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Quinoa response to different transplanting dates and nitrogen fertilization levels in an arid environment

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Abstract. Quinoa is recognized as a water-stress tolerant crop. Nevertheless, few findings are presently available on fully-irrigated quinoa growth and productivity grown in arid Mediterranean area. Field experiments conducted in Syria for two growing seasons (2017/18 and 2018/19) determined the response of quinoa crop (ICBA-Q5 cultivar) to five different transplanting dates (TD) (December, January, February, March, and April) and four nitrogen fertilizer levels (0, 90, 180 and 270 kg N ha^{-1}). Main findings showed that quinoa had a good adaptation (up to 5.30 and 15.9 t ha^{-1} of seed and dry matter yields, respectively) to very low N-inputs, with a high capacity to evapotranspirate (ETc), resulting in high crop coefficient (kc). ETc and kc varied in the range of 590-1136 mm and 0.37-2.05 among the TDs, respectively. Moreover, quinoa growth and productivity were highly affected by TDs, and varied from year to year, influenced mainly by temperature. Emphasis in future experiments should probably be given to TD in December, which exhibited a high degree of consistency over years with high crop performance, and to TDs in January and February, which performed extremely well in the first year.

Keywords. Agro-meteorology, water productivity, irrigation water use efficiency, quinoa seed yield potentials, arid Mediterranean area.

1. INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.) is a well-known highly nutritional crop due to the high-quality proteins contained in its seeds (Repo-Carrasco et al., 2003). The whole plant of quinoa can also be used as livestock feed (Blanco Callisaya, 2015). Moreover, quinoa is recognized as a resilient crop to abiotic stresses, such as salinity (Hinojosa et al., 2018), drought (Fuentes and Bhargava, 2011), heat (Alvar-Beltrán et al., 2020) and frost (Jacobsen et al., 2003), and there is a wider global interest in its cultivation (Choukr-Allah et al., 2016). Thanks to its exceptional features, the Food and Agriculture Organization of the United Nations (FAO) considered quinoa as one of the most important crops, playing a crucial role on ensuring food security (FAO and CIRAD, 2015).

Quinoa crop performed well under deficit irrigation without detriments to yield (Geerts et al., 2008a, b; Razzaghi et al., 2011, 2012; Pulvento et al., 2012;

Alvar-Beltrán et al., 2019). However, very little information is available on growth and seed and biomass productivity potentials of quinoa crop grown under full irrigation in hot and dry environment (Al-Naggar et al., 2017; Ahmadi et al., 2019). Under such climate conditions, Ahmadi et al. (2019) indicated that quinoa showed very high crop evapotranspiration (1448-1687 mm) and transpiration (777-1228 mm) rates for different plant density rates. They reported that quinoa has a specific physiological system (relatively high stomata conductance and sizes) transpiring continually and allowing better leaf cooling under hot climate conditions, resulting in high water consumption. However, Alvar-Beltrán et al. (2019) showed crop evapotranspiration rates of 400-500 mm under full irrigation in Burkina Faso for short-cycle quinoa cultivas (about 3 months). This indicates that quinoa crop water needs may vary under full irrigation according to the agro-climatic context.

Moreover, many findings indicated that quinoa seed yields increased with increasing nitrogen applications. Different N-fertilizer needs of quinoa crop were reported: 120 kg N ha^{-1} (Schulte auf'm Erley et al., 2005), 240 kg N ha^{-1} (Hirich, 2014), 350 kg N ha^{-1} (Ahmadi et al., 2019), 360 kg N ha^{-1} (Shams, 2017; Shoman, 2018), 570 kg N ha^{-1} (Rao and Shahid, 2012), and 200 mg N per kg of soil (equivalent to 780 kg N ha^{-1} for 30-cm soil profile with a supposed density of 1.35 g cm^{-3}) (Lavini et al., 2014). The obtained N-requirements were very high and pose the question on the eco-environmental impacts of quinoa crop fertilization. On the other hand, there is another contradictory trend indicating that N-fertilizer had no critical role on quinoa crop growth or seed production. For instance, Alvar-Beltrán et al. (2019) found a high performance of quinoa under very low nitrogen applications (25 kg N ha^{-1}). Moreale (1993) also showed that the N-uptake of quinoa crop was of 25 kg N per ton of seed production. Hence, selecting the optimal nitrogen application rate for quinoa is a continuous need in ever changing agro-pedo-climatic conditions.

In the context of semi-arid and arid Mediterranean region, where water scarcity is a constraint to agricultural production, scientists considered quinoa as an alternative crop to sustain seed crop production (Rao and Shahid, 2012; Benlhabib et al., 2015; Dost, 2015; Choukr-Allah et al., 2016). Several studies were carried out in the northern Mediterranean countries (e.g. in Italy (Pulvento et al., 2015), in Turkey (Yazar et al., 2015) and in Greece (Noulas et al., 2015)), as well in most of the MENA (Middle East and North Africa) countries (Choukr-Allah et al., 2016). However, to the best of our knowledge, very limited attempts related to quinoa cultivation in Syria were conducted (Lavini et al., 2014; Jbawi et al., 2018). Almost no research findings based on multi-year field experiments are presently available on quinoa cultivation, adaptation and productivity in Syria, and therefore, important scientific outcomes are much needed. Therefore, the objectives of this two-year field experiment were (i) to determine crop water and N-fertilizer requirements and crop coefficient for quinoa crop, (ii) to determine the suitable transplanting date for quinoa crop under arid Mediterranean climate in Syria and (iii) to determine potential seed and dry matter yields, water productivity and irrigation water-use efficiency under full irrigation.

2. MATERIALS AND METHODS

2.1. Study site, soil and agricultural practices

Field experiments were conducted during two consecutive growing seasons 2017/18 and 2018/19 at the Agricultural Experiment Station, Deir Al-Hajar, Damascus Countryside in Syria (33°20'N, 36°26'E, 600 m a.s.l.). The arid Mediterranean climate type dominates the study area with a yearly potential evapotranspiration (ET_0) exceeds 2000 mm, and with a yearly precipitation of about 120 mm. The main climate data which were collected during both tested growing seasons (maximum and minimum air temperatures and precipitation) and those estimated based on the procedures of Allen et al. (1998) are displayed in Tables (1 and 2) and Figures (1 and 2).

The soil was classified as a clay loam texture, containing 29.5% clay, 42.7% silt, 27.8% sand, with a bulk density of 1.35 g cm^{-3}. Some chemical and physical soil properties were: pH 8.0; ECe 0.19 ds m^{-1}; organic matter <1%; available P 5.7 ppm; NO_3^- 10.9 ppm; NH_4^+ 19.8 ppm. Volumetric soil water contents at field capacity and permanent wilting point were 0.36 and 0.18 m^3 m^{-3}, respectively. Irrigation water properties were of pH 8.4; ECe 0.46 ds m^{-1}; NO_3^- 1.05 ppm; NH_4^+ 1.99 ppm.

The quinoa seeds of Q5 cultivar (with long cycle of around 150 days) used in this study were obtained from ICBA (the International Centre for Biosaline Agriculture). Due to the difficulties encountered in seed germination in the field, quinoa seedlings, which were produced indoor at room temperature (20-25 °C), were used instead of direct sowing. Seedlings were transplanted 15-20 days after sowing, with seedling density of 8 plants m^{-2}. Five different transplanting dates separated with one month were tested in each year: TD-Dec (mid-December), TD-Jan (mid-January), TD-Feb (mid-February), TD-Mar (mid-March) and TD-Apr (mid-April). At each planting date, four N-fertilizer levels were evaluated: 0 (N0), 90 (N90), 180 (N180) and 270 (N270) kg N ha^{-1}. N-fertilizer as urea (N: 46%) was broadcasted in 2, 4, and 6 equally split applications, for N90, N180 and N270, respectively, with two-week intervals. The 1st application of urea was at transplanting. Experiments were arranged in a split-plot design involving

Tab. 1. The main climate data for the experimental station during both growing seasons 2017/18 and 2018/19.

Parameter	Growing season	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
Mean temperature (^{0}C)	2017/18	11.2	8.7	12.3	16.1	18.6	23.5	26.4	28.3	28.7
	2018/19	10.2	7.9	10.0	11.9	15.1	24.6	27.8	28.3	29.0
Maximum temperature (^{0}C)	2017/18	18.9	14.2	18.8	24.3	27.2	31.5	34.6	36.9	37.1
	2018/19	14.8	13.2	15.1	18.3	22.2	34.2	36.6	37.3	38.0
Minimum temperature (^{0}C)	2017/18	3.6	3.3	5.7	7.9	10.0	15.6	18.2	19.8	20.2
	2018/19	5.6	2.6	4.8	5.5	8.1	15.0	19.0	19.4	20.1
Precipitation (mm)	2017/18	0.0	34.0	30.3	1.0	14.0	9.9	6.4	0.0	0.0
	2018/19	35.8	48.0	32.5	17.4	11.6	0.0	0.0	0.0	0.0
Reference evapotranspiration, ET_0 (mm day^{-1})	2017/18	3.31	2.56	3.56	5.18	6.33	7.35	8.15	8.66	8.26
	2018/19	2.40	2.44	2.87	3.92	5.11	8.43	8.79	8.86	8.59

Tab. 2. Agro-climate parameters during the growing period of each transplanting date for both seasons 2017/18 and 2018/19.

Treat.	Trans-planting date	Harvesting date	Flowering date	Growing period (days)	I (mm)	P (mm)	ΔS (mm)	ETc (mm)	kc (-)	Tmean (^{0}C)	VPD (kPa)	Rn (mm)	ET0 (mm)	α (-)
TD-Dec	10/12/2017	22/04/2018	14/02/2018	133	540	66.7	32.6	639.3	1.16	1757.8	127.6	361.2	549.5	1.77
TD-Jan	14/01/2018	04/06/2018	25/03/2018	141	800	84.0	-18.3	865.7	1.15	2350.9	173.0	565.9	755.9	1.53
TD-Feb	15/02/2018	24/06/2018	20/04/2018	129	956	54.2	-37.5	972.7	1.18	2553.0	191.7	634.1	827.6	1.53
TD-Mar	18/03/2018	15/07/2018	16/05/2018	119	1083	31.3	-11.4	1102.4	1.22	2712.5	214.1	679.6	903.4	1.62
TD-Apr	15/04/2018	06/08/2018	10/06/2018	113	1010	28.9	15.0	1053.9	1.13	2850.8	226.4	689.8	936.7	1.53
TD-Dec	16/12/2018	01/06/2019	09/03/2019	167	450	138.9	-0.7	588.2	0.80	2256.3	165.9	574.8	739.7	1.02
TD-Jan	16/01/2019	01/07/2019	09/04/2019	166	804	80.5	-2.4	882.1	0.93	2825.3	222.0	733.7	948.8	1.20
TD-Feb	11/02/2019	09/07/2019	26/04/2019	148	930	41.2	61.2	1032.4	1.08	2820.0	226.1	741.6	957.5	1.39
TD-Mar	17/03/2019	21/07/2019	19/05/2019	126	1010	26.4	100.2	1136.6	1.19	2808.5	231.4	724.0	958.8	1.57
TD-Apr	14/04/2019	22/08/2019	18/06/2019	130	1005	9.4	36.6	1051.0	0.93	3339.4	285.5	806.4	1131.8	1.30

I=total irrigation water amount; P=total precipitation; ΔS= the change in soil water storage; ETc=seasonal crop evapotranspiration; kc=the average of crop coefficient computed as kc=ETc/ET0; Tmean=cumulative mean temperature; VPD=cumulative vapour pressure deficit; Rn=cumulative net radiation (converted from MJ m^{-2} into mm); ET0=cumulative reference evapotranspiration; α=the advection correction factor computed as α=ETc/Rn.

five transplanting dates as main-plots and four N-fertilizer levels as sub-plots, with three replicates.

The field was conventionally prepared before transplanting. In each transplanting date, 12 plots (4 N-levels with 3 replicates) were prepared with 3×4 m^2 per plot, each surrounded by dikes from all sides. Enough spacing (about 1.5 m) was maintained between plots to minimize water and N-fertilizer intervention. Weeds were removed by hand three times within 10–50 days after transplanting during the growing season.

2.2. Irrigation management and crop evapotranspiration

During the growing season full irrigation was applied to all quinoa plots. Irrigation water was delivered through a polyethylene pipe of 25 mm diameter to each plot, in order to enhance irrigation practices; and volumes of applied water were measured by flow meters. Irrigation was scheduled once a week based on the soil water content measurements just before each irrigation event. Monitoring the soil water content was done using *in-situ* calibrated neutron probe, which ensured that the soil moisture depleted in the previous week was precisely replenished. For irrigation scheduling purposes, the depths of active roots were 0.30 m from the beginning until peak flowering, and then 0.60 m until termination. The amount of irrigation water applied per irrigation event (I, mm) was estimated as follows:

$$I = 1000 \times (\theta_{fc} - \theta_{ob}) \times Z_r \quad (1)$$

where θ_{fc} is the volumetric soil water content at field capac-

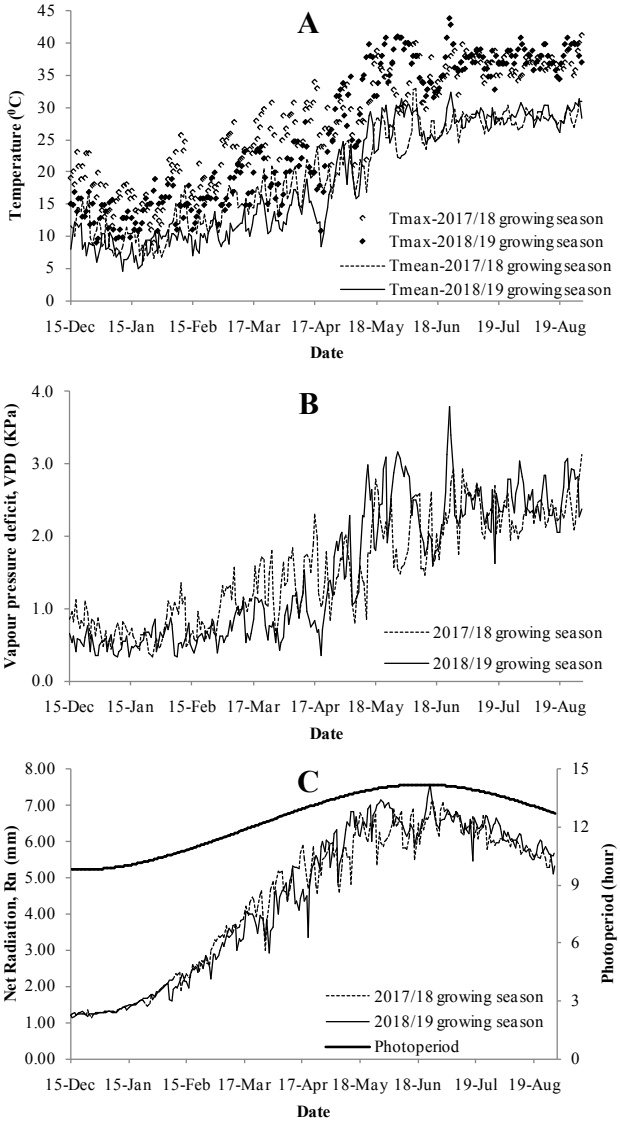

Fig. 1. Variations of (A) mean and max air temperatures, (B) vapor pressure deficit and (C) net radiation and photoperiod during both growing seasons.

ity (=0.36 $m^3\ m^{-3}$), θ_{ob} is the volumetric soil water content observed just before irrigation event ($m^3\ m^{-3}$), Z_r is the soil depth (active root depth) to be considered (m). To convert this amount into m^3 per plot, it was multiplied by the plot area (m^2) and then divided by 1000.

Quinoa crop evapotranspiration (ETc) was estimated using the water balance equation:

$$ETc = I + \mathrm{P} - Dp - R_o \pm \Delta S \quad (2)$$

where I is the amount of irrigation water applied (mm), P is the precipitation (mm), Dp is the deep percolation (mm), and R_o is the amount of runoff (mm), ΔS is the change in soil water storage in the specified soil profile (mm), as measured by the neutron probe. Since the amount of irrigation was controlled, runoff was assumed to be zero. Observing soil water content showed that the deep percolation below 0.60 m in depth was negligible. The daily crop evapotranspiration (mm day^{-1}) was estimated by dividing the *ETc* calculated using Eq. (2) by the days between two successive irrigations (7 days). The seasonal *ETc* was the summation of the daily *ETc*, which represented the total crop water requirements for each planting set. The daily reference evapotranspiration (ET_0) was calculated by FAO Penman-Monteith equation (Allen et al., 1998). Crop coefficient (*kc*) for quinoa was calculated by dividing *ETc* by ET_0 as:

$$kc = \frac{ETc}{ET_0} \quad (3)$$

2.3. Seed yield, dry matter and crop water productivities

Quinoa plants were harvested when seeds were ripened and dry. Representative 1-m^2 area (8 plants) was selected from each experimental unit (a total of 60 units = 5 TDs × 4 N-levels × 3 replicates). The heads of selected plants were cut off and the seeds were separated and weighted to estimate quinoa seed yield (QSY). The empty heads (after seed separation) and the aboveground vegetative parts of selected plants were gathered, and then oven dried at 70°C until constant weight for dry matter yield (DMY) determination. Weights of grains and vegetative parts of selected plants were converted into ton per hectare (t ha^{-1}). The harvest index (HI) was calculated by dividing the seed yield (QSY) by the total plant biomass (the sum of QSY and DMY). The weights of thousand seeds (manually counted) were also recorded (W1000). Both crop water productivity (WP, kg per m^{-3}) and irrigation water use efficiency (IWUE, kg per m^{-3}) were determined using equations (4) and (5), respectively.

$$WP = \frac{QSY}{ETc} \quad (4)$$

$$IWUE = \frac{QSY}{I} \quad (5)$$

2.4. Statistical analysis

All measured variables (QSY, DMY, HI, W1000, WP and IWUE) were subjected to a two-way analysis of variance using the DSAASTAT add-in version 2011 (Onofri, 2007). A combined analysis of data over both years was performed to identify transplanting date and N-level

managements whose average effect over years is stable and high (Gomez and Gomez, 1984). As both tested factors are quantitative, trend comparison (regression analysis) was conducted to test the functional relationship between measured variable and tested factors. The coefficient of determination of regression function and its significance were presented.

3. RESULTS

3.1. Climate data, crop evapotranspiration and crop coefficient

Mean and max air temperature (Tmean and Tmax), vapour pressure deficit (VPD), reference evapotranspiration (ET0) variations over both growing seasons are shown in Figures 1A, 1B and 2A, respectively. In general, these parameters decreased from December to mid-January, to gradually increase up to the end of June before they reached a plateau for the rest of growing season. Comparing of both growing seasons reveals two distinguished parts: from December to April, and from May to the end of August. In the 1st part, the four parameters Tmean, Tmax, VPD and ET0 in the 2017/18 season were 20, 23, 25 and 37% higher than those in the 2018/19, respectively. While in the 2nd part they were about 3, 4, 7 and 11% lower. Starting from the flowering stage till the maturity, the critical 35 °C threshold was exceeded0, 7, 14, 31 and 39 times for TD-Dec, TD-Jan, TD-Feb, TD-Mar and TD-Apr in the 2017/18 season, but 15, 33, 41, 45 and 56 times in the 2018/19 season, respectively.

Figure 1C shows variations of both net radiation (Rn, converted from MJ m^{-2} to mm) and photoperiod parameters over both growing seasons. Due to the latitude of the experimental site, the photoperiodicity and Rn varied strongly during growing cycle. The values of Rn from December to April in the 2017/18 season were higher than those in the 2018/19 season; after that, they were somewhat lesser.

Rainfall distribution patterns during both studied years are illustrated in Figure 2B. The 2018/19 recorded 145.3 mm (21% more than the annual precipitation), almost uniformly distributed from December to mid-April. However, the cumulative precipitation in the 2017/18 was 95.6 mm (20% less than the annual record), with no rain in December or from the end of February to the last third of April. However, cumulative precipitation (P) recorded within each transplanting date were presented in Table 2.

The total values of Tmean, VPD, ET0 and Rn which quinoa plants were exposed to during the growing cycle of each transplanting date, were also presented in Table 2. Minimum values were observed for quinoa transplanted in TD-Dec, and then they increased as the transplanting date delayed. During the 2018/19 season the total values of the accumulated climatic parameters were much higher than those accumulated during the 2017/18 season, due to the prolongation in growing periods for all TDs as mentioned below. For instance, cumulative ET_0 for TD-Dec, TD-Jan, TD-Feb, TD-Mar and TD-Apr in the 2018/19 season were 35, 26, 16, 6 and 21% higher than those in the 2017/18 season.

The differences in climatic parameters within a growing season influenced the lengths of growing periods, so that they decreased after January (Table 2). The growing period lengths were also affected by the differences between both growing seasons, so that they prolonged for all TDs in the 2018/19 season compared with those in the 2017/18 season. This prolongation was obvious for the earlier transplanting dates in December, January and February.

The soil water balance components (I, P and ΔS) and seasonal ETc for each transplanting date are shown in Table 2. Minimum ETc was observed for quinoa transplanted in TD-Dec (639 and 588 mm in the 2017/18 and the 2018/19 seasons, respectively), and then increased as the transplant-

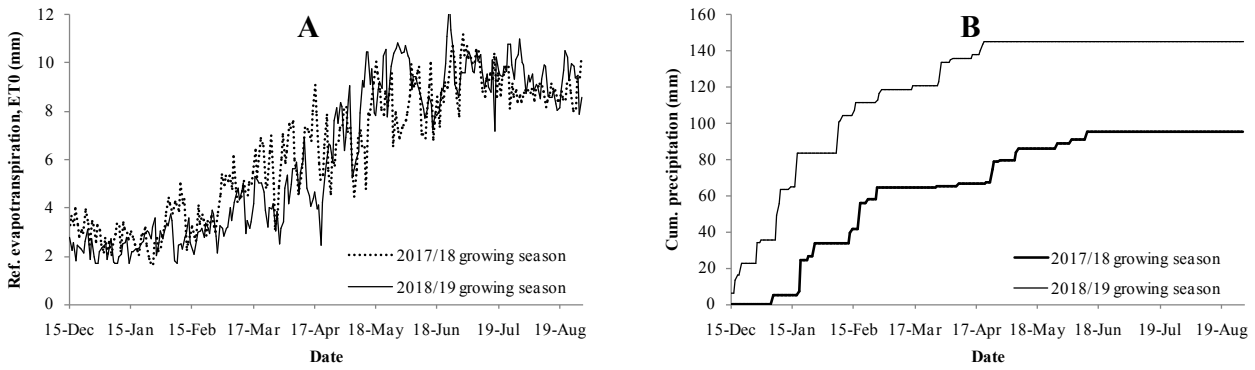

Fig. 2. Variations of (A) reference evapotranspiration and (B) cumulative precipitation during both growing seasons.

Tab. 3. Analysis of variance of the combined data of quinoa crop responses as affected by transplanting date, N-fertilizer level and year (significance of *F-test*).

Source of variance	*df*	QSY	DMY	HI	W1000	WP	IWUE
Year (Y)	1	[b]	[b]	[b]	[b]	[b]	[b]
Rep. within Y	4						
Transplanting date (TD)	4	ns	ns	ns	ns	ns	ns
N-fertilizer level (N)	3	ns	*	ns	ns	ns	ns
Y × TD	4	**	**	**	**	**	**
Y × N	3	ns	ns	ns	ns	ns	ns
TD × N	12	ns	ns	ns	ns	ns	ns
Y × TD × N	12	ns	ns	ns	ns	ns	ns
Pooled error	60						
Total	119						

[b] = Reps. within year d.f. is not adequate for valid test of significance.
* = significant at 5% level; ** = significant at 1% level; ns = non-significant at 5% level,
df = degree of freedom; QSY= quinoa seed yield; DMY = dry mater yield; HI = harvest index; W1000 = weight of 1000 seeds; WP = water productivity and IWUE = irrigation water use efficiency.

ing date delayed (Table 2). These results reveal the effects of transplanting date on crop water requirements.

Crop coefficient (kc) of quinoa was nearly weekly calculated using Eq. (3) (data not shown). Its minimum values varied between 0.53 and 0.62 in the 2017/18 growing season and between 0.37 and 0.56 in the 2018/19 season. Whereas its maximum values varied between 1.83 and 2.05 in the 2017/18 growing season, and between 1.23 and 1.93 in the 2018/19 season. However, the kc values presented in Table 2, were determined for the whole growing period for each TD using the seasonal ETc and the cumulative ET_0 as inputs for Eq. (3). The time-averaged kc values varied among TDs and from year to year. It was higher in the 2017/18 season compared with the 2018/19 season, for all TDs.

3.2. Nitrogen fertilizer impact

Except for DMY, the combined analysis over years indicated that the main effect of N-fertilizer level and the interaction effects involving N-level were not statistically significant (Table 3). However, only the main effect of N-fertilizer on DMY was significant at the 5% level, but with a very high *p*-value (p=0.04). Trend analysis demonstrated that the relationship between DMY and N-fertilizer level was cubic (equation not presented) with significant values of R-square at the 5% level. DMY peaked at N90 (7.92 t ha^{-1}) and bottomed out at N270 (6.49 t ha^{-1}). However, although the trend analysis indicated that the maximal DM yield could be mathematically obtained at 90 kg N ha^{-1}, the increase in DMY between 0 and 90 kg N ha^{-1}, following the regression equation, is very small (less than 7%). Although no statistical significant differences were found to the increasing N-fertilizer level, adding 90 kg N ha^{-1} (N90) showed superiority over the other tested levels for W1000 (2.16 g), WP (0.20 kg m^{-3}) and IWUE (0.22 kg m^{-3}). While QSY and HI reached their maximum averaged values under N180 (1.71 t ha^{-1} and 20.6%, respectively). The averaged values of QSY over both growing seasons were 1.37, 1.62, 1.71 and 1.57 t ha^{-1} under N0, N90, N180, and N270, respectively; while the averaged values of DMY over both growing seasons were 6.99, 7.92, 7.03 and 6.49 t ha^{-1} under N0, N90, N180, and N270, respectively.

3.3. Transplanting date impact

As mentioned above, irrigation water amounts and seasonal crop evapotranspiration (ETc) for the studied TDs are shown in Table 2 for both growing seasons. The seasonal ETc differed slightly from the applied irrigation water amounts, due to the different precipitations. However, irrigation water amount followed the same tendency as the seasonal ETc, where it increased considerably as the transplanting date delayed. Compared with the irrigation amount applied to plants transplanted in December (TD-Dec), irrigation water amount increased by 260, 416, 543 and 470 mm in the 2017/18 season, and by 354, 480, 560 and 555 mm in the 2018/19 season, for TD-Jan, TD-Feb, TD-Mar and TD-Apr, respectively. This indicates the role of transplanting date on irrigation water requirements of quinoa crop.

Figure 3 shows the evolutions over time of both water productivity (WP) and irrigation water use efficiency (IWUE) for both growing seasons. In the 2017/18, both parameters reached high points for TD-Jan, and bottomed out for TD-Mar and TD-Apr. However, in the 2nd season TD-Dec rivalled both TD-Jan and TD-Feb with very high values of both WP and IWUE, and they both decreased as TD delayed. Trend analysis indicated that the relationships between WP and IWUE and transplanting date for each growing season were cubic in the 2017/18 growing season and quadratic in the 2018/19 season (equations not presented) with significant values of R-square at the 1% level.

The combined analysis over years indicated that the main effects of TD were not significant. However, only the year × transplanting date interaction effect was detected to be highly significant with p<0.01 (Table 3). Therefore, the response of quinoa crop to transplanting date varied from year to year.

The QSY data of different transplanting dates was compared under both growing seasons (Fig. 4A). In the

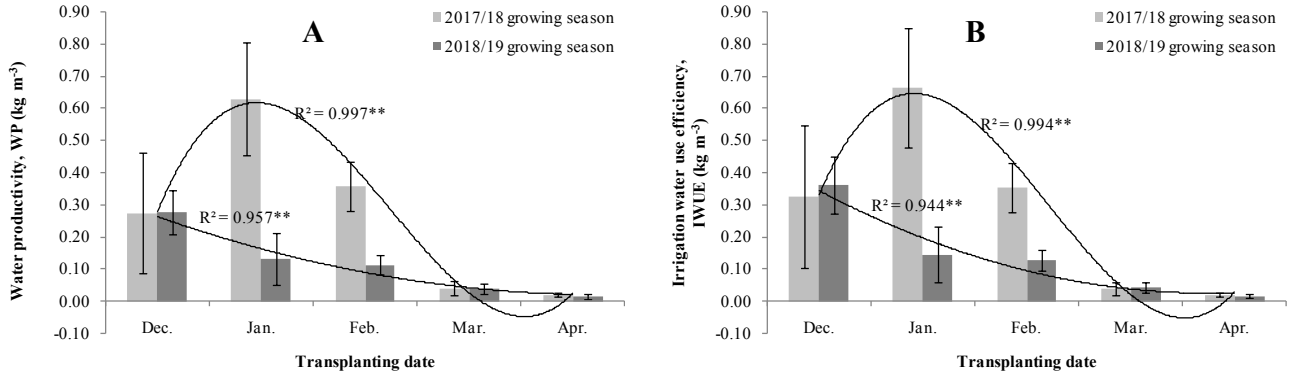

Fig. 3. Variations of (A) water productivity and (B) irrigation water use efficiency during both growing seasons. Error bars represent the standard deviations. R-square represents the coefficient of determination of regression equations fitted but not showed. ** = significant at the 1% level.

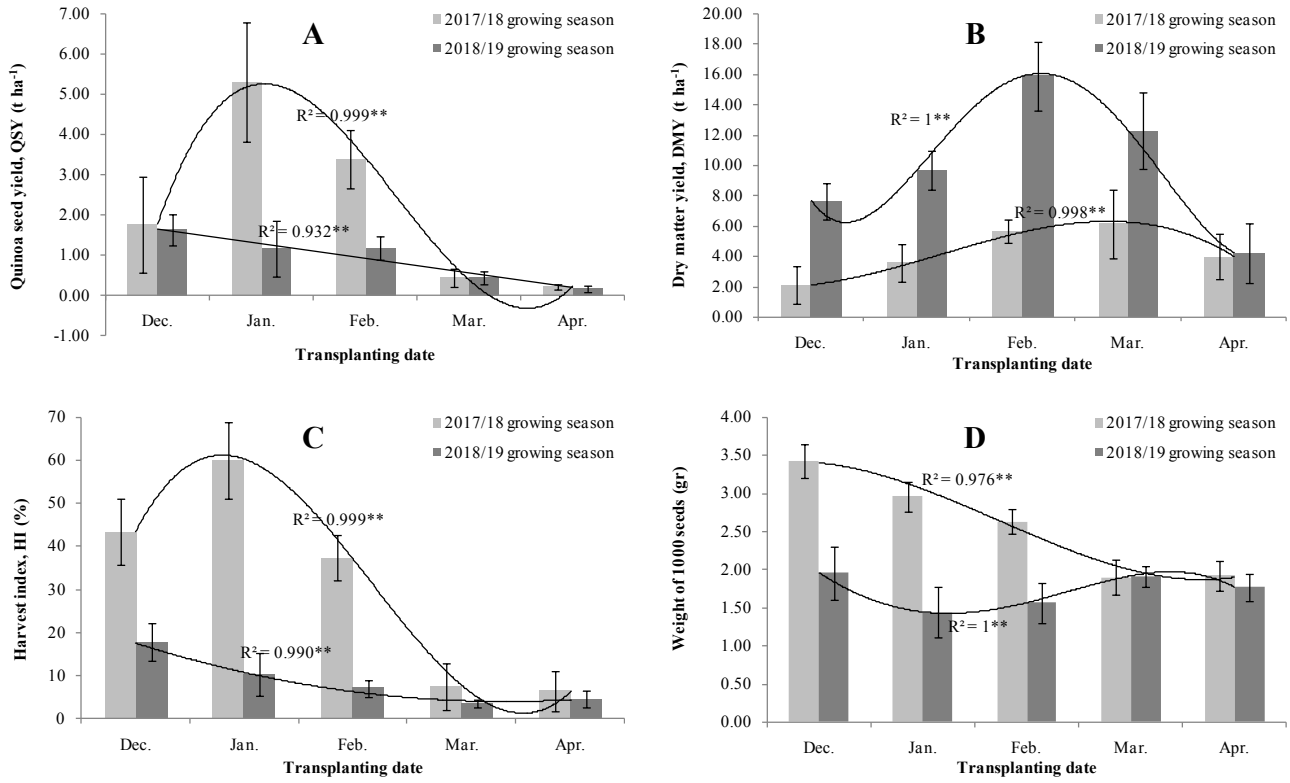

Fig. 4. Variations of (A) quinoa seed yield, (B) dry matter yield, (C) harvest index and (D) weight of 1000 seeds during both growing seasons. Error bars represent the standard deviations. R-square represents the coefficient of determination of regression equations fitted but not showed. ** = significant at the 1% level.

2017/18 growing season, QSY peaked in TD-Jan and bottomed out in TD-Mar and TD-Apr. While in the 2018/19 growing season, QSY decreased as transplanting date delayed. However, quinoa plants transplanted in December, March and April showed somewhat similar seed productions when both growing seasons were compared, while plants transplanted in January and February produced seeds much higher in the 2017/18 growing season than their homologues in the 2018/19 season. This difference in QSY evolutions could explain the nature of the year × transplanting date interaction. Trend analysis indicated that the relationships between QSY and transplanting date

were cubic in the 2017/18 growing season and linear in the 2018/19 season (equations not presented) with significant values of R-square at the 1% level (Fig. 4A).

The variations over both growing seasons in dry matter yield could also explain the nature of the interaction effects of year × transplanting date on DMY (Fig. 4B). Dry matter yield varied between 2.10 and 6.14 t ha^{-1} in the 2017/18 growing season, and between 4.21 and 15.88 t ha^{-1} in the 2018/19 growing season. DMY reached a peak with plants for TD-Mar in the 1st season, while it peaked with plants transplanted for TD-Feb in the 2nd season. Moreover, DMYs of the 2018/19 growing season were found to be much higher than those of the 2017/18 season for all TDs. Trend analysis indicated that the relationships between DMY and transplanting date were quartic in the 2017/18 growing season and cubic in the 2018/19 season (equations not presented) with significant values of R-square at the 1% level (Fig. 4B).

The values of harvest index (HI) varied between 6.5 and 59.9% and between 5.5 and 17.7% in the 2017/18 and 2018/19 growing seasons, respectively (Fig. 4C). In the 1st growing season, HI peaked for TD-Jan and bottomed out for TD-Mar and TD-Apr. While it dropped as transplanting date delayed in the 2nd growing season. However, its values were much higher in the 1st growing season than their homologues in the 2nd season for all TDs. Its different evolutions over time among TDs and from year to year could explain the nature of the year × transplanting date interaction effects on HI. Trend analysis indicated that the relationships between HI and transplanting date were cubic in the 2017/18 growing season and quadratic in the 2018/19 season (equations not presented) with significant values of R-square at the 1% level (Fig. 4C).

The weight of 1000 seeds (W1000) significantly varied over time for both growing seasons (Fig. 4D). It dropped as the transplanting date delayed in the 2017/18 season. However, it decreased from TD-Dec to TD-Jan, then it recover after that in the 2018/19 season. Quinoa seeds of TD-Dec, TD-Jan and TD-Feb in the 2017/18 season were much heavier than those of the 2018/19 season, while both TD-Mar and TD-Apr produced seeds with somewhat similar weights in both seasons. Trend analysis showed that the relationships between W1000 and transplanting date were quartic in the 2017/18 growing season and cubic in the 2018/19 season (equations not presented) with significant values of R-square at the 1% level (Fig. 4D).

4. DISCUSSION

Unlike the common idea that quinoa crop needs large quantity of N-fertilizer (Rao and Shahid, 2012; Hirich, 2014; Lavini et al., 2014; Shams, 2017; Shoman, 2018; Ahmadi et al., 2019), this study revealed contrasting findings under full irrigation conditions in an arid environment. Our findings showed that quinoa crop has a very good adaptation to low fertility soil, i.e., <1% organic matter and very low N-requirements. Either the nitrogen quantities initially found in both soil (about 43.5 kg N ha^{-1}) and irrigation water (about 1.06 kg N per 1000 m^3) were satisfactory to meet the crop N-requirements, and no extra N-fertilizer amount was required, or the quinoa crop N-requirements exceed the range of N-levels tested herein (> 270 kg N ha^{-1}) to probably have significant impacts. Our results are in agreement with those of Alvar-Beltrán et al. (2019) who found that quinoa crop can be highly performing under very low nitrogen applications (25 kg N ha^{-1}). Moreover, these results are in accordance with those of Moreale (1993) who showed that the N-uptake of quinoa crop was of 25 kg N per ton of seed production, indicating that N-fertilizer had no critical role on quinoa crop growth or seeds produced. The combined effect of both full irrigation (high level of soil water content) and high temperature could cause ammonia volatilization and hydrolysis, especially under high N-fertilizer levels (Alvar-Beltrán et al., 2019). On the other hand, our findings are not in harmony with those of other studies showing quinoa yield enhancement with increasing N-fertilizer applications. The optimal N-fertilization needs of quinoa crop obtained by those studies were of about 360 kg N ha^{-1} (Shams, 2017; Shoman, 2018), 570 kg N ha^{-1} (Rao and Shahid, 2012), and 200 mg N per kg of soil (Lavini et al., 2014). These various values could be attributed to the growing region, soil type and quinoa cultivar tested. However, these very huge N-requirements pose the question on the eco-environmental impacts of quinoa crop fertilization.

Variations over time in quinoa crop response could be attributed to climatic fluctuation condition, which caused variation among TDs from year to year. Temperature, photoperiod, hydric status and radiation are the main factors affecting both growth and productivity of quinoa crop (Hirich et al., 2014; Bertero, 2015; Hinojosa et al., 2018; Hinojosa et al., 2019a, b; Alvar-Beltrán et al., 2019; Alvar-Beltrán et al., 2020). Quinoa crop tolerates a wide range of temperatures (from -8 to 35 °C) depending on genotype characteristics and phenological stage (Jacobsen et al., 2005). Temperature has the highest relative impact on the duration of development, which was reported to be longer in colder environments and shorter in high temperature environments (Bertero, 2015). In this study, the low temperature in January and February slowed down quinoa plant growth and increased the lengths of growing period. This was intensified during the 2nd season (2018/19) which was colder for the period from December to April,

as compared with the 1st season (2017/18). In addition, more net radiation and daylight hours led to more quinoa leaf elongation and growth, and therefore, reduced growing period as in late-date TDs (TD-Mar and TD-Apr). In other words, increasing solar radiations and photoperiod was found to shorten the growing cycle of quinoa crop under the context of the study. Our results are in agreement with similar investigations which found that growing period was strongly depended on the year (Jacobsen, 2003) and on TD within a year (Hirich et al., 2014). A negative relationship between both solar radiation and time-averaged photoperiod and the length of growing period was also reported by Hirich et al. (2014) in south Morocco. Temperature and photoperiod both interact to determine the growing length of crop under field conditions by controlling the rate of leaf appearance (Bertero et al., 1999). This could explain genotype×environment interaction patterns for quinoa crop yield (Bertero, 2001 and 2015). Moreover, photoperiod sensitivity is manifested from the early stages of development up to advanced stages of grain filling; but plants grown under short days before flowering present less inhibition for photoperiod during seed filling than those from long days (Bertero, 2015).Dry matter productivity of quinoa was increased as daylight hours were low and temperatures were cool during early development period and warmer after that. Prolonged growing periods before seed initiation resulted in active plant's growth and high plant biomass production, as found in the 2nd season.

In the 1st season, plants for TD-Jan and TD-Feb were grown most of the time within mean temperatures closer to the optimal growing temperatures of quinoa (15-25 ˚C, according to Garcia et al., 2015), resulting in higher seed yields. However, plants in the 2nd season were exposed to a heat stress starting from flowering, resulting in yield depletion. In fact, high-temperature stress negatively affected pollination process, and therefore, high seed abortion (Hinojosa et al., 2018; Alvar-Beltrán et al., 2019; Alvar-Beltrán et al., 2020). The translocation of the nutrients manufactured in leaves to storage organs maybe also affected. This led to considerable decreases in seed yields associated with considerable increases in dry matter yields, which was reflected by low harvest index. Many investigations demonstrated that quinoa plants would become fruitless at high temperatures above 34 ˚C at flowering (Lesjak and Caldeini, 2017), 35 ˚C during flowering and seed set (Hirich et al., 2014; Breidy, 2015; CNRADA, 2015; Djamal, 2015; Hassan, 2015; Saeed, 2015; Bazile et al., 2016; Eisa et al., 2017), but above 39 ˚C as found by Alvar-Beltrán et al. (2019). Alvar-Beltrán et al. (2020) concluded that most of the seed yield losses occurred between 34 and 38 ˚C, and considered that 38 ˚C is the highest temperature threshold at flowering. However, inflorescences were observed to be either lacked seeds or contained empty seeds when the temperature pass 35 ˚C (Walters et al., 2016). Herein, starting from the flowering stage, the critical 35 or 39 ˚C thresholds were passed in the 2nd season many times much more than in the 1st season, for all TDs. In fact, pollen vitality is strongly related to its humidity, which in its turn is related to the vapour pressure deficit (VPD). The last was highest at high temperatures (Fig 1). This could reduce the pollen viability and might lead to pollen dehydration (Hatfield and Prueger, 2015, Alvar-Beltrán et al., 2019).

According to the economic yields and upon comparison of the mean difference between both growing seasons for each variable, two groups of transplanting dates can be identified. The first one is composed of TD-Dec, TD-Mar and TD-Apr, which gave similar QSYs, WPs and IWUEs in both growing seasons, but with an obvious better preference in TD-Dec. The second one is composed of TD-Jan and TD-Feb, which performed better in the 1st growing season than the 2nd season. Even though it is evident that a consistently optimal transplanting date cannot be specified in this experiment, emphasis in future investigations should probably be given to TD-Dec, which exhibited a high degree of consistency over both growing seasons with high mean values of HI, W1000, WP and IWUE, and to TD-Jan and TD-Feb which, also showed very high mean values of all variables (QSY, DMY, HI, W1000, WP and IWUE) over growing seasons, and performed extremely well in the first growing season.

It is worth noting that both the maximum and time-averaged values of kc found herein are higher than the common maximum values for quinoa crop reported in its natural distribution region (1.00 as found by Garcia et al., 2003), and in a temperate and humid environment (1.22 as found by Razzaghi et al., 2012), but less-than or somewhat equal to those found in a very hot and dry climate in Iran, as reported by Ahmadi et al. (2019). The last observed high single crop coefficients (kc) for the same quinoa cultivar tested herein (ICBA-Q5 cultivar) which varied from nearly 1 to 2.4 during the growing period. The very high values of kc found under high evaporative demand (Fig. 2A) reveal the outstanding of quinoa plant. This could be explained by its physiological properties such as large rooting system that facilitate water uptake (Ahmadi et al., 2019) and high number of stomata and stomatal size and conductance that facilitate transpiration (Kaushal et al., 2016; Yang et al., 2016; Becker et al., 2017; Hinojosa et al., 2019a, b). Moreover, another reason for the high kc values for quinoa crop could be strongly associated with the climatic conditions. The values of advection correction factor, which is estimated as the ratio between crop evapotranspiration and net radiation (α = ETc/Rn) according to Ahmadi et al. (2019), are presented in Table 2 for each TD for both growing sea-

sons. Advection factor values varied between 1.53 and 1.77 in the 2017/18 growing season and between 1.02 and 1.57 in the 2018/19 season. These values, which are higher than unity (1.00), reflect that there was regional advection effect of sensible heat flux during the growing periods of all TD tested, which was due to the horizontal transfer of sensible heat from hot and dry air from outside the area toward quinoa plants, thereby increasing transpiration and evaporation rates (ETc), which increased kc (Ahmadi et al., 2019). These results indicate that quinoa crop in order to survive, consumes high amounts of water when grown under full watering conditions in arid environment.

Our results of seed yield were similar to those published in other works for the ICBA-Q5 quinoa cultivar: 2.86-3.65 t ha^{-1} under different planting density in Iran (Ahmadi et al., 2019); 3.90 t ha^{-1} in Morrcoo (Hirich, 2016); from 0.40 t ha^{-1} in Kyrgyzstan to 5.57 t ha^{-1} in Uzbekistan (Choukr-Allah et al., 2016); about 2 to 10 t ha^{-1} in five different locations in United Arab Emirates (Rao, 2016); 4.62 t ha^{-1} at ICBA Research Station in United Arab Emirates (Rao and Shahid, 2012). Similarly, DMY results were in agreement with those reported earlier (Sells, 1989; Stolen and Hansen, 1993; Rao and Shahid, 2012). The maximum value of dry matter yield obtained in our study (15.9 t ha^{-1}) was similar to that found by Rao and Shahid (2012) for the ICBA-Q5 cultivar (14.9 t ha^{-1}). Moreover, HI results were comparable with those documented earlier (Hirich et al., 2014; Hassan, 2015; Alvar-Beltrán et al., 2019). Finally, the obtained values of QSY and DMY (5.30 and 15.9 t ha^{-1}, respectively) reveal that quinoa crop has high potentials in seed and/or forage production in this area and in other areas with similar climatic contexts.

5. CONCLUSIONS

Unlike the common idea that quinoa crop needs huge quantity of nitrogen fertilizer, our study revealed contrasting findings under full irrigation conditions in an arid environment. Our findings showed that quinoa crop had a very good adaptation to low fertility soil with very low N-requirements. Quinoa crop showed a very high crop evapotranspiration resulting in high crop coefficient that was higher than the common values. One main reason is the advection effect of sensible heat flux during the growing periods, considerably increased evapotranspiration.

It was demonstrated that quinoa crop growth and productivity were highly affected by transplanting dates and varied from year to year, influenced by climate conditions, mainly by maximum and mean temperatures. Emphasis in future work should probably be given to transplanting date in December, which demonstrated a high degree of consistency over years with high mean values of harvest index, weight of 1000 seeds, water productivity and irrigation water use efficiency. Furthermore, transplanting dates in January and February should be considered, which showed very high mean values of seed and dry matter yields and water use efficiencies over years and performed very well in the first year.

In this study, seed and dry matter yield potentials of quinoa crop (ICBA-Q5 cultivar) were investigated under full irrigation in an arid environment. However, as full irrigation may not be an eco-environmental option in water-scarce zones, further studies are needed to assess the quinoa crop response to water-saving irrigations such as drip irrigation method under partial root zone drying and regulated deficit irrigations. Moreover, adapting economically sound and scientifically proven agronomic and irrigation practices, such as mulching, increasing irrigation interval to deepen rooting system, short-cycle cultivars and/or earliness of planting date, etc... is recommended to substantially reduce soil evaporation, and therefore, seasonal water requirements of quinoa crop and increasing water use efficiency in the arid Mediterranean area. Due to the scant information in Syria, further studies are also needed in order to provide further information on quinoa crop cultivation, adaptation and productivity in the country's different agro-pedo-climatic zones.

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