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Impact of deficit irrigation strategies on water use and productivity of vegetable crops in a semi-arid context of Tunisia

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ABSTRACT

Irrigated agriculture in arid and semi-arid environments is characterized by acute imbalance between rainfall and evapotranspiration and tough competition for water. It is against this backdrop that water use efficiency is becoming a must. This study is targeted to evaluate the effect of deficit irrigation on water requirements, yield and water productivity of potato and tomato crops under average and very high climatic conditions of 2016 and 2017 respectively. The case study is the Cherfech irrigation district located in the northern of Tunisia. For this purposes, the FAO/CROPWAT irrigation scheduling and simulation model was used to identify appropriate deficit irrigation strategies for improving water conservation with acceptable impacts on yields. Deficit irrigation strategies were evaluated through parameters of irrigation, relative crop evapotranspiration, relative yield loss as well as water productivity and economic water productivity. Results indicate that deficit irrigation is practicable under average water demand for both potato and tomato crops. For tomato, adoption of deficit irrigation is less feasible particularly under very high demand. For a relative yield losses threshold of 25%, results show that for potato, optimal season irrigation could be reduced by 43.3% and 31.6%, respectively for average and very high climatic conditions. For tomato crop, optimal irrigation requirements could be reduced by 33.3% for average demand and 31% for very high water demand. Regarding the water use indexes, results show that water conservation due to deficit irrigation strategies improves water productivity under the average water demand more than the very high demand. This improvement was more noticeable for potato than tomato. Furthermore, economic water productivity is more affected by the difference in potato and tomato prices for average (2016) and very high (2017) water demand conditions.

Keywords: Deficit irrigation; Irrigation simulations; Relative yield loss; Water productivity

1. Introduction

Tunisia is ranked among the countries most deprived of water in the Mediterranean basin with a water quota of less than 500 m^3/cap/y. Water demand of agriculture is constantly increasing due to the intensification of irrigation and the associated increase of irrigated acreages. Irrigation accounts for near 80% of the total water demand for an irrigated area of 435,000 ha [1]. Although the irrigated agriculture represents only about 8% of the cropped area, it nevertheless contributes to 30%–35% of the total agricultural production [2]. Among irrigated crops, potato and tomato are considered as strategic crops and are widely cultivated in various regions of the country. In 2018, the Tunisian

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potato production accounts for 465,000 tons over a cultivated area of near 24,300 ha. For tomato crop, the tomato production was about 1.187 million of tones for a harvested area of 21,200 ha [3]. Many studies have shown that potato is sensitive to water stress; hence, water shortages may result in reduction in tuber yield and quality [4–6]. Tomato can tolerate moderate drought once good canopy cover is achieved. On the other hand, mild to moderate water stress early in the season, if lasting for many days, can result in a markedly smaller canopy, and hence, less biomass production resulting from reduced radiation capture [7]. In arid and semi-arid areas, as the most of Tunisia, where water is the main limiting factor for plant growth, optimization of water use efficiency is becoming a must for increasing agricultural productivity, improving food security and ensuring sustainability water-resources [8–10]. The increasing pressure of different sectors on water resources (agriculture, industry, tourism, water drinking, ecological needs) augurs a water stress, which should evolve crescendo. Several studies reported that the climatic change projections in Mediterranean region would be critical for the cropping systems considering the increase in the temperature and the significant rainfall decrease [11,12]. Given the recurrence of drought periods in recent years, Tunisian irrigation managers have even adopted severe restriction measures for water supply to cope with water scarcity. Indeed, in 2017 the volumes intended for irrigation were reduced by 20%–30% of the water requirement of the irrigated areas [13]. To cope with scarce water supplies, adoption of deficit irrigation stands as an important tool to reduce irrigation water use and potentially improve water productivity of many field crop [14,15].

The aim of this study was to assess the effect of deficit irrigation on crop water requirements, yield and water productivity under different water demand conditions. The FAO CROPWAT irrigation scheduling and simulation model is used to evaluate the effect of deficit irrigation on crop yield and irrigation requirements. The objective was also to identify appropriate deficit irrigation strategies that allow water conservation with acceptable impact on yields and thus ensuring sustainability of irrigation systems in the semi-arid conditions of the Medjerda lower valley of Tunisia.

2. Materials and methods

2.1. Case study

The case study for this research was Cherfech irrigation district, Medjerda lower valley, near Ariana, northeast of Tunisia (37°N, 10.5°E, elevation of 328). The climate is semi-arid Mediterranean with yearly average precipitation of 443 mm. The season distribution of rainfall is typical of a Mediterranean pattern, with a minima in summer, the period of maximum crop water requirements. The average reference evapotranspiration (ET_0) as computed by the Penman-Montheith method [16] is 1,105 mm. The water deficit ($P-ET_0$) extends from March to October with a peak in July, which corresponds to the water requirement peak month.

According to the USDA soil classification, the soil texture at the study area can be classified as silty clay loam (34.8% clay, 57.6% loam, 7.6% sand). The total available water is 160 mm/m (water content at field capacity and wilting point are 0.42 and 0.26, respectively). The average electrical conductivity of the irrigation water is 2.6 dS m^{-1}.

2.2. Crop water-yield simulations

Assessment of crop evapotranspiration and irrigation requirements under standard and deficit conditions were performed using FAO CROPWAT 8.0 irrigation scheduling and simulation model (http://www.fao.org/land-water/databases-and-software/cropwat/en/). CROPWAT is a decision support tool developed by the Land and Water Development Division of FAO for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data [16]. The soil is managed as a unique reservoir, refilled by irrigation water and precipitation and depleted by drainage and crop evapotranspiration. The model can be used to determine the optimum irrigation schedules and to evaluate the effect of deficit irrigation on water use and crop yield.

In this work, the irrigation simulations were performed for potato and tomato crops based on meteorological, agronomic, and soil data of the case study area in 2016 and 2017. Crop coefficients K_c during the crop season determined using the KCISA program [17] are presented in Table 1. Data on the

Table 1
Potato and tomato crop parameters for Cherfech region

		Crop development stages			
		Initial	Development	Mid-season	Final-season
Potato	Planting date: 10/02				
	Period length (days)	30	35	50	16
	K_c (2016)	0.91	0.91–1.12	1.12	0.4
	K_c (2017)	0.65	0.65–1.15	1.15	0.45
Tomato	Planting date (01/04)				
	Period length (days)	30	35	50	27
	K_c (2016)	0.83	0.83–1.15	1.15	0.68
	K_c (2017)	0.45	0.45–1.15	1.15	0.60

Table 2
Available soil water at planting for potato and tomato crops

	2016		2017	
	Potato	Tomato	Potato	Tomato
Initial soil moisture depletion (% TAW)	50	85	50	95
Initial available soil moisture (mm/m)	80	24	80	8

available soil water at planting used by CROPWAT for simulations purposes are shown in Table 2.

2.3. Deficit irrigation strategies

In this study, the CROPWAT model was used to simulate the crop response to irrigation management under different water availability conditions. For this purpose, deficit irrigation strategies corresponding to different levels of water restriction were adopted in order to assess the effect of deficit irrigation on water use and crop yield. This approach is based on the water restriction measures adopted by local irrigation managers in order to cope with water scarcity. CROPWAT model allows different timing options related to when irrigation is to be applied. Thereby, the deficit irrigation strategies were selected based on the irrigation timing options that allow for a stress level for agronomic reasons as described in Allen et al. [16]. When irrigation is applied before the depletion of the readily available moisture, the maximum yield is achieved. Conversely, the deficit irrigation strategies were selected by adopting soil moisture depletion levels that induce water stress and thus yield reduction. In CROPWAT, evaluation of the deficit irrigations strategies were performed using the yield – water stress function [18]:

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{\mathrm{ET}_a}{\mathrm{ET}_m}\right) \tag{1}$$

where Y_a is the actual yield, Y_m is the maximum yield, ET_a is the actual season crop evapotranspiration, and ET_m is the maximum season crop evapotranspiration and K_y is the yield response factor representing the effect of reduction in crop evapotranspiration on yield. ET_m, is determined through the product of the reference crop evapotranspiration (ET_0) times the crop coefficient (K_c) [16]:

$$\mathrm{ET}_m = K_c\mathrm{ET}_0 \tag{2}$$

Using the above original FAO water production function, deficit irrigation strategies were evaluated trough parameters of irrigation (mm), relative crop evapotranspiration $\mathrm{ET}_a/\mathrm{ET}_m$ (%), and relative yield loss, computed as RYL = $(1 - Y_a/Y_m)$ expressed in %. Previously, optimum irrigation alternative to meet the maximum yield (exercised when readily available moisture RAM is depleted) was determined for both tomato and potato crops.

2.4. Water productivity

Two water productivity indexes [19] were computed:

Water productivity WP (kg/m^3) defined as the ratio of actual crop yield achieved Y_a (kg/ha) to gross irrigation water use IWU (m^3/ha).

$$\mathrm{WP} = \frac{Y_a}{\mathrm{IWU}} \tag{3}$$

When replacing the numerator of Eq. (3) above by the monetary value of the actual yield (TND, Tunisian Dinar), the economic water productivity EWP (TND/m^3) can be defined by:

$$\mathrm{EWP} = \frac{\mathrm{Value}\left(Y_a\right)}{\mathrm{IWU}} \tag{4}$$

EWP was computed based on the prices of potato in the local market for 2016 and 2017.

3. Results and discussion

3.1. Climate analysis: rainfall and reference evapotranspiration

Statistical analysis of the 30 years' time series (1986–2015) shows that yearly average rainfall in the study area is 443 mm while maximum and minimum values are 703 and 282 mm respectively. Monthly rainfall and reference evapotranspiration (ET_0, estimated by Penman–Monteith method [16] for 2016 and 2017 vs. average year are presented in Figs. 1 and 2 respectively. In 2016, annual rainfall was 439 mm and ET_0 amounts 1,083 mm/y. The water deficit (P-ET_0) extends from February until October with a peak in July (Fig. 1). While Fig. 2 shows that 2017 was drier with annual rainfall of 283 mm and ET_0 of 1481 mm/y. In addition, the water deficit (P-ET_0) was spread over the whole year 2017 except for February including maximum values on July, August and September (Fig. 2)

Regarding the evaporative demand estimated by reference evapotranspiration ET_0, Fig. 1 indicates that water demand for 2016 was very close for the average year. Moreover, Fig. 2 exhibits the very high water demand conditions of 2017 compared to the average year particularly during the period lasting from July until the end of the year.

With respect to season rainfall, results show that 2016 was very close to the average year for potato growing season (February – June) and relatively deficient for tomato growing season (April – August) with a rainfall shortage of about 30 % compared to the average year. In addition, 2017 was marked by rainfall deficit of 60% with respect to the average year for both potato and tomato crop season.

3.2. Crop response to deficit irrigation strategies

In a first step, CROPWAT was used to identify the net irrigation requirements for optimal irrigation schedules. Results showed that potato maximum yield is achieved with net season irrigation of 300 mm under average climatic conditions of 2016 and 380 mm under very high climatic conditions of 2017. For tomato, maximum yield is reached

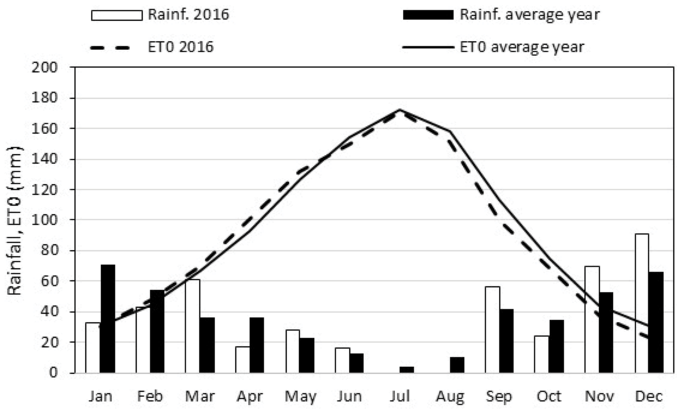

Fig. 1. Monthly rainfall and reference evapotranspiration in 2016 for Cherfech region.

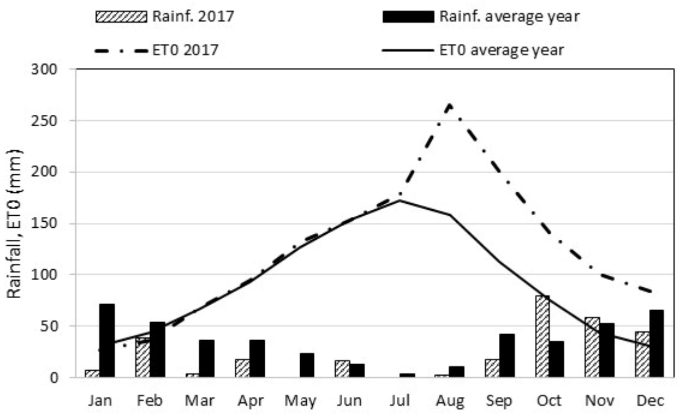

Fig. 2. Monthly rainfall and reference evapotranspiration in 2017 for Cherfech region.

applying 600 mm in 2016 and 720 mm in 2017. The deficit irrigation evaluations performed for the climatic conditions of 2016 and 2017 are displayed in Fig. 3 for potato crop and Fig. 4 for tomato crop.

Results indicate that under average water demand of 2016, reducing potato season irrigation by 46.7% (from 300 to 160 mm) induces a RYL of 26.7%. For the very high water demand of 2017, RYL would be 40.3% when potato irrigation requirements are reduced by 47.4% (from 380 to 200 mm). Furthermore, for average demand, results showed that small reduction in potato season irrigation from 300 to 260 mm would induce a RYL of 6%, easily acceptable by farmers. Conversely, for the very high demand, reducing irrigation to 260 mm would generate a much higher RYL (24.7%). These results indicates that adopting deficit irrigation is more practical for average water demand of 2016. While for very high water demand of 2017, only low to moderate water shortage are tolerated. Under limited water availability, and when considering a production target such that the RYL remains below a 25% threshold, results showed that potato optimal irrigation could be reduced by 43.3% and 31.6% respectively for average and very high climatic conditions (Fig. 3).

For tomato crop, results indicate that under average demand conditions of 2016, decreasing season irrigation from 600 to 400 mm generates a RLY of 25%. Under very high demand of 2017, it is worth emphasizing that applying 400 mm would result in a RYL of 40% making adoption of deficit irrigation more difficult particularly under water scarcity conditions. For a RYL threshold of 25%, results showed that tomato optimal water requirement could be reduced by 33.3% and 31%, respectively under average and very high water demands (Fig. 4).

This difference in crop response to deficit irrigation can be explained mainly by the season rainfall. In fact, for average water demand of 2016, precipitation beneficially reduces potato irrigation requirements, which are much greater under very high water demand of 2017. Consequently, when water is limited, adoption of deficit irrigation with acceptable RYL will be more feasible under average demand conditions than under very high conditions. Whereas for tomato, which is a summer crop, rainfall faintly contributes to crop evapotranspiration. For both average and very high demands, irrigation decrease generates a reduction in crop evapotranspiration and crop yield making it more difficult to adopt deficit irrigation mainly for very high demand of 2017. These results bolster those [20] who stated that in the semi-arid central of Tunisia, adoption of deficit irrigation is feasible for wheat, potato and tomato crops under average water demand.

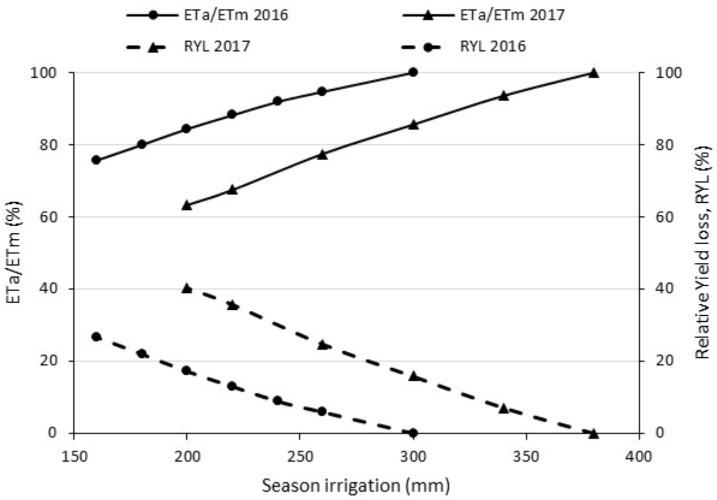

Fig. 3. Potato response to deficit irrigation in Cherfech for average (2016) and very high (2017) water demand conditions.

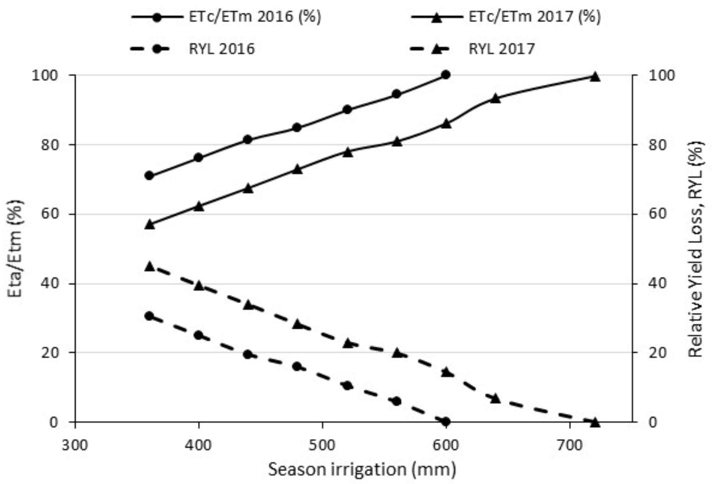

Fig. 4. Tomato response to deficit irrigation in Cherfech for average (2016) and very high (2017) water demand conditions.

Zairi et al. [20] indicated that deficit irrigation is not feasible for potato and tomato crops under high and very high climatic conditions; the alternative is to reduce the cultivated area.

3.3. Water productivity

For the water use indexes, results showed that water savings due to deficit irrigation strategies improve water productivity under average water demand more than very high demand (Figs. 5 and 6). This improvement was more noticeable for potato than tomato crop. Indeed, for average demand, a water saving of 150 mm increases by 30% potato water productivity. This result upholds the finding showing that reducing irrigation increases water productivity of potato in the Cherfech region [21]. However, for tomato the increase in water productivity would be 12.5% for a water saving of 250 mm. This result confirms that deficit irrigation is a difficult option for tomato crop.

For a RYL set at 25% threshold, results indicate that potato water productivity decreases by 34.9% under the very high demand of 2017 in comparison with average demand of 2016. This decrease was less discernible for the economic water productivity (21.3%) due to the increase of potato prices at local market in 2017. For tomato, although water productivity decreased by 20.7% from average to very high water demand, economic water productivity have even increased by 35.8% due to the substantial increase in tomato prices in 2017.

4. Conclusion

Beyond the regional implications of this work, the presented methodology represents a contribution to the use of a crop simulation model and water productivity

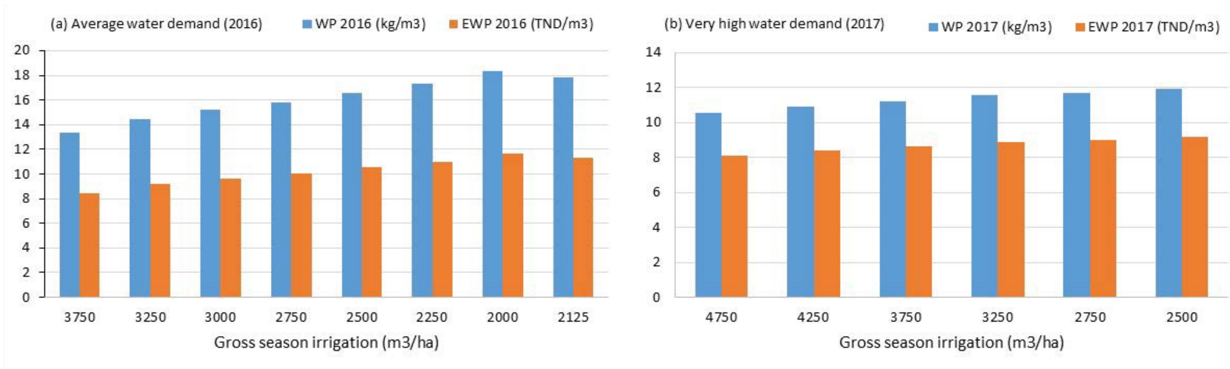

Fig. 5. Water productivity and economic water productivity for deficit irrigation strategies of potato crop in Cherfech region for average (a) and very high (b) water demand conditions (1 TND = 0.37 USD).

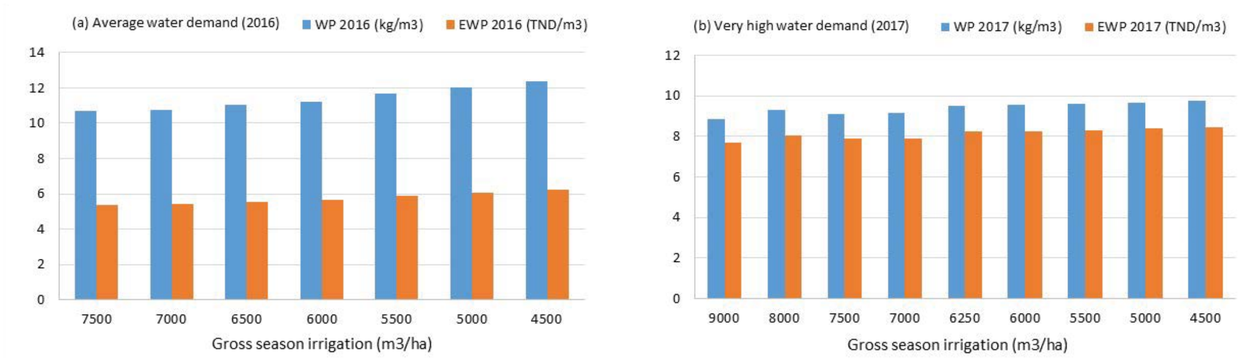

Fig. 6. Water productivity and economic water productivity for deficit irrigation strategies of tomato crop in Cherfech region for average (a) and very high (b) water demand conditions.

indicators as decision support tools leading to recommend proper deficit irrigation scenarios under limited water conditions. Results indicate that potato and tomato crops differently react to deficit irrigation strategies for the climatic conditions of the study area. Although the deficit irrigation strategies has been demonstrated as an appropriate water management choice under average water demand, the socioeconomic implications need to be more assessed under different climatic and water availability conditions. Additional research on coupling the crop model with an economic optimization model needs to be explored in order to evaluate the impact of deficit irrigation on the farmer's income and thus ensure sustainability of production systems in the arid and semi-arid conditions of Tunisia and in other regions where climatic conditions could be similar.

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