 25% deficit, I_{50} – 50% deficit, I_0 – 100% deficit (no irrigation); *P* – significant value, ns – not significant; there were significant differences among the different letter(s) at $P < 0.05$ level according to Duncan's multiple comparison test.

Plant height (PH). The effect of cultivar and irrigation regime on PH was significant in both years (Table 4). The highest PH was determined in the 'Titicaca' in 2018 and 2019. In both years, the highest PH was determined in the I_{100} treatment, and PH decreased with irrigation water deficit. According to the two-year average, in the 'Carmen', 37.2%, 20.8%, and 6.2% decreases were realised in the I_0, I_{50}, and I_{75} treatments, respectively, compared to the I_{100} one; in the 'Titicaca', 44.8%, 36.9%, and 15.9% reductions were realised in the I_0, I_{50}, and I_{75} treatments, respectively, compared to the I_{100} one. In 2018 and 2019, in the I_0 treatment, PH decreased by 40.70% and 33.80%, respectively, and by 46.4% and 43.3%, respectively, in the 'Carmen' and 'Titicaca', compared to the I_{100} treatment. The difference in PH between the years was found to be insignificant. Although the difference between the years was found to be insignificant, PH was higher in 2018 than in 2019.

Table 4. Effect of the cultivar and irrigation regime (IR) on the plant height (PH) (cm) (± standard error) of quinoa plants during the experimental years

Year	Cultivar	Irrigation regime				Mean
		I_{100}	I_{75}	I_{50}	I_0	
2018	Carmen	78.7 ± 2.03 c	73.3 ± 1.45 c	61.7 ± 2.60 d	46.7 ± 1.76 e	65.1 B
	Titicaca	114.3 ± 3.53 a	94.7 ± 4.06 b	71.0 ± 2.08 c	61.3 ± 2.33 d	85.3 A
	Mean	96.5 A	8.0 B	66.4 C	54.0 D	
2019	Carmen	72.0 ± 1.53 c	68.0 ± 2.08 cd	57.7 ± 1.20 e	47.7 ± 1.45 f	61.4 B
	Titicaca	102.3 ± 2.96 a	87.3 ± 1.45 b	65.7 ± 2.33 d	58.0 ± 1.53 e	78.3 A
	Mean	87.2 A	77.7 B	61.7 C	52.9 D	
2018ns		75.2				
2019		69.8				
P_{2018}	PH	0.000		P_{2019}	PH	0.000
	IR	0.000			IR	0.000
	PH × IR	0.001			PH × IR	0.000

Explanation under Table 3

Thousand-grain weight (TGW). The effect of cultivar and irrigation regime on TGW was significant in both years (Table 5). The interaction between cultivar and irrigation regime was found to be insignificant. For the PH value, the highest TGW was determined in the 'Titicaca'. In the I_0, I_{50}, and I_{75} treatments, TGW decreased by 24.6%, 8.2%, and 3.0% in 2018, and 27.4%, 8.2%, and 6% in 2019, respectively, compared to the I_{100} one. The higher TGW loss in 2019 may be due to the reduced precipitation in 2019, compared to 2018. When analysed by cultivar,

Table 5. Effect of the cultivar and irrigation regime (IR) on the 1000-grain weight (TGW) (g) (± standard error) of quinoa plants during the experimental years

Year	Cultivar	Irrigation regime				Mean
		I_{100}	I_{75}	I_{50}	I_0	
2018	Carmen	2.82 ± 0.02	2.70 ± 0.02	2.62 ± 0.01	2.11 ± 0.05	2.56 B
	Titicaca	2.95 ± 0.03	2.89 ± 0.03	2.68 ± 0.05	2.24 ± 0.05	2.69 A
	Mean	2.89 A	2.80 B	2.65 C	2.18 D	
2019	Carmen	2.80 ± 0.03	2.69 ± 0.01	2.62 ± 0.02	2.00 ± 0.04	2.53 B
	Titicaca	2.90 ± 0.02	2.67 ± 0.03	2.61 ± 0.05	2.14 ± 0.04	2.58 A
	Mean	2.85 A	2.68 B	2.62 B	2.07 C	
2018ns		2.63				
2019		2.55				
	TGW	0.000			TGW	0.039
P_{2018}	IR	0.000		P_{2019}	IR	0.000
	TGW × IR	0.371			TGW × IR	0.068

Explanation under Table 3

the TGW of the 'Carmen' decreases by 26.8%, 6.7%, and 4%, and of the 'Titicaca' – by 25.2%, 9.6%, and 5% in the I_0, I_{50}, and I_{75} treatments, respectively, compared to the I_{100} one. In the case of water deficit (especially I_{75}), the TGW of the 'Carmen' decreased more than that of the 'Titicaca'. Although the data for 2018 were higher than that of 2019, the difference between the years was insignificant.

Harvest index (HI). The effect of cultivar and irrigation regime on the HI was significant in both years (Table 6). The interaction between cultivar and irrigation regime was found to be insignificant. In both years, the highest HI was determined in the I_{100} treatment with full irrigation and the lowest in the I_0 treatment with no irrigation. Deficit irrigation caused significant differences in the HI among treatments – the HI decreased when the water deficit increased. The HI was higher in the 'Titicaca' in both years: in 2018 and 2019, a 16.8% and 8.1% higher HI was determined in the 'Titicaca' than in the 'Carmen', respectively. In 2018 and 2019, the difference between HI values was insignificant.

Table 6. Effect of the cultivar and irrigation regime (IR) on the harvest index (HI) (%) (± standard error) of quinoa plants during the experimental years

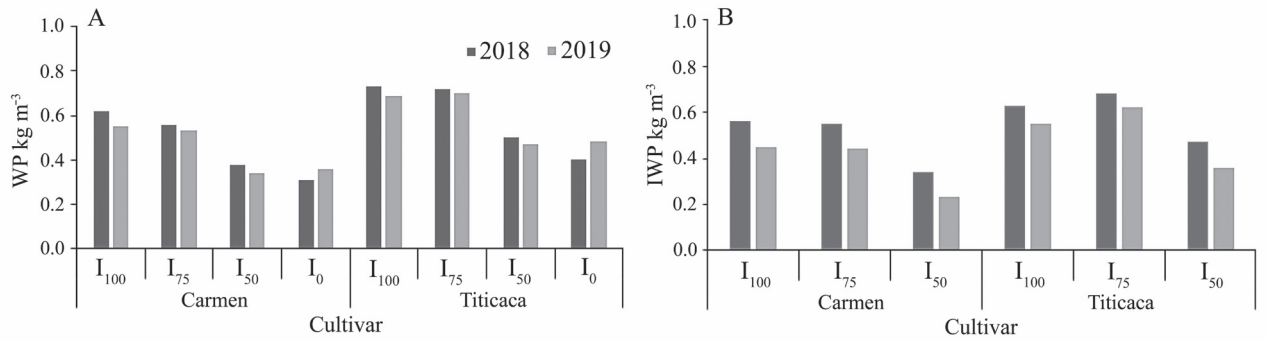
Year	Cultivar	Irrigation regime				Mean
		I_{100}	I_{75}	I_{50}	I_0	
2018	Carmen	37.3 ± 0.9	33.0 ± 0.6	27.0 ± 0.6	21.3 ± 0.9	29.7 B
	Titicaca	41.0 ± 1.0	38.0 ± 0.0	33.0 ± 1.5	26.7 ± 0.7	34.7 A
	Mean	39.2 A	35.5 B	30.0 C	24.0 D	
2019	Carmen	38.0 ± 1.7	35.3 ± 0.7	29.3 ± 1.2	20.7 ± 1.2	30.8 B
	Titicaca	40.0 ± 0.6	38.7 ± 0.3	32.7 ± 0.3	21.7 ± 0.7	33.3 A
	Mean	39.0 A	37.0 A	31.0 B	21.2 C	
2018ns		32.2				
2019		32.0				
	HI	0.000			HI	0.000
P_{2018}	IR	0.000		P_{2019}	IR	0.003
	HI × IR	0.599			HI × IR	0.565

Explanation under Table 3

Water productivity (WP) and irrigation water productivity (IWP). In both years of the experiment, the highest WP was determined in the 'Titicaca' and the lowest in the 'Carmen' (Figure 3). The highest WP values were realised in the I_{100} (full irrigation) and I_{75} treatments, and the WP of both cultivars was similar in the I_{100} and I_{75} ones.

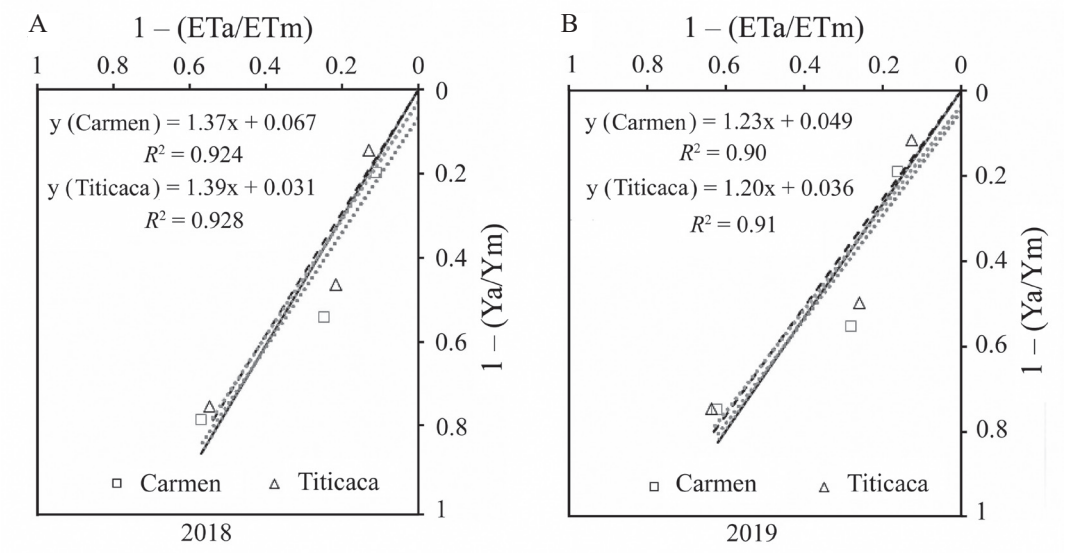
IWP was calculated from SY and irrigation water use. IWP was determined to be high when the seed yield was high, and the water use was lower. In both years, the highest IWP value was determined in the 'Titicaca' in the I_{75} (25% water deficit) treatment. In the I_{50} treatment, where both I and SY (Table 2) were low, the lowest IWP value was determined in both cultivars (Figure 3).

Yield response factor (ky). The linear correlation graph between ET and SY is shown in Figure 4. The ky values of 'Carmen' and 'Titicaca' were 1.37 (R^2 = 0.92) and 1.39 (R^2 = 0.93) in 2018, and 1.22 (R^2 = 0.90) and 1.20 (R^2 = 0.91) in 2019, respectively.



Note. The interaction was not significant in both years.

Figure 3. Effect of the water productivity (WP) (a) and irrigation water productivity (IWP) (b) on quinoa cultivars during the experimental years



ETa – actual evapotranspiration (mm), ETm – maximum evapotranspiration (mm), Ya – actual yield (kg ha^{-1}), Ym – maximum yield (kg ha^{-1})

Figure 4. Yield response factor values of quinoa cultivars during the experimental years

Discussion

As a result of unplanned, inadequate, uncontrolled, and unconscious irrigation, available freshwater resources are decreasing, and access to irrigation water is becoming more difficult. Therefore, for the effective irrigation water management, it is necessary to increase water productivity, especially in arid and semi-arid regions. Therefore, quinoa was subjected to decreasing amounts of irrigation water (I_{100}, I_{75}, $I_{50,}$ and I_0). In 2019, there was 50% less rainfall than in 2018. These changes have been caused by climate differences between the years (Figure 1). Previous studies have reported that seasonal rainfall should be 300–1000 mm, depending on the region, to obtain an optimum seed/grain yield of quinoa (Gomez-Pando, Aguilar-Castellanos, 2016; Hinojosa et al., 2019).

Compared to the literature data, the precipitation in the experimental area is very low and the irrigation is compulsory. In the full irrigation treatment (I_{100}), 408.1 mm of irrigation water was applied in the 1st year and 436.4 mm in the 2nd year of the experiment. Significant differences were found between the irrigation treatments. The seed yield decreased with increasing the water stress. Similarly, Fghire et al. (2022) reported that seed yield decreased with increasing water stress.

In different countries (regions), the seed yield of quinoa has been reported to range from 500 to 6000 kg ha^{-1} under water stress conditions (Hirich et al., 2014; Bazile et al., 2016; Ahmadi et al., 2019). In present experiment, the two-year average seed yield varied between 3172 and 2917 kg ha^{-1} in the 1st and 2nd years under full irrigation conditions and between 733–2639 and 736–2486 kg ha^{-1} in the 1st and 2nd years under deficit irrigation conditions, respectively. The results of the research confirm the literature data. Hinojosa et al. (2019) reported that temperature reduced seed yield. In 2019, temperature was higher during germination and development than in 2018. This is consistent with the results of present experiment, as higher temperatures were measured in the 2nd year (2019) of the experiment. Muchow et al. (1990) reported that high temperature accelerates the ontogenetic processes of plants and reduces dry matter accumulation. Similarly, Valdivia-

Cea et al. (2021) reported that the high air temperature reduces the seed dry matter accumulation and seed yield by promoting the stomatal closure. As a matter of fact, a higher seed yield was obtained in the 1st year of the experiment. Between the cultivars, the seed yield was higher in the 'Titicaca' than in the 'Carmen'.

The plant height (PH) decreased with the irrigation water deficit in both years and cultivars. The difference between the years may be because precipitation occurred in the 1st year, especially during the germination of the seed. The plant height was higher in 1st year in both cultivars; it shows that there was no difference due to the cultivar. Many researchers have also reported that plant height decreases with water deficit (El-Shamy et al., 2022; Maestro-Gaitán et al., 2022). The results of present research support previous studies showing that water deficit leads to a decrease in plant height. Similar to current research data, Sadak and Bakhoum (2022) reported a 22.2% decrease in the I_{60} irrigation treatment, compared to the I_{100} one.

Water stress negatively affects many physiological processes such as assimilate transfer, cell expansion and division (Devnarain et al., 2016). The decrease in plant height may be due to a decrease in cell elongation as a result of water stress. In addition, photosynthesis decreases with the decrease in water in the plant tissue and the closure of the stomata. In parallel with this decrease, the plant height also decreased.

A high seed yield (SY) also corresponds to a high 1000-grain weight (TGW) (Tables 3 and 5). Similarly, considering that the plant height was high in the 'Titicaca' in both years, it can be expected that TGW was also high due to the high growth of the plant. In both years, the TGW decreased with the decrease in irrigation water. Similarly, Bahrami et al. (2022) reported that seed yield decreased with decreasing irrigation water: 11.1% and 53% decrease in the I_{50} and I_{75} treatments, compared to the I_{100} one, respectively. When the water needed by the plant is insufficient, seed filling cannot be completed, and the seed weight may decrease. Deficit irrigation negatively affects photosynthesis (Fghire et al., 2015). Growing plants under long-term deficit irrigation can reduce the flow of assimilation to the seeds. The weight of the seeds may also decrease due to the reduced assimilate fraction. Similarly, the consumption of photosynthetic products is reduced in leaves growing with reduced water (Endres et al., 2010). Thus, under water deficit, substances delivered from leaves to other parts are reduced. With reduced photosynthesis, seed self-filling is reduced and the seed weight may decrease accordingly.

Water deficit affected the harvest index (HI) in both cultivars, and there were significant differences between decreasing water treatments. In 2019, the significance between the I_{100} and I_{75} treatments was similar. In other words, in 2019, the harvest index was similar for both the I_{100} and I_{75} treatments, which applied 25% less water, compared to the I_{100} one. The lowest harvest index was determined in the I_0 treatment in both years. It is expected that the harvest index will decrease as the seed yield decreases due to the water deficit. As reported by Razzaghi et al. (2012), soil exposure to water stress during the seed-filling stage significantly reduced the HI value of quinoa. In the present experiment, the harvest index decreased with decreasing the irrigation water, seed yield, and plant height. Similarly, Maestro-Gaitán et al. (2022) reported that the harvest index decreased in the case of drought. The highest HI value in the 'Titicaca' in both years was due to the high seed yield in the 'Titicaca'.

Water productivity (WP) is an important parameter for drought. During the experiment, WP was high in the I_{100} and I_{75} treatments in both years. This closeness is due to the high seed yield. The plant seed yield decreased in the I_{50} and I_0 irrigation regimes (Table 2). The decrease in seed yield after the amount of water deficit exceeded 25% caused a decrease in WP values. Many studies have reported that seed yield decreases with decreasing irrigation amount (Hirich et al., 2014; Bazile et al., 2016; Ahmadi et al., 2019). Particularly in the I_0 treatment, where the lowest seed yield was obtained, WP was determined to be low, because the I_0 treatment was irrigated only with rainfall, and the seed yield was determined low due to insufficient water. Higher WP was determined in 'Titicaca', compared to 'Carmen'. The high seed yield of 'Titicaca' is the most important component in the high determination of WP. Researchers have reported that the WP of quinoa was determined to be in a range of 0.3–1.57 kg m^{-3} in different regions (Hirich et al., 2014; Riccardi et al., 2014; Yazar et al., 2017; Bozkurt Çolak et al., 2021). The WP values obtained in the experiment also are supported by the literature. The differences from the literature can be seen in plant water consumption, which varies depending on the climate and different soil properties. Molden (2003) reported that WP may vary according to climatic conditions.

Irrigation water productivity (IWP) refers to the seed yield obtained per unit of water applied (Howell, 2007). In the 'Carmen', at the I_{100}, I_{75}, and I_{50} application, IWP decreased by 19.6%, 20%, and 32.4%, respectively, in 2019, compared to 2018. In the 'Titicaca', at the I_{100}, I_{75}, and I_{50} application, IWP decreased by 12.7%, 8.8%, and 23.4%, respectively, in 2019, compared to 2018 (Figure 3). In 2018, high IWP values were determined due to the high seed yield. A higher IWP was determined in the 'Titicaca', which had higher seed yield in both years. The high seed yield, harvest index, and plant height of the 'Titicaca' also support the high IWP value.

During present experiment, for the 'Carmen' and 'Titicaca', the yield response factors (ky) were determined to be 1.37 and 1.39 in 2018, and 1.23 and 1.20 in 2019, respectively (Figure 4). The ky value was determined to be high due to the high seed yield in 2018. Kaya et al. (2015) reported that the ky value for quinoa in the Mediterranean region of Turkey was 0.96, Garcia et al. (2003) reported that in Bolivia it was 0.67, and Bozkurt Çolak et al. (2021) reported that in the Çukurova region of Turkey it was 0.54–0.89. In those studies, it was found that ky values varied according to the regions. The high ky values of the present experiment may be due to the differences in the climatic characteristics and soil structure of the of semi-arid region.

Conclusions

1. The results showed that different irrigation regimes (IR) had a significant effect on the plant height (PH), seed yield (SY), 1000-grain weight (TGW), and harvest index (HI) of quinoa cultivars 'Carmen' and 'Titicaca'.

2. Water productivity (WP) was similar in the full (I_{100}) and 25% deficit (I_{75}) irrigation treatments. Irrigation water productivity (IWP) was highest in the I_{75} treatment.

3. Although a high temperature reduced SY of both quinoa cultivars, the least SY loss was realised in the I_{75} treatment of the 'Titicaca'.

4. 'Titicaca' provided a high seed yield in both seasons for all irrigation regime treatments and was found to be more adapted to the climate and soil structure of the of semi-arid region.

5. Although quinoa is known as a drought-tolerant crop, irrigation is recommended for the optimum seed yield, especially in semi-arid regions. Future research should focus on increasing the WP of quinoa in regions with different climatic characteristics.

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