Using deficit irrigation with treated wastewater in the production of quinoa (*Chenopodium quinoa* Willd.) in Morocco

El uso de riego deficitario con aguas residuales tratadas en la producción de quinua (*Chenopodium quinoa* Willd.) en Marruecos

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ABSTRACT

Scarcity of water resources and growing competition for water, reduce water availability for irrigation. In this experiment which was carried out in the south of Morocco, treated wastewater was used as an alternative resource for irrigation of quinoa (*Chenopodium quinoa* Willd.). During the first season (2010), six deficit irrigation treatments were applied during all crop stages on DO708 cultivar alternating water stress level at either 100 or 50% of ETm (maximal evatranspiration), while during the second season (2011), three deficit irrigation treatments 100, 50 and 25% were applied only during vegetative growth stage on two quinoa cultivars DO708 and QM1113. The highest water productivity was obtained when deficit irrigation was applied during the vegetative growth stage. Applying 50% of ETm during first season and second season resulted in highest yield. The most sensitive growth stage of quinoa to drought stress was the seed filling stage, and during this stage it is recommended to supply water to avoid yield and water productivity decrease. Combining deficit irrigation strategy, engineering solution (modernization of the irrigation systems, soil moisture monitoring), and the reuse of treated wastewater for irrigation, could improve water productivity of this drought tolerant crop under conditions of limited water resources.

Key words: Drought stress, water productivity, leaf area index, salinity, yield

RESUMEN

La escasez de recursos hídricos y la creciente competencia por el agua reduce la disponibilidad de agua para el riego. En este experimento que se llevó a cabo en el sur de Marruecos, el agua residual tratada se utilizó como un recurso alternativo para el riego de quinua (*Chenopodium quinoa* Willd.). Durante la primera temporada (2010), se aplicaron seis tratamientos de riego deficitario alternando 100 y 50% de la ETm (evapotranspiración máxima) durante todas las etapas del cultivo en el cultivar DO708, mientras que en la segunda temporada (2011) se aplicaron tres tratamientos de riego deficitario 100, 50 y 25% sólo durante la etapa de crecimiento vegetativo en dos cultivares de quinua DO708 y QM1113. La mayor productividad del agua se obtuvo cuando se aplicó el riego deficitario durante la etapa de crecimiento vegetativo. Un tratamiento de riego deficitario con 50% de la ETm durante la primera y la segunda temporada registró la mayor productividad del agua. La etapa de crecimiento más sensible de la quinua al estrés hídrico fue la etapa de llenado de la semilla y durante esta etapa se recomienda el suministro de agua para evitar la disminución del rendimiento y reducir la productividad del agua. La combinación de la estrategia de riego deficitario, solución de ingeniería (modernización del sistema de riego, sensores de humedad del suelo) y la reutilización de aguas residuales tratadas para el riego, podría mejorar la productividad del agua de este cultivo tolerante a la sequía bajo condiciones de los recursos hídricos limitados.

Palabras clave: Estrés hídrico, productividad del agua, índice de área foliar, salinidad, rendimiento

INTRODUCTION

A sustainable food production will depend on the judicious use of water resources as fresh water for human consumption and agricultural water is becoming increasingly scarce, so we have to look for other water resources to satisfy this water deficit (Smith, 2000). One of the major constraints to development of southern Mediterranean countries is the limited water resources (Bennouna and El

Nokraschy, 2009). This is also the case in the south of Morocco in Agadir, where the present experiment took place. It is considered the most productive region of the country in terms of horticultural products (EACCE, 2009). About 75% of the vegetables are cultivated in greenhouses. Annual cumulative precipitation is 250 mm falling in the winter months of October, November and December (Villeneuve, 2007). The water situation in the region is becoming critical because of overexploitation of ground water resources (Baroud and El Fasskaoui, 2008). Treatment of domestic wastewater and reuse is becoming an important field of research, especially in arid, semi-arid areas where water scarcity is increasing due to continuously increase in water demand among various sectors of society. Hence, the decreasing water availability for agricultural irrigation has become a limiting factor for food production in many countries (Finley *et al*., 2009). Morocco has implemented several strategies to improve water resource management by increasing irrigation efficiency, prevent water pollution, and reuse of wastewater. The quantity of wastewater in Morocco was about 600 10^6 m^3 in 2008, and this quantity is estimated about 900$10^6$ m^3 in 2020 (Choukr-Allah, 2009).

It is widely believed that an increase in agricultural water productivity is the key approach to mitigate water shortage and to reduce environmental problems (Ali and Talukder, 2008), but there is a range of biochemical, physiological, agronomical and ecological processes that may affect water productivity (Passioura, 2006). Deficit irrigation strategy (DI) has been widely investigated as a valuable and sustainable production strategy in dry regions. By limiting water applications to drought-sensitive growth stages, this practice aims to maximize water productivity and to stabilize, rather than maximize, yields (Geerts and Raes, 2009). The potential benefits of deficit irrigation derive from three factors: increased irrigation efficiency, reduced costs of irrigation and the opportunity costs of water (English and Raja, 1996).

Quinoa (*Chenopodium quinoa* Willd.) comes from the Andean highlands of South America, where it is grown at altitudes of more than 3000 m above sea level in Bolivia and Peru. It has a high nutritional value of protein, vitamins and minerals (Repo-Carrasco *et al*., 2003), and it is drought (Jensen *et al*., 2000; Garcia *et al*., 2003; 2007; Jacobsen *et al*., 2009), frost (Jacobsen *et al*., 2005; 2007; Bois *et al*., 2006), and salt (Jacobsen *et al*., 2001; Jacobsen, 2009; Hariadi *et al*., 2010) tolerant plant, and in general rustic (Bertero *et al*., 2004; Jacobsen *et al*., 2003). There are some experiences with the crop in Morocco aiming to adapt this new crop as alternative crop to wheat (Benlhabib, 2005, Hirich *et al*., 2012a,b).

This experiment aimed to test the effect of deficit irrigation on crop productivity using treated wastewater as a source of irrigation water.

MATERIALS AND METHODS

Experiment implementation

The experiment was performed on the Institute for Agronomy and Veterinary Medicine HASSAN II farm in Agadir (30°35’ N, -9°47’ E, 3 m.a.s.l) in 2010 and 2011. Soil type was loamy with a pH of 8.3 and ECe (soil electrical conductivity) of 0.17 dS/m. The soil was moderately rich in organic matter (1.6%), field capacity humidity (FC_{RH}) was 30%, and permanent wilting point humidity (PWP_{RH}) 15%. The irrigation water used was treated domestic wastewater (Table 1), very rich in nitrogen (since 1000 m^3 can provide 22 kg of N), with ECw equal to 1.4 dS/m and pH 7.8. According to the nutrient content in this water, most of the fertilizer requirements of the crop can be covered. In terms of microbiological analysis, the irrigation water remains within the standards of the World Health Organization (WHO, 2006).

Table 1. Chemical and micro-biological characteristic of the irrigation water at Agadir, Morocco.

Chemical characteristics	Content in mg l^{-1}
NH_4^+	64.8
NO_3^-	99.2
P	15
K	8.19
Ca	66.8
Na	51.29
Cl	101.5
Mg	39.6
Total suspended matter	55.46
Suspended mineral matter	29.2
pH	7.77
EC	1448 (uS cm^{-1})
Micro-biological characteristics	**Content in 100 ml of water**
Total coliform	133 (<1000)
Fecal coliform	240 (<1000)
Fecal streptococci	250 (<1000)
Helminth eggs	0

Experimental units (18 m^2) were organized in a completely randomized design with 24 plots. Inside plot there were 5 sowing lines, a distance of 50 cm between lines and 20 cm between sowing holes.

Differences between response variables to deficit irrigation treatments were assessed with a general linear model in the StatSoft STATISTICA 8.0.550 software. Statistical differences was significant at $\alpha = 0.05$ or lower.

First season (2010)

Quinoa growing period was between February and July 2010, with a semi-arid to arid climate. A quinoa cultivar DO708 was sown on 25 February 2010. Six treatments and four replications for each treatment have been adopted as shown in the Table 2. All treatment received full irrigation during initial stage (20 days after sowing).

Second season (2011)

In this trial two cultivars were tested: DO708 and QM1113, sowing date was in 1st April 2011 and growing period was between April to mid July. In this season only 3 deficit irrigation treatments were used in combination with 2 cultivars, that is total of 6 combinations.

Deficit irrigation treatments were carried out taking into consideration the results of the first season 2010 in order to confirm those results. Treatment were applied only during the vegatative growth stage while during germination, flowering and grain filling all treatments received full irrigation. Table 3 shows the treatments adopted.

For irrigation application, a dripper of 4 Lhr^{-1} was installed to supply 100% of ETm, 2 Lhr^{-1} to supply 50% of ETm and 1 Lhr^{-1} to supply 25% of ETm.

Soil moisture control: installation of the telemetry system

The water quantity required by each treatment was supplied, as any control loss in treatment application or soil moisture sensing will affect negatively the experiment results. Two kinds of telemetry system, short and long range telemetry (Figure 1a) were installed in control plot at 10 cm away from plant an dripper. The short range telemetry is based on the installation of a capacitance based continuous logging probe (AquaCheck Wireless Probe ACBIIW) in the control plot (Figure 1 b1). These sensors can be controlled by a mobile datalogger (AquaCheck BII Logger) (Figure 1 b2) which collects data automatically, from a maximum of 6 depths (10, 20, 30, 40, 50 and 60 cm). In each soil depth soil moisture and temperature were recorded, the data downloaded can be transferred to the computer in which they can be analyzed by a special program named CropGRAPH.

In the long range telemetry a fixed sensor with analogical output was used (Fig. 1 b3), combined with other sensors for monitoring climate or plants. The communication was made in two different ways, by radio from the field to the server and by GPRS (General Packet Radio Service) that offer unlimited access to data via the internet where the graphs related to the soil moisture was showed and treated by a program named addVANTAGE Pro 5.4.

Table 2. Irrigation treatments in 2010 (% of ETm) of quinoa (*Chenopodium quinoa* Willd.) cv. DO708 at Agadir, Morocco.

Treatment	Germination	Vegetative growth	Flowering	Seed filling	Senescence
T1 (control)	100	100	100	100	0
T2	100	50	50	50	0
T3	100	100	50	100	0
T4	100	100	100	50	0
T5	100	50	100	100	0
T6	100	50	50	100	0

Table 3. Irrigation treatments in 2011 (% of ETm) of two quinoa (*Chenopodium quinoa* Willd.) cultivars at Agadir, Morocco.

Quinoa cultivars	Treatment	Germination	Vegetative growth	Flowering	Seed filling	Senescence
DO708 QM1113	T1	100	100	100	100	0
	T2	100	50	100	100	0
	T3	100	25	100	100	0

Irrigation scheduling

Calculation of irrigation volume and frequencies

To calculate irrigation requirement, four approaches related to soil, climate, crop and irrigation system, have been used. From the soil approach the net maximal dose (NMD) expressed in mm was (Elattir, 2005),

$$NMD = f \times (FC_{RH} - PWP_{RH}) \times Z \times \%\ SH$$

where:

f: allowable depletion = 10%

FC_{RH} : humidity at field capacity (volumetric) = 30%

PWP_{RH}: humidity at permanent wilting point = 15%

Z: roots depth = 0.25 m

% SH: percentage of wet area = 30% (The percentage of wet area was calculated based on sowing density, distance between sowing lines and drippers, the maximal wet area (30%) was achieved when water bulbs of drippers were closes to each other)

So, NMD = 1.125 mm

Five drippers were installed per m^2 and the nominal discharge of each dripper was 2 L/h (first season), so the hourly pluviometry (PH) was: PH = 2 L/h × 5 = 10 L/h. Irrigation time (T_{irri}) required to give 1 NMD was T_{irri} =NMD/PH = 1.125/10 = 7 min, it means that to supply 1 NMD and to satisfy the allowable depletion was needed 7 min.

The net irrigation requirement (NIR) was NIR = ETm/Eff, where ETm is the maximal evapotranspiration and Eff is the system efficiency of 0.85 (drip irrigation). ETm = Kc × ETo, with crop coefficient (Kc) and reference evapotranspiration (ETo). The Kc coefficient serves as an aggregation of the physical and physiological differences between crops (Allen *et al*., 2000). ETo represents the climate approach, provided by the Institut Agronomique et Vétérinaire Hassan II, Complexe Horticole d'Agadir (IAV-CHA) weather station. It is calculated from the Penman equation (Penman, 1948) which was the first to combine energy and atmospheric vapor transport components to estimate ETo (Zhao *et al*., 2009).

The gross irrigation requirement (GIR) was GIR = ETm/Eff, where ETm is the maximal evapotranspiration and Eff is the system efficiency of 0.85 (drip irrigation). ETm = Kc × ETo, with crop coefficient (Kc) and reference evapotranspiration (ETo). The Kc coefficient serves as an aggregation of the physical and physiological differences between crops (Allen *et al*., 2000). ETo represents the climate approach, provided by the Institut Agronomique et Vétérinaire Hassan II, Complexe Horticole d'Agadir (IAV-CHA) weather station. It is calculated from the Penman equation (Penman, 1948) which was the first to combine energy and atmospheric vapor transport components to estimate ETo (Zhao *et al*., 2009).

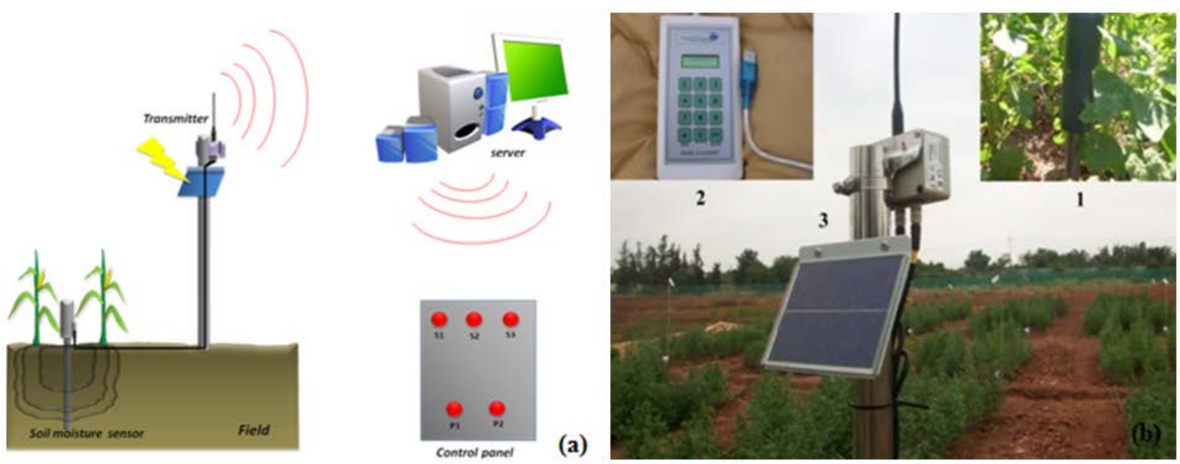

Figure 1. Long range telemetry system design (a), soil moisture sensor (b1), Data logger (b2) and soil moisture data transmitter (b3) used in the experiment of irrigation treatments of quinoa (*Chenopodium quinoa* Willd.) at Agadir, Morocco.

For example, if we yesterday had ETo = 4, and Kc = 0.95, so for irrigation today we must supply:

$$GIR = ETm/Eff = Kc \times ETo/Eff = 0.95 \times 4/0.85 = 4.47 \text{ mm}$$

Irrigation frequency is one of the most important factors in drip irrigation scheduling. Due to the differences in soil moisture and wetting pattern, crop yields may be different when the same quantity of water is applied under different irrigation frequencies (Wang *et al.*, 2005).

Frequency, F = GIR/NMD = 4.47 / 1.125 = 3.97, so we have to irrigate 3 times, 7 min each time, the rest (0.97) must be supplied next day.

Use of soil moisture sensing to schedule irrigation

Irrigation scheduling was controlled by soil moisture sensing. Soil humidity sensor was installed in a control (100% of ETm) plot, an allowable depletion of 10 % under FC_{RH} was fixed for irrigation scheduling. The major part of roots was localized around 20 cm of depth. When the soil moisture curve decreased under the allowable depletion, the irrigation supply should be increased by increasing slightly the crop coefficient, and if this curve increased the Kc should be slightly decreased.

Parameters to measure

Agronomic parameters

Measurements of agronomic parameters (roots, above ground matter and leaf area) were carried out on 4 plants per treatment at the end of each crop stage. Fresh weight of roots, stem, leaves and flowers or fruits was measured, thereafter dried at 60 °C during 48 hours.

Final harvest

Dry weight of seeds was measured using a subsample of 12 randomly selected plants per plot. After separating flowers, seeds were hand threshed.

Pedological parameters

When irrigating with treated domestic wastewater, it is necessary to analyze salinity and nitrate accumulation in the soil. If the irrigation is well controlled, it will not have an effect on nitrogen leaching, and the irrigated crops will quickly take up the nitrogen (Choukr-Allah, 1995).

Soil samples were taken before sowing (for each plot and for 3 depths, 15, 30 45 cm) for analysis of initial chemical and physical properties of the soil, and after harvesting for EC and nitrate.

RESULTS

Soil EC and Nitrate accumulation

After harvesting soil analysis was performed in each plot in order to assess environmental impacts of irrigation by wastewater, because an excess in irrigation supply can lead to soil degradation from nitrate and salt accumulation (Baumont *et al*., 2005).

First season results

A significant difference in terms of the nitrate accumulation between treatments after harvesting (Figure 2) was obtained ($p = 0.03$). The highest accumulation was obtained in the plot stressed during the whole growing period (T2) because in this treatment the water quantity required for nitrate leaching was not sufficient. Lowest nitrate accumulation was obtained in the plot fully irrigated (T1). There was no significant difference between the other treatments, with irrigation supply alternated 50 and 100% of ETm.

For salt accumulation (Figure 3) there was no significant difference between treatments, but generally the highest accumulation was obtained in

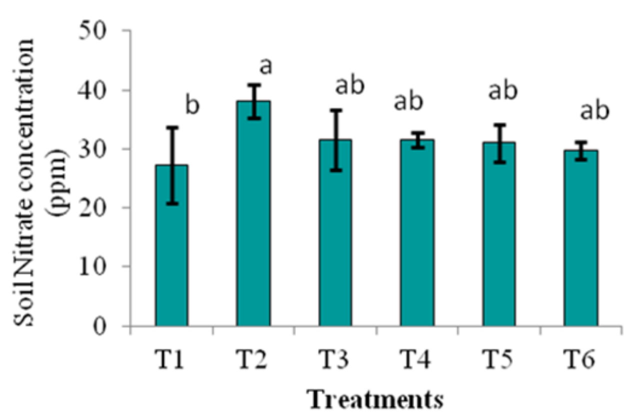

Figure 2. Soil nitrate concentration (ppm) after quinoa (*Chenopodium quinoa* Willd.) cv. DO708 harvesting of first season (2010) at Agadir, Morocco. Means with different letters are significantly different ($p<0.05$) according to Tukey test. Irrigation treatments based in % of ETm.

the plots fully stressed (T2) and the lowest salt accumulation was obtained in the plots stressed during the vegetative growth stage (T5). This can be explained again by the leaching of the salt (Hanson, 1993). The soil EC increased after the growing period from 170 to 370 μS/m for T2 and 250 μS/m for T5, but no significant difference was revealed.

Second season (2011)

There was no difference between cultivars in terms of nitrate accumulation, but a highly significant difference between treatments and the interaction cultivars x treatments ($p < 0.001$) (Figure 4). This means that the irrigation treatments affected soil nitrate concentration. Highest nitrate accumulation was recorded for cultivar QM1113 receiving full irrigation (T1), followed by cultivar DO708 receiving full irrigation (T1) and 50% of ETm during vegetative growth stage (T2). Lowest nitrate accumulation was obtained for cultivar DO708 receiving 25% of ETm during vegetative growth and cultivar QM1113 receiving 50 and 25% of ETm during the same crop stage.

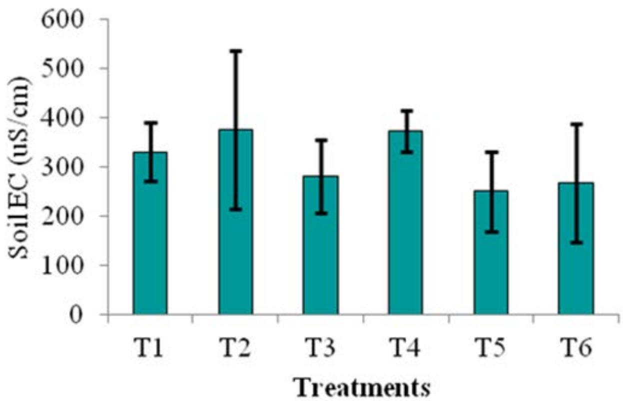

Figure 3. Soil electrical conductivity (EC) (μS/cm) after quinoa (*Chenopodium quinoa* Willd.) cv. DO708 harvesting of first season (2010) at Agadir, Morocco. Irrigation treatments based in % of ETm.

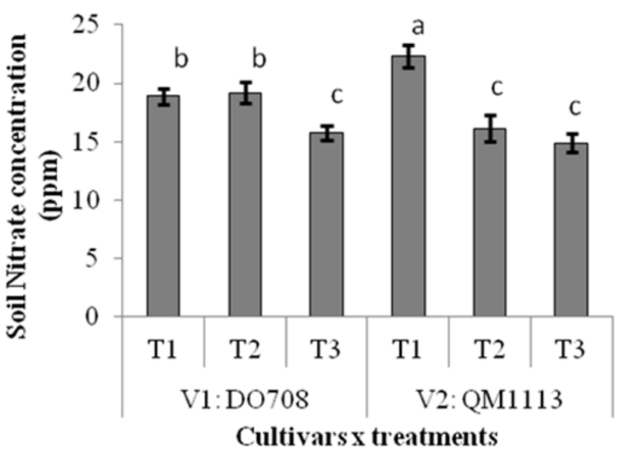

Figure 4. Soil nitrate concentration after quinoa (*Chenopodium quinoa* Willd.) harvesting of second season (2011) at Agadir, Morocco. Means with different letters are significantly different ($p<0.05$) according to Tukey test. Irrigation treatments based in % of ETm

For soil salinity (Figure 5) there was a highly significant difference ($p = 0.004$) between cultivars x treatments combinations. Cultivar DO708 receiving full irrigation (T1) showed the highest salinity accumulation followed by all treatments of cultivar QM1113 and treatment receiving 50% of ETm during vegetative growth stage of cultivar DO708.

Growth parameters

Leaf area index

First season results (2010)

There were significant differences in vegetative growth, flowering and seed filling stage, for different irrigation strategies (Figure 6).

After being well irrigated during vegetative growth, stressed during flowering (T3) showed a significant decrease in LAI while treatment stressed during vegetative growth (T5) showed a significant increase after it was subjected to full irrigation during flowering stage comparing to T2 and T6.

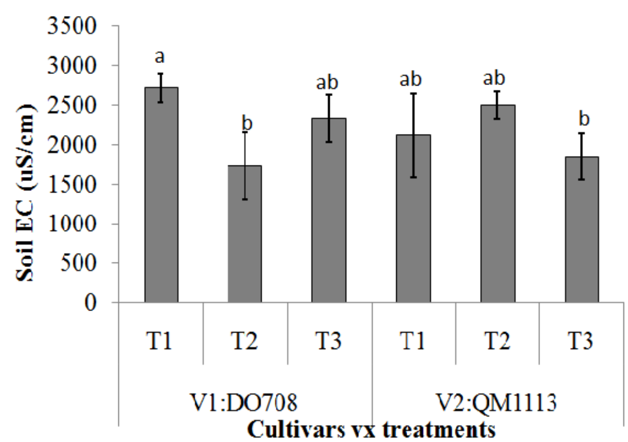

Figure 5. Soil electrical conductivity (EC) (μS/cm) after quinoa (*Chenopodium quinoa* Willd.) harvesting of second season (2011) at Agadir, Morocco. Means with different letters are significantly different ($p<0.05$) according to Tukey test. Irrigation treatments based in % of ETm

At the end of seed filling stage, leaf area of the treatment fully stressed (T2) remained the lowest one. Treatment well irrigated in this stage after being stressed during flowering stage (T3 and T6) showed an increased LAI, treatment stressed during vegetative growth (T5) showed a slightly decreased LAI.

Second season results (2011)

Cultivar QM1113 showed highest Leaf Area Index with deficit irrigation during the vegetative growth stage 6 weeks after sowing (6 WAS) (Table 4). Within the two cultivars it is the treatment receiving 50% of ETm (T2) that showed the highest LAI followed by control (T1) and treatment receiving 25% of ETm (T3).

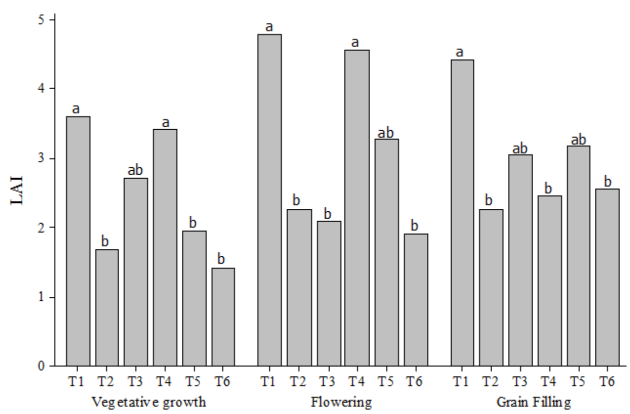

Figure 6. Leaf area index of quinoa (*Chenopodium quinoa* Willd.) cv. DO708 for each treatment of the first season (2010) at Agadir, Morocco. Means with different letters within a stage are significantly different ($p<0.05$) according to Tukey test. Irrigation treatments based in % of ETm.

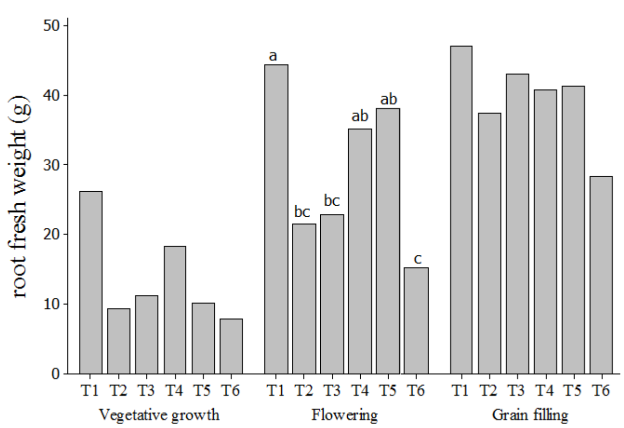

Figure 7. Fresh weight of roots (g) of quinoa (*Chenopodium quinoa* Willd.) cv. DO708 in the first season (2010) at Agadir, Morocco. Means with different letters within a stage are significantly different ($p<0.05$) according to Tukey test. Irrigation treatments based in % of ETm.

Fifteen weeks after sowing (WAS) the LAI of treatment receiving 50% of ETm during vegetative growth remained the highest comparing to other treatments and this finding was obtained for both cultivars. DO708 was able to retrieve its leaf area in the seed filling stage to be near to leaf area recorded by QM1113.

Root weight

First season results (2010)

For fresh weight of roots (Figure 7) the statistical analysis did not reveal any significant difference during vegetative growth and seed filling stage, while this difference was very highly significant ($p= 0.0008$) at the end of flowering stage. Treatment stressed during this stage (T2, T3 and T6) showed the lowest root weight.

Second season results (2011)

There was a very highly significant difference ($p < 0.001$) between DO708 and QM1113 two weeks after sowing (Table 5), QM1113 showed more root development in the initial stage, this root system development will have an effect during the rest of growing period. There was no significant difference between treatments or cultivars 6 weeks after sowing, while 15 weeks after sowing statistical analysis has not revealed any significant difference between cultivars or interactions cultivars x treatments but the difference between treatments

Table 4. Leaf area index of two quinoa (*Chenopodium quinoa* Willd.) cultivars for each irrigation treatment of the second season (2011) at Agadir, Morocco.

Cultivar	Treatments	Leaf area index		
		2 WAS	6 WAS †	15 WAS
DO708	T1	0.42	1.95	2.54
	T2	0.49	2.19	3.30
	T3	0.32	1.68	2.57
QM1113	T1	0.57	3.09	2.81
	T2	0.61	4.05	3.90
	T3	0.54	2.58	2.48

WAS: weeks after sowing. † Irrigation treatment application termination. Irrigation treatments based in % of ETm.

inside the same cultivar was significant (p = 0.032). Treatment T2 which was receiving 50% of ETm during the vegetative growth stage showed the highest fresh weight of roots followed by control (100% of ETm) and the lowest fresh weight of roots was recorded when applying 25% of ETm as water deficit degree during vegetative growth stage (T3).

Above ground biomass production

First season results (2010)

Figure 8 presents the above ground biomass evolution for 6 different deficit irrigation treatments. At the end of vegetative growth stage, the statistical analysis was highly significant difference (p = 0.01). Treatments well irrigated (T1, T3 and T4) during vegetative growth stage showed the highest biomass production. Treatment T2, T5 and T6 stressed during this stage showed the lowest biomass production in one homogeneous statistical group which mean that water stress has affected the above ground fresh biomass.

At the end of flowering stage a very highly significant difference between treatments (p < 0.001) was revealed. Treatment well irrigated during vegetative growth and flowering stage (T1 and T3) showed the two highest biomass productions. While treatment stressed during vegetative growth and flowering stage (T2 and T6) showed the lowest biomass production, T2 and T6 formed one homogeneous statistical group with treatment T3 which was subjected to water stress during flowering stage, which mean that water stress during flowering stage has severely affected the above fresh biomass production comparing to control treatment (T1). Treatment T5 which was stressed during vegetative growth stage and well irrigated during flowering stage showed a significant increasing in biomass production.

Statistical analysis revealed a highly significant difference between treatments (p = 0.003). Comparing between control treatment (T1) and treatment T4 which was subjected to water stress during seed filling stage we found that water stress has severely affected biomass production. Treatment T3, T5 and T6 showed an increasing in their biomass production after being stressed in vegetative growth for T5, flowering for T3 and both vegetative growth and flowering stage for T6. While treatment stressed during the whole of growing period (T2) remain the most affected by water deficit.

Second season results (2011)

According to statistical analysis, there was no significant difference between treatments or cultivar in terms of the effect of deficit irrigation on the above ground fresh biomass (Table 6). But generally the tendency for the two cultivars was that treatments T2 receiving 50% of full irrigation showed the highest biological yield in terms of leaves and stems and this difference was revealed from the end of treatments application (6 weeks after sowing) to harvest (15 WAS).

Table 5. Fresh weight of roots (g/plant) of two quinoa (*Chenopodium quinoa* Willd.) cultivars in the second season (2011) at Agadir, Morocco.

Cultivar	Treatments	Fresh weight of roots (g/plant)		
		2 WAS	6 WAS †	15 WAS
DO708	T1	4.40	31.77	43.29 b
	T2	3.93	34.25	46.00 a
	T3	4.25	27.49	31.90 c
QM1113	T1	5.33	30.39	50.93 b
	T2	5.80	40.91	56.40 a
	T3	5.53	27.01	33.92 c

WAS: weeks after sowing. † Irrigation treatment application termination. Irrigation treatments based in % of ETm. Means with different letters within a cultivar are significantly different (p<0.05) according to Tukey test. Irrigation treatments based in % of ETm.

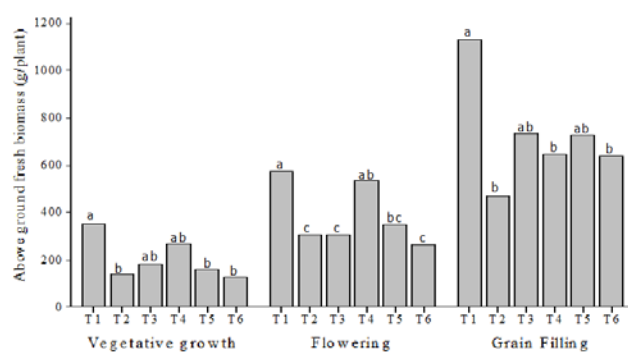

Figure 8. Above ground fresh biomass (g/plan) of quinoa (*Chenopodium quinoa* Willd.) cv. DO708 of the first season (2010) at Agadir, Morocco. Means with different letters within a stage are significantly different (p<0.05) according to Tukey test. Irrigation treatments based in % of ETm.

Yield and crop water roductivity

Seed yield

First season results (2010)

The main objective of this experiment was to increase the water productivity of quinoa irrigated with treated wastewater. There was a very highly significant difference ($p < 0.001$) among treatments for seed yield (Table 7), the control T1 (fully irrigated) showed the highest yield of 74 g/plant, followed by the treatment stressed during the vegetative growth stage (T5) with 72 g/plant. The treatment stressed during the flowering stage (T3) had a seed yield of 50 g/plant, the seed yield of the treatment stressed during the seed filling stage (T4) was 47 g/plant, and with stress during both the vegetative growth and flowering stage (T6) we obtained 40 g/plant. Lower yield was obtained when the crop was subjected to water stress during all the crop stages (T2), which was 36 g/plant.

Second season results (2011)

Taking problematic of the 1st season results during the 2nd season the objective was to apply during the vegetative growth stage 3 deficit irrigation treatments, 100, 50 and 25% of ETm in order to test different water deficit degrees effect on two cultivar of quinoa productivity. Statistical analysis revealed highly significant difference between cultivars and treatments (Table 8). Cultivar DO708 showed the highest productivity in terms of seed yield comparing to cultivar QM1113. Treatment receiving 50% of ETm (T2) recorded the highest seed yield inside each cultivar, while treatment receiving 25% of ETm (T3) showed the lowest seed yield.

Table 6. Above ground fresh biomass (g/plant) of two quinoa (*Chenopodium quinoa* Willd.) cultivars of the second season (2011) at Agadir, Morocco.

Cultivar	Treatments	Above ground fresh biomass (g/plant)		
		2 WAS	6 WAS †	15 WAS
DO708	T1	39.78	288.69	389.31
	T2	34.28	300.83	409.42
	T3	41.13	252.87	350.90
QM1113	T1	46.48	320.13	400.16
	T2	42.90	337.71	425.07
	T3	42.38	266.21	346.87

WAS: weeks after sowing. † Irrigation treatment application termination. Irrigation treatments based in % of ETm.

Water productivity and water saving

First season results (2010)

The optimal treatment that recorded the highest water productivity (Figure 9A) was T5 stressed during the vegetative growth stage. Figure 9B shows the consumed and saved water for each treatment. This high water productivity was due to high obtained yield which was statistically not different to control treatment. Treatment fully stressed (T2) showed water productivity similar to WP obtained by the control, and this was mainly due to little water consumed (Figure 9B).

Second season results (2011)

As seed yield there was a significant difference between cultivars and between treatments (Figure 10), cultivar DO708 showed the highest water

Table 7. Seed yield (g) per plant of quinoa (*Chenopodium quinoa* Willd.) cv. DO708 obtained by irrigation treatments during the first season (2010) at Agadir, Morocco.

Treatments	Seed yield per plant (g)	Standard deviation (g)
T1	74.3 a	26.9
T2	37.0 c	11.0
T3	50.3 b	14.1
T4	46.7 bc	17.1
T5	72.0 a	17.0
T6	40.2 bc	15.0

Means with different letters are significantly different ($p<0.05$) according to Tukey test. Irrigation treatments based in % of ETm.

Table 8. Seed yield (g) per plant of two quinoa (*Chenopodium quinoa* Willd.) cultivars obtained by irrigation treatments during the second season (2011) at Agadir, Morocco.

Cultivar	Treatments	Seed yield per plant (g)	Standard deviation (g)
DO708	T1	61.8 b	8.00
	T2	68.9 a	1.54
	T3	42.1 c	2.96
QM1113	T1	52.7 b	4.26
	T2	56.2 a	2.88
	T3	32.9 c	2.76

Means with different letters within a cultivar are significantly different ($p<0.05$) according to Tukey test. Irrigation treatments based in % of ETm.

productivity, while treatment receiving 50% of ETm (T2) recorded the highest crop water productivity inside each cultivar.

Table 9 shows that quantity of about 350 m^3/ha could be saved when applying 50% of ETm during vegetative growth stage and obtaining the highest yield even more than when full irrigation was provided.

DISCUSSION

Soil nitrate concentration increased after harvest from 10 to more than 27 ppm in the control treatment the first season. This result shows there is a risk of the reuse of wastewater that nitrate may leach to the groundwater (Tagma *et al*., 2009). The fully stressed treatment increased salinity accumulation due to increased water deficit. The increasing soil salinity affected negatively crop growth and development, including yield, as also demonstrated by (Katerji *et al*., 1992; Katerji *et al*., 1996; Katerji *et al*., 1998; Soussi *et al*., 1998; Katerji *et al*., 2003; Muscolo *et al*., 2003)

Leaf area index (LAI) plays an important role in controlling the interaction between terrestrial environments and atmospheric variables (Gobron, 2005). Flowering was the most sensitive stage to drought stress in terms of leaf area, which was also demonstrated by Ezzeddini *et al*. (2008). The reduction of LAI seems to be a mechanism related to drought tolerance of quinoa (Geerts *et al*., 2005). The seed filling stage was the most sensitive stage to drought stress according to first season results.

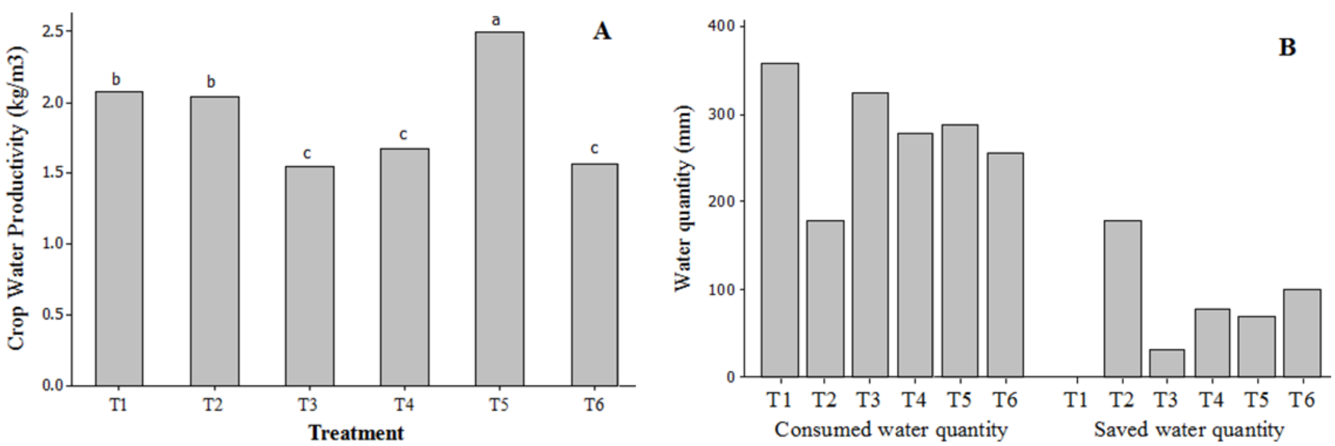

Figure 9. Water productivity (A), water supplies and saving (B) of quinoa (*Chenopodium quinoa* Willd.) cv. DO708 of the first season (2010) at Agadir, Morocco. Means with different letters are significantly different (p<0.05) according to Tukey test. Irrigation treatments based in % of ETm.

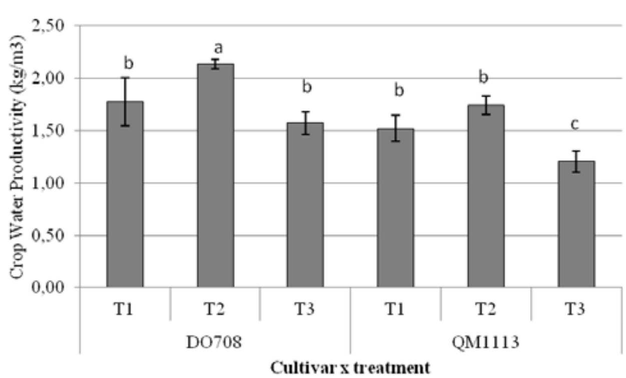

Figure 10. Quinoa (*Chenopodium quinoa* Willd.) cultivars' water productivity of the second season (2011) at Agadir, Morocco. Means with different letters are significantly different (p<0.05) according to Tukey test. Irrigation treatments based in % of ETm.

Table 9. Water supplies consumption and saving of quinoa (*Chenopodium quinoa* Willd.) cultivars of the second season (2011) at Agadir, Morocco.

Cultivar	Treatments	Water supplies (mm)	Saved water quantity (mm)
DO708	T1	348	0
	T2	323	35
	T3	273	85
QM1113	T1	348	0
	T2	323	35
	T3	273	85

Irrigation treatments based in % of ETm.

The effect of deficit irrigation on roots growth indicated that applying drought stress during the vegetative growth stage induced more roots growth, indicating that quinoa avoids the negative effects of drought through a deep, dense root system (Geerts *et al.*, 2005; Jensen *et al.*, 2000; Jacobsen *et al*., 2009).

The above ground biomass production was affected by water status. The vegetative growth stage was the most tolerant stage to drought stress followed by flowering and seed filling.

Drought tolerance in quinoa was enhanced by a decrease in growth rate and plant size (Sanchez *et al.*, 2003; Geerts *et al*., 2005) as water deficit is known to decrease leaf production and size, and increase rate of leaf death (Sánchez *et al.*, 2003).

An experiment carried out on the Bolivian Altiplano reported that using only half of the water required for full irrigation (FI), allowed the stabilization of quinoa yields between 1.2 and 2 T/ha with a density of 11 plants/m^2. Yield could be increased above 2 T/ha with FI (Geerts *et al.*, 2008). In the 1st season of this research a yield of 7.4 T/ha was recorded for the treatment fully irrigated with a sowing density of 100,000 plants/ha, with the same density during the 2nd season 6.9 T/ha was obtained when applying 50% of ETm during the vegetative growth stage. In the present trial treated wastewater was used as irrigation water source which is rich in nutrients and organic matter and also an integrated approach of irrigation taking in consideration the continuum Soil-Plant-Atmosphere was applied, that has a remarkable effect on the quinoa productivity in both seasons 2010 and 2011.

Yield differences can be explained by the same differences in leaf area, more leaf area allowed having more photosynthetic activity, this difference in yield can be also explained by differences in root and shoot weight, as a more developed root system leads to more nutrient and water uptake.

During the first season of this research, yield obtained with a water deficit of 50% during vegetative growth was similar to yield obtained with full irrigation. During 2nd season the idea was to test during vegetative growth other deficit irrigation degrees as 50 and 25% of ETm, those results indicated that applying 50% of ETm can lead to higher yield even more when full irrigation was applied.

When water supply is insufficient to meet full crop water demand (or too expensive), alternative strategies of irrigation can be used, that is deficit irrigation. Deficit irrigation aims to add a limited water amount during critical and drought stress sensitive crop development stages, such as flowering and initial seed setting, or early establishment (Zhang, 2003; Passioura, 2006; Ali *et al*., 2007; Ali and Talukder, 2008; Geerts and Raes, 2009; Kijne *et al*., 2009).

Water productivity (WP) is defined as units of crop yield per amount of water supplied or used (Passioura, 2006). It expresses the benefit derived from the consumption of water and can be used for assessing the impact of on-farm strategies under water scarce conditions. They provide a proper vision of where and when water could be saved. WP indicators are also useful for looking at the potential increase in crop yield that may result from increased water availability (Vazifedoust *et al.*, 2008). These present studies indicated that deficit irrigation applied for quinoa during the vegetative stage resulted in higher water productivity than full irrigation, whereas a limiting water supply during the sensitive growth stages flowering and seed filling affected crop productivity because of yield loss.

CONCLUSION

Through this study it was demonstrated that the optimal stage to apply deficit irrigation in quinoa without affecting yield negatively is the vegetative growth stage, when the crop will develop a denser root system. Quinoa will then be able to cover its needs for water and nutrient supply during the rest of growing period under non-stress conditions during the flowering and the seed filling stage. Deficit irrigation during the vegetative growth saved 20% of the water supply (690 m^3/ha) compared to the control.

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