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REGULAR ARTICLE

Grain yield, biomass productivity and water use efficiency in quinoa (*Chenopodium quinoa* Willd.) under drought stress

Dalel Telahigue*[1], Laila Ben Yahia[1], Fateh Aljane[1], Khaled Belhouchett[1], Lamjed Toumi[2]

[1]*Dry lands and Oases Cropping Laboratory, Arid Area Institute (IRA), Medenine 4119, Tunisia.*

[2]*Silvo Pastoral Institute of Tabarka, 8110, Tunisia.*

Abstract

Five quinoa cultivars introduced from Egypt DRC (Desert Research Center-Caire) were tested in an experimental station in Tunisia located under arid climatic conditions. In order to test their adaptation to abiotic constraints; water requirements, yield (grain, dry matter) and water use efficiency (WUE) were correlated to three water stress: T100% of field capacity (T1), T60% of field capacity (T2) and T30% of field capacity (T3). Net irrigation water requirement was estimated using CROPWAT 8.0 software. The study aims to develop an irrigation scheduling for quinoa from January to Jun during 2015 season. The ET0 was between 1.08 mm/day and 4.95 mm/day and net irrigation water requirement was 287.2 mm. For grain yield, 1000 grains weight and dry matter production results show significant differences between cultivars and water stress. The seeds productivity of the five cultivars ranges between 2092.6kg/ha and 270kg/ha under full irrigation and it decreases to reach up 74% under T3 of field capacity stress in comparison with control stress. Similar results were shown for dry matter production. Upon re-watering, 70% field efficiency was achieved. For WUE, highest value of irrigation and total water use efficiency for both grain and dry matter were recorded to the T2 hydrous stress.

Key words: CROPWAT, quinoa, evapotranspiration, scheduling irrigation, yield, WUE

Introduction

Water deficit stress in soil is the biggest challenges in arid and semi dry regions due to the increase of temperature (Riadh et al., 2011). The main reason remains the reduction in rainfall and increased rate of evapotranspiration together with improper management of water resources (FAO 1992). In this context, it is important to have a rearrangement in cropping systems. The best approach is to stick with tolerant species which can tolerate various stresses and adaptable to unfavorable situations (Allen et al., 1998).

Quinoa (*Chenopodium quinoa* Willd.) can be a good candidate in cropping in marginal agricultural areas due to its abiotic stress tolerant characteristics (Garcia, 2003). In the light of predicted water scarcity and salinity all over the world, the adoption to these type of crops is promising (Garcia et al., 2003). It is a nutritious grain with all the essentials, trace elements, and many vitamins (Marica & Cuculeau, 1999; Smith, 1992). Recently, quinoa attracted interest all over the world (Andarzian et al., 2011).

There are many stress tolerant mechanisms operating quinoa, including drought escape,

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*Corresponding Authors

Dalel Telahigue

Dry lands and Oases Cropping Laboratory, Arid Area Institute (IRA), Medenine 4119, Tunisia

Email: telahigue_dal@yahoo.fr

tolerance and avoidance (Addiscott et al., 1995; Power, 1993). The exact modeling of water stress-crop response in quinoa is needed to increase its usability in marginal land like the one developed by FAO recently, which includes the decision support tool in planning and scenario analysis in different seasons and locations (Nain & Kersebaum, 2007; Salazar et al., 2009; Andarzian & Ayeneh, 2008). Quantitative scheme, CROPWAT 8.0 is good for the prediction of growth, development, and yield of a crop.

This study was conducted with an aim of testing quinoa cultivars to areas characterized by recurrent drought by the calibration of CROPWAT model and field measurements.

Materials and methods

Study area and location and experimental details

The field experiments were carried out on june 19th 2015 in the Arid Area Institute (IRA), located at el FJE Medenine (33°03' N; 10°38' E) in south-east Tunisia (Fig. 1). The experimental site shows typical arid climate characteristics with a minimum and maximum air temperature respectively ranging from 7.5°C to 18.5°C and 35 °C to 45°C. The annual rainfall varies between 100 mm and 200mm (Riadh et al., 2011). Five quinoa's cultivars were used in this study. The seeds were introduced from Egypte DRC (Desert Research Center- Caire); cultivars and their origin were presented in the Table 1.

The experiment was conducted using split lot design with water stress as a major factor and cultivar as a secondary factor. The surface of each elementary parcel is 4 m2, consisting of 3 lines of 5m long, separated by a space of 40cm. The plots of the five cultivars are arranged randomly, side by side, spaced 70 cm apart. Drought stress is consisting of three stress levels: The first treatment consists in delivering 100% of the evapotranspiration water, thus bringing the soil back to the field capacity (100% ETc). The other treatments consist in delivering only 60% and 30% of the quantities given for the T100ETc treatment respectively for T60% ETc and T30% ETc throughout the growing season. Irrigation was done by drip with a 40 mm polyethylene pipe delivering water from the tap into different drip lines. The spacing between the rails is 50 cm, and between two dripper units is 40 cm. The rated flow of the self-regulating dripper is 4 l/h. The amount of water by each dripper is 20 mm /h. The application of the stress was by varying the interval of irrigation, the drip lines that were to be irrigated were opened while those not to receive irrigation were closed using a gate valve installed on each branch leading from the PVC pipe.

Table 1. Quinoa cultivars and their origins.

Cultivar	Origins
C2 : KVL-SRA-2	Danemark
C3 : KVL-SRA-3	Danemark
C4 : Regalona	Chile
C5 : Q-37	Chile
C6 : Q-52	Chile

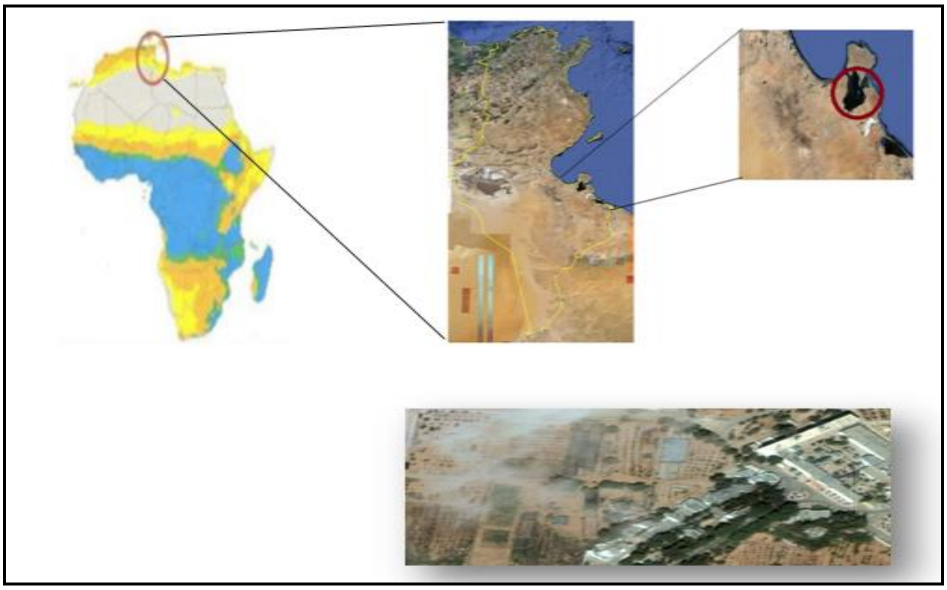


Fig. 1. Location of field experiment, Arid Area Institute (IRA) El Fjé, southern Tunisia (33°03' N; 10°38' E).

The fertilization consisted of a homogeneous supply of 5 t/ha organic matter before planting. As for mineral fertilization, it was conducted according to the practices adopted for quinoa cited in the bibliography. Inputs were 225 kg / ha of nitrogen, 280 kg / ha of phosphate and 280 kg / ha of potash for all water treatments. P and K fertilizers were brought before planting; nitrogen was fractionated and delivered to the irrigation water during the period from emergence to branching.

Crop water requirement and irrigation scheduling was calculated using CROPWAT.8 for Windows.

CROPWAT Model

CROPWAT for Windows is a decision support system developed by the Land and Water Development Division of FAO, Italy with the assistance of the Institute of Irrigation and Development Studies of Southampton, UK and National Water Research Center, Egypt. CROPWAT model includes a simple water balance model that uses the FAO Penman-Monteith method for calculating reference crop evapotranspiration (FAO, 1992; Marica & Cuculeau, 1999; Smith, 1992).

Data collection and analysis

Climatic data required for model as input include maximum and minimum temperature (˚C), evapotranspiration (mm/day) and rainfall (mm).

However, for determination of evapotranspiration the humidity (%), wind speed (km/day) and sunshine duration (hours) data is required. All the required climatic data was collected from automated meteorological station installed inside the field which is an automatic recording station (Data logger CR510 Campbell Scientific) (Table 2).

Reference evapotranspiration (*ETo*) was estimated using the meteorological data and the FAO version of the Penman-Monteith (FAO, 1998).

Soil and water data were obtained from Arid Area Institute Eremology and Combating Desertification Laboratory. The soil consists of 81% sand, 6 % clay and 13% silt and has low organic matter content (< 8 g/kg). Soil pH values range between 7.23 and 7.5. The initial soil ECe ranges between 3.4 dS/ m and 3.9 dS/m.

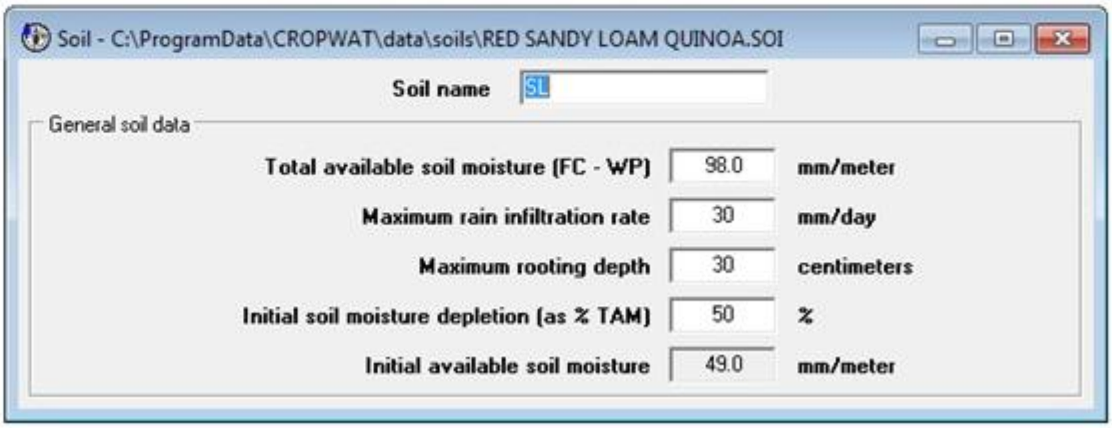
The soil model requires the following data: total available water (TAW), maximum infiltration rate, maximum rooting depth, initial soil moisture depletion (Fig. 2). The following crop data are necessary for CROPWAT: crop name, planting date, crop coefficient (K_c), stages length, rooting depth (Z_r), critical depletion fraction (*p*), yield response factor (K_y), maximum crop height. For K_c, Z_r and the soil water depletion factor *p* we have choose those used for a typical quinoa cultivar *p* derived by Garcia et al. (2003) and Garcia (2003) (Table 3).

Table 2. Monthly average maximum and minimum temperature, humidity, wind speed, sunshine duration, total rainfall and evaporation, el Fjé (2015).

Month	Temperature(°C)		Humidity (%)	Wind speed (Km/day)	Sunshine duration (h)	Rainfall (mm)	Evaporation (mm/day)
	Min	Max					
January	8.8	20.8	59	13	6	2.0	1.08
February	8.0	22.9	55	10	7	49.0	1.66
March	8.7	20.0	68	14	9	43.2	2.45
April	12.4	26.0	56	11	9	0.6	3.30
May	14.4	27.6	57	10	10	18.6	4.03
June	18.5	31.2	58	10	12	0.0	4.95

Table 3. Crop growth stages and crop parameters for quinoa (crop coefficient (K_c), stages length, rooting depth (Z_r), critical depletion fraction (p), yield response factor (K_y))

Growth stage	Length (day)	K_c	K_y	Z_r (m)	p
Initial	15	0.14	1.00	0.1	0.67
development	50	$K_{c.ini} \rightarrow 1.00$	0.8	$0.1 \rightarrow 0.3$	0.67
Mid-season	50	1.00	0.5	0.3	0.67
Late season	45	$1.00 \rightarrow 0.60$	1.05	0.3	0.67



Soil name: SL

Total available soil moisture (FC - WP): 98.0 mm/meter

Maximum rain infiltration rate: 30 mm/day

Maximum rooting depth: 30 centimeters

Initial soil moisture depletion (as % TAM): 50 %

Initial available soil moisture: 49.0 mm/meter

Fig. 2. CROPWAT model inputs soil data.

To study the response of the five quinoa cultivars to water stress plants of each individual plot were harvested by hand to determine grain yield, final dry matter production (stems + leaves), and 1000-grain weight. The dry matter of the aerial part was determined after drying in an oven at 70 ° C for 48 hours.

Irrigation monitoring and yield data were used to assess water use efficiency (WUE) as the ratio of yield (grain and dry matter) to rainfall and irrigation water of quinoa under the effect of three level of hydrous stress:

$$WUE\ (kg/ha/mm) = \frac{\text{Yield (kg/ ha)}}{\text{Providing Water (mm)}}$$

For the analysis of the WUE results, we considered the effect of water stress only.

Statistical analysis was done by ANOVA followed by means separation using Duncan's multiple range t-test at $P < 0.05$.

Result and discussion

Quinoa water requirement

Evapotranspiration of quinoa

All meteorological data were obtained from the meteorological station in El Fjé during 2015 season. CROPWAT was used to calculate the average monthly reference evapotranspiration (ET0) values using the Penman-Monteith method. The planting of quinoa takes place in January; this period from January to February is characterized by a low evaporative demand that ranged between 1.08mm/day and 1.66 mm/day and then increase to reaches 5mm/day at the end of the growing season.

Regression analysis between the evolution of crop evapotranspiration (ETc) and reference evapotranspiration (ET0) of quinoa crop during the growing period shows a similar trend during the recording period (Figure 3). The reasons might be the solar radiation, air humidity and wind speed (Monteith, 1981; Raupach, 2001; Allen et al., 1998).

Development of CROPWAT illustrates the variation of quinoa crop factor (Kc) during the growing period from January to June, it varies from 0.14 during initial stage to reach a maximum during mid-season with 0.94 and it decreases during late season (0.56) (Fig. 4). The crop facto is influenced by irrigation methods and production practices such as intervals, ground cover at full growth stage and the wetted area (Augustin et al., 2015).

The effective rainfalls calculating using CROPWAT was 109.5 mm which is far less than crop water requirements (287.2mm). This proves the necessity off irrigation in the study area due to the unguaranteed reliability and distribution of the effective rainfall.

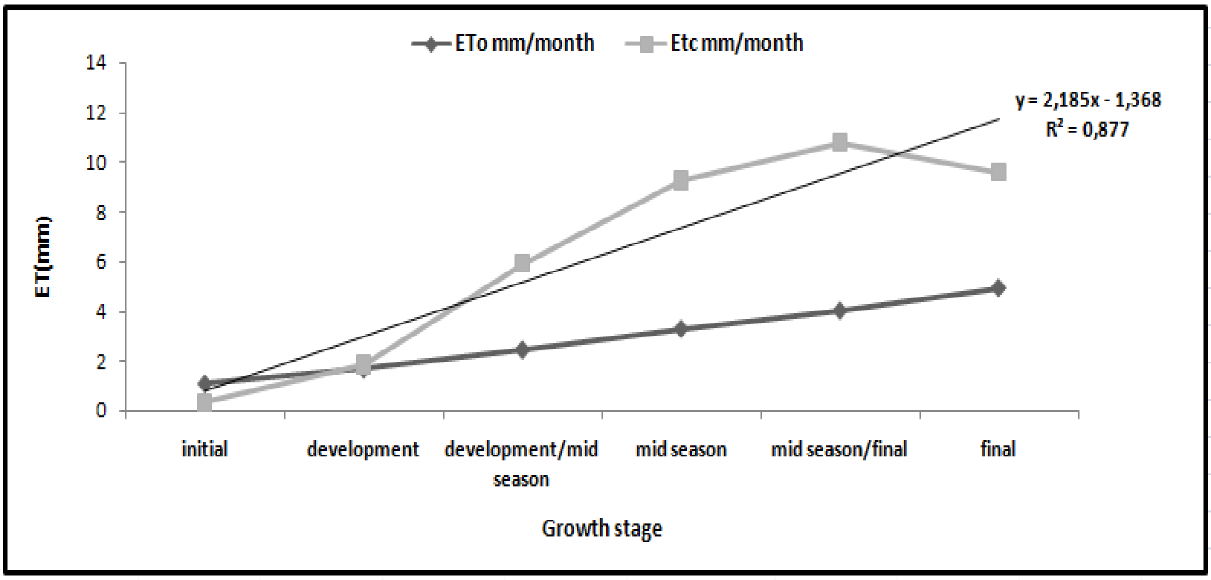


Fig. 3. Crop evapotranspiration ETc and reference evapotranspiration ETo of quinoa crop during the 2015 season.

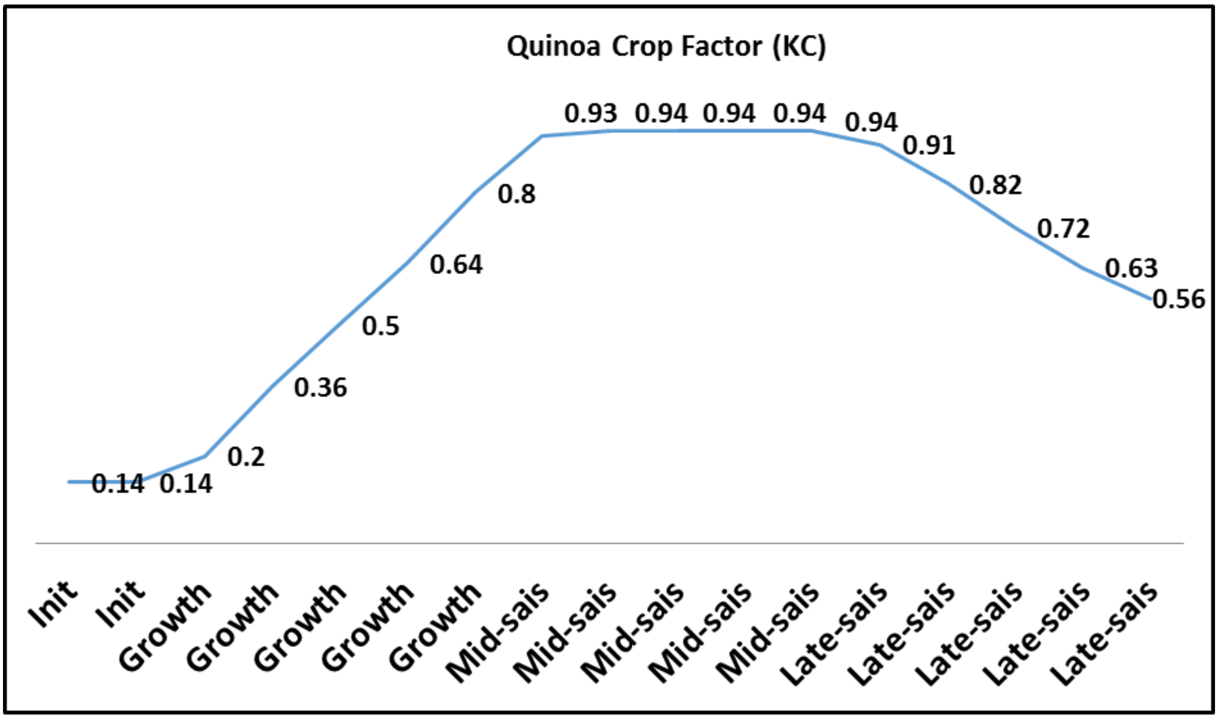


Fig. 4. Variation of quinoa crop factor during the growing period from January to June.

Soil water balance

The figure 5 illustrates the effect of an increasing root zone on the readily available water (RAW). The soil water depletion may exceed the allowable limit for triggering irrigation therefore plants could be, occasionally, subject to a slight stress on the day prior to irrigation. This is because irrigations are applied only when the drying up of water in the root zone at the end of the previous day is above or equal to the permissible limit for triggering irrigation. Each time the irrigation water is applied, the root zone is replenished to field capacity. Generally, the irrigation will be frequent during peak periods when the crop water demand is high and rainfalls are low from March to June for this study.

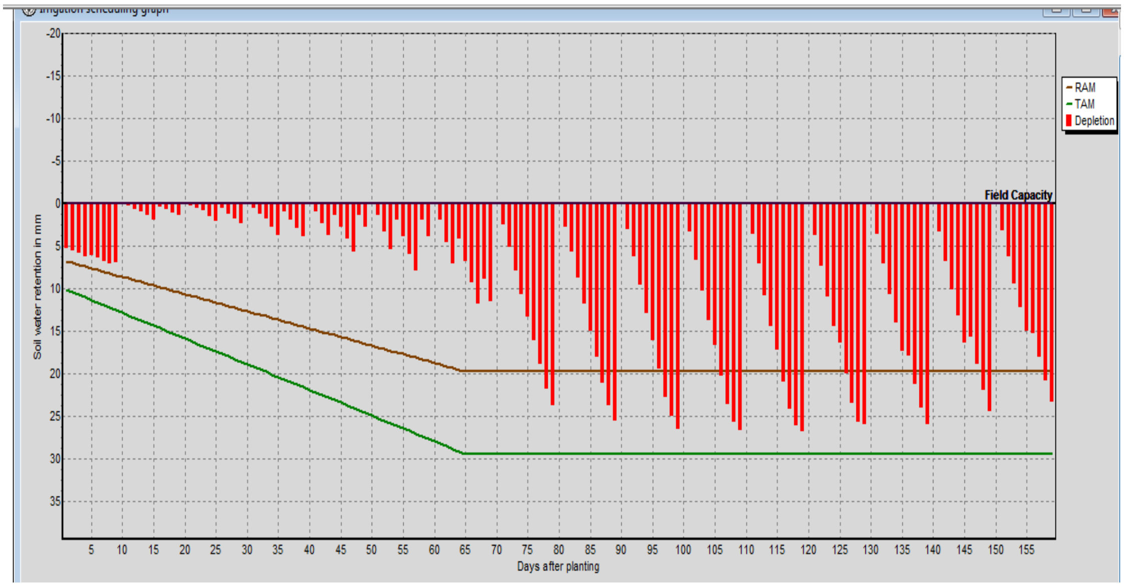


Fig. 5. Soil water depletion of irrigated quinoa crop at 100% ETc during the 2015 season.

Table 4. Amount of irrigation water (IW) provided during growth phases under full and deficit irrigation.

Growth stage	Irrigation interval (day)	Number of application	Irrigation rate (mm)	Rainfall (mm)	IW(mm) T100%ETc	IW(mm) T60%ETc	IW(mm) T30%ETc
Initial	10	2	6-13	2	10.4	10.4	10.4
Development	10	6	1-8	92	17	10 .2	5.1
Mid-season	10	6	20-48	6.3	173 .4	104	52
Final	10	3	34-49	18	148	88 .8	44.4
Total	-	15	-	118.3	348.9	209.3	104.6

Irrigation schedule

Crop water requirements are affected by rainfall, temperature, humidity, wind speed and radiation. A high intensity of irradiation results in a high rate of water evaporation from soil and plant surface. CROPWAT develops an irrigation schedule that enabled us to determine the number of irrigations, irrigations intervals and the water irrigation requirements during the growth stages of quinoa crop under arid climate of the experimental site (Table 4).

The gross irrigation requirements expressed in mm/month are: 10.4 (January), 2.6 (February), 34.4 (March), 113.9 (April), 118.1 (May), 69.4 (June).

The quantities of water introduced during the initial stages of development for T100%ETc, T60% ETc and T30% ETc is the same (10.4 mm) to ensure startup culture. For the deficit treatments, irrigations were applied to the same frequency as the T100%ETc treatment, but with reduced amounts of 60% and 30% of the ETc. For all treatments, total water requirements (rainfall and irrigation) supplies are, respectively, 348.9 mm, 209.3 mm and 104.6 mm, for the T100% ETc treatment, T60% ET and T30% ETc. The water economies recorded for deficient treatments in comparison with the full irrigation regime are about 40% and 70% respectively for T60% ETc and T30% ETc.

Effect of hydrous stress on yield of five quinoa cultivars

1000 seeds weight

According to table 5 and figure 6, the 1000 seeds weight depends on cultivar and it ranges from 1.7 g (KVL-SRA) to 2.6g (Q-37) under T100% ETc.. Rojas (2003) showed that, using germplasm preserved in Bolivia, 1000 grain weight varies between 1.2 g and 6 g under non-stress conditions.

The 1000-grain weight decreases significantly with water stress ($p < 0.01$) (table 6). We can also notice a slight increase of 1000 seeds weight for the two cultivars KVL-SRA2 and Q-52 under T30% ETc stress (figure 6). The minimum average is recorded to KVL-SRA3 cultivar with 1.4g (T30%ETc).

Table 5. Two-way ANOVA to evaluate the effect of cultivar and drought stress on 1000 seeds weight (1000SW), grain yield (GY) and dry matter production (DM) of quinoa crop.

Source	Parameters	df	Mean square	F	Sig.
Cultivar (C)	1000SW	4	0.344	8.676	0.000
	GY(Kg/ha)	4	2178059.078	160.905	0.000
	DM(Kg/ha)	4	6189555.927	748.505	0.000
Treatment (T)	1000SW	2	0.287	7.241	0.003
	GY(Kg/ha)	2	1795129.622	132.616	0.000
	DM(Kg/ha)	2	4039224.562	488.465	0.000
C×T	1000SW	8	0.120	3.3039	0.13
	GY(Kg/ha)	8	255152.261	18.849	0.000
	DM(Kg/ha)	8	438893.457	53.076	0.000

Effect of drought stress on grain yield

Drought stress treatments significantly decreased grain yield and yield components (Table 6). Well-watered plants had a significantly higher grain yield than mildly and severely-stressed plants ($P<0.001$). For fully irrigated plants, the yield is between 270 kg /ha and 2092 kg/ha. The most productive cultivars are ascending C6, C5 and C3 with respectively 2092 kg/ha, 1330 kg/ha and 717 kg/ha. The least productive are C4 and C2 with respectively 499 kg/ha and 270 kg/ha (Fig. 7). Razzaghi et al. (2011) reported 3.3 t ha/1 yield from quinoa cultivar Titicaca under non stress.

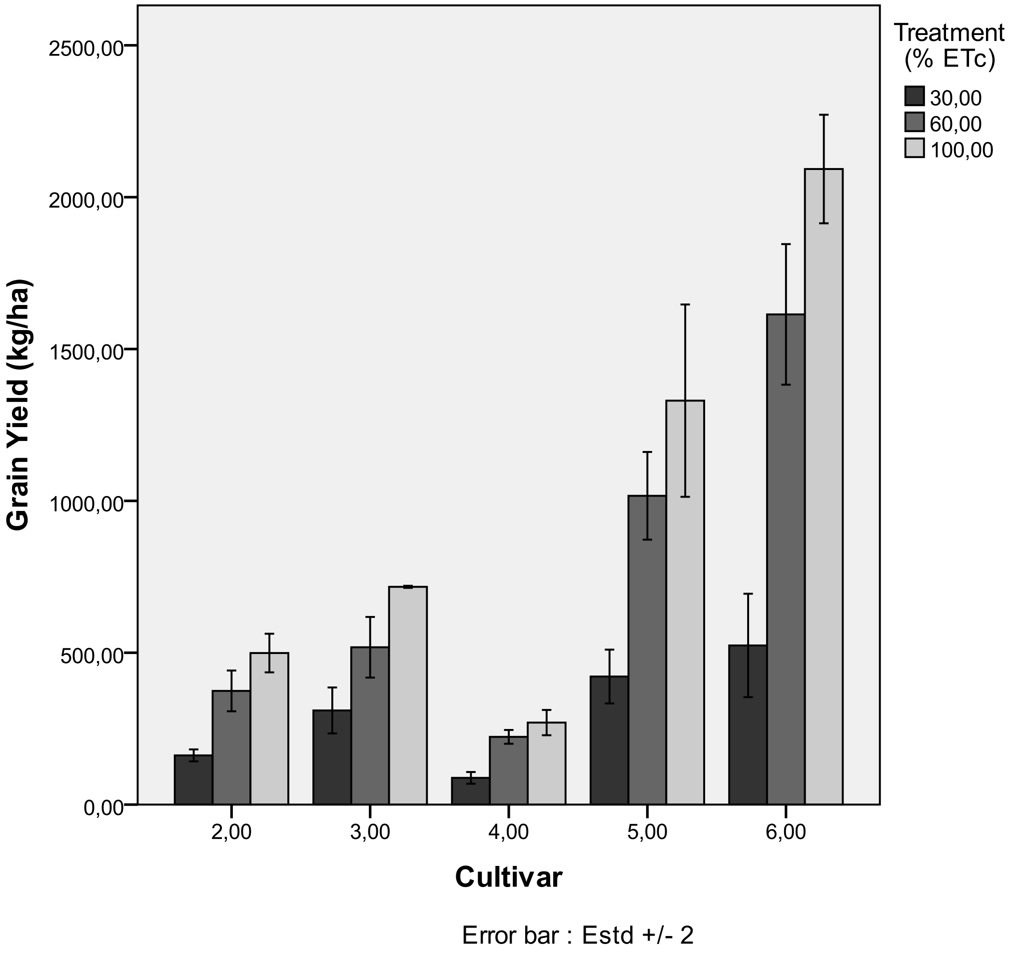


Fig. 7. Mean yield of 5 quinoa's cultivars (C2,C3,C4,C5,C6) under three drought stress (T100% ETc,T60% ETc,T30% ETc), vertical lines represent standard error.

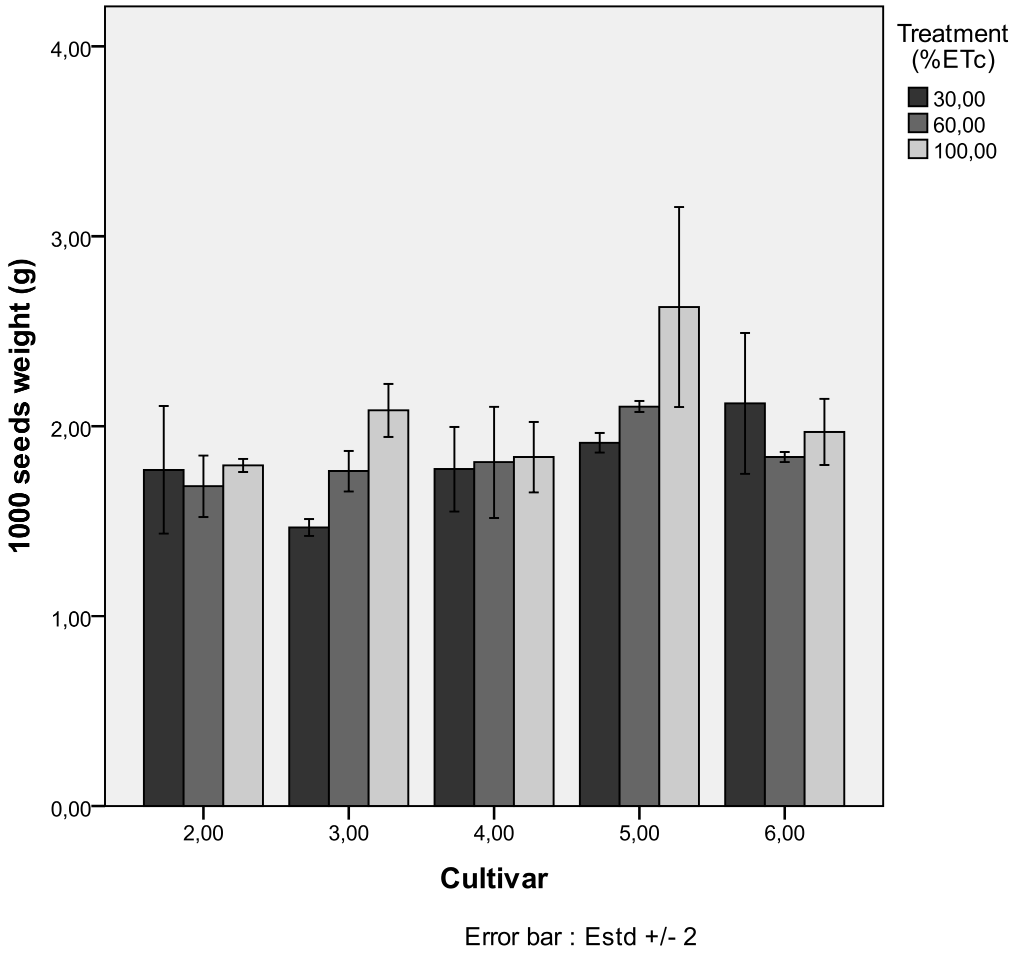


Fig. 6. Mean 1000 seed weight of 5 quinoa's cultivars (C2,C3,C4,C5,C6) under three drought stress (T100%ETc,T60%ETc,T30%ETc, vertical lines represent standard error.

Under T2, the reduction of yield of the five quinoa cultivars is not exceeding 27% in comparison with non-stressed plants. A more pronounced yield reduction was observed with the stress T3, it reached up to 74% for the cultivar C6 compared to controls.

The interaction between the cultivar and the treatment is very significant for yield per hectare (P <0.001). In fact, most studies in many crop species (barley, maize, rice, sunflower, potato....) reported that drought induced yield reduction which depends upon the severity and duration of the stress period (Samara, 2005; Monneveux et al., 2006; Lafitte et al., 2007; Mazahery et al., 2003; Kawakami et al., 2006).

Effect of hydrous stress on dry matter production (stems + leaves)

The stem and leaves dry matter production of the five quinoa cultivars cultivated under drought stress is given in Figure 8. The Table 5 shows that dry weight is significantly affected by both hydrous stress (P=0.000), cultivar (P=0.000) and interaction between cultivar and treatment (P<0.001).

Table 6. Water Use Efficiency of irrigation (IWUE) and total water (irrigation+ rainfall) (WUET) of grain yield and dry matter production (DM) of quinoa under three water regimes.

Water stress	WUEI (grains) (kg/ha/mm)	WUET (grains) (kg/ha/mm)	WUEI (DM) (kg/ha/mm)	WUET (kg/ha/mm)
100% ETc	2.814^{a}±0.154	2.101^{b} ±0.088	4.481^{a} ±0.126	3.346^{b} ±0.071
60% ETc	3.580^{b}±0.154	2.287^{b} ±0.088	5.612^{c} ±0.126	3.585^{c} ±0.071
30% ETc	2.879^{a} ±0.154	1.351^{a} ±0.088	5.121^{b} ±0.126	2.403^{a} ±0.071

Under non stress conditions, the highest total dry matter yield was registered with the two cultivars Q-52 and Q-37 with respectively 2953.43 ± 52.5 kg / ha and 2710.13 ± kg / ha.

The dry biomass registered under stress conditions have significantly decreased. This reduction varies between 16% (C4) and 30% (C3) under medium water stress and it reaches the 73% for the same cultivars under T30%ETc stress.

Variations in the response to drought stress could be attributed to the rusticity of quinoa crop, in fact, this specie exhibits a strong variability for cultivar-specific responses to environmental variation (Pulvento et al., 2010; Fuentes & Bhargava, 2011; Burrieza et al., 2012).

Crop water use efficiency (WUE)

WUE is the ratio of crop yield to the amount of water taken up and used for crop growth. Values of water use efficiency (irrigation and irrigation+ rain) of grain yield and dry matter yield (stems + leaves) under the three water regimes are shown in table 6.

Proper and optimal scheduling of irrigation using CROPWAT 8.0 enabled the efficient water use to 70% with only 9.6% reduction of grain yield

The highest values of irrigation and total water use efficiency for grain and dry matter was recorded to the T60%ETc hydrous stress, this is because the reduction of yield is about 24% and the water economy is 40%.

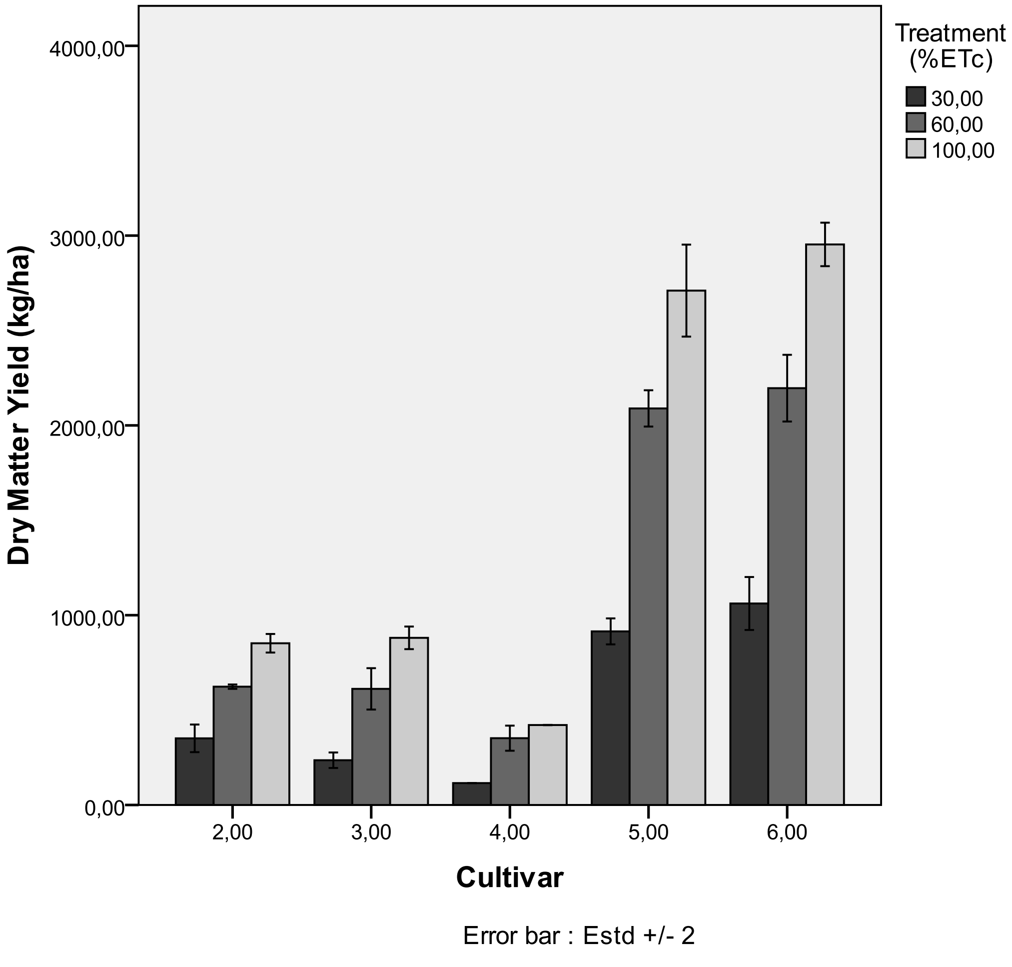


Fig. 8. Mean Dry Matter production of 5 quinoa's cultivars (C2,C3,C4,C5,C6) under three drought stress (T100% ETc,T60% ETc,T30% ETc), vertical lines represent standard error.

For the full irrigation (T100%ETc), we have recorded the lowest irrigation water use efficiency due to the amounts of water applied to the crop. The T30%ETc stress which is accompanied by a pronounced fall in yield has the lowest total EUE averages.

These results show that the irrigation water requirements of quinoa can be reduced without a significant reduction in yield by adopting deficit irrigation. Similar results have been proved for barley (Nagaz et Ben Mechlia, 1998, 2000).

Conclusion

Meteorological and sol data of the experimental were used to calculate net irrigation requirements and to develop scheduling of irrigation for quinoa using CROPWAT 8.0. The analysis of the water requirements revealed the necessity off irrigation in the study area due to the unguaranteed reliability and distribution of the effective rainfall essentially from March to Jun when crop requirements for water is most important and when irrigation is essential.

The yields of the various cultivars appear to be quite promising for the region. Q-37and Q-52 seems to be the most interesting for the production and adaptation under water stress. Results showed also that with water management (how much and when irrigate) we can detect stress of the crop to determine timing related to quantity and stress threshold, we can also impose stress with less risk.

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Author contribution

All authors contributed equally in the present study. All authors approved the final version of the manuscript for publication.

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