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ORIGINAL ARTICLE

Impacts of irrigation regimes with saline water on carrot productivity and soil salinity

Kamel Nagaz [a,*], Mohamed Moncef Masmoudi [b], Netij Ben Mechlia [b]

[a] *Institut des Régions Arides, 4119 Médenine, Tunisia*
[b] *INAT, 43 avenue Charles Nicolle, 2083 Tunis, Tunisia*

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Abstract A three-year study was conducted to evaluate the effects of different irrigation regimes with saline water on soil salinity, yield and water productivity of carrot as a fall-winter crop under actual commercial-farming conditions in the arid region of Tunisia. Carrot was grown on a sandy soil and surface-irrigated with a water having an ECi of 3.6 dS/m. For the three years, a complete randomized block design with four replicates was used to evaluate five irrigation regimes. Four irrigation methods were based on the use of soil water balance (SWB) to estimate irrigation amounts and timing while the fifth consisted of using traditional farmers practices. SWB methods consisted in replacement of cumulated ETc when readily available water is depleted with levels of 100% (FI-100), 80% (DI-80) and 60% (DI-60). FI-100 was considered as full irrigation while DI-80 and DI-60 were considered as deficit irrigation regimes. Regulated deficit irrigation regime where 40% reduction is applied only during ripening stage (FI-DI60) was also used. Farmer method (Farmer) consisted in giving fixed amounts of water (25 mm) every 7 days from planting till harvest. Results on carrot production and soil salinization are globally consistent between the three-year experiments and shows significant difference between irrigation regimes. Higher soil salinity in the root zone is observed at harvest under DI-60 (3.1, 3.4, 3.9 dS/m, respectively, for the three years) and farmer irrigation (3.3, 3.6, 3.9 dS/m) treatments compared to FI-100 treatment (2.3, 2.6 and 3.1 dS/m).

* Corresponding author. Tel.: +216 75633005; fax: +216 75633006.
E-mail address: Nagaz.Kameleddine@ira.rnrt.tn (K. Nagaz).

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Relatively low ECe values were also observed under FI-DI60 and DI-80 treatments with respectively (2.7, 3, 3.5 dS/m) and (2.5, 2.9, 3.3 dS/m). ECe values under the different irrigation treatments were generally lower than or equal to the EC of irrigation water used. Rainfall received during fall and/or winter periods (57, 26 and 29 mm, respectively, during the three years) contributed probably to leaching soluble salts from the root zone. Highest carrot yields for the three years were obtained with SWB scheduling technique FI-100, (29.5, 28.7 and 26.8 t/ha) although we didn't find significant differences with the regulated deficit irrigation regime (FI-DI60). Compared to FI-100, significant reductions in carrot yields were observed under DI-80 and DI-60 deficit irrigation treatments resulting from a reduction in roots number/m^2 and average root weight. The farmer's method not only caused significant reductions in yield but also resulted in using 43–57% more water and increased soil salinity. For all irrigation treatments, carrot yields were higher in the first year compared to the two following years. Water productivity (WP) values reflected this difference and varied between 3.2 and 9.7 kg/m^3. The lowest WP values were observed for the farmer's method, while the highest values were obtained under DI-60 deficit irrigation treatment. The scheduling technique using SWB with variable doses is more efficient than the traditional technique used by farmers in carrot production. The FI-100 irrigation scheduling seems to optimize the use of saline water in carrot production and to control soil salinity. Under situations of water shortage, adopting deficit irrigation strategies (FI-DI60 and DI-80) could be an alternative for irrigation scheduling of carrot crop under the conditions of Mediterranean arid in southern Tunisia.

1. Introduction

Water scarcity and recurrent droughts characterizing the southern Mediterranean region are becoming a serious problem especially in the context of alarming predictions of climate change for the region. Good quality water is becoming a major constraint to crop production in Tunisia and the use of highly saline water for irrigation is expanding. This is particularly true in the arid part of the country where the demand for intensification is increasing under the pressure for creating more jobs and improving income of the rural population. Irrigation of a wide range of crops such as potatoes, lettuces, green beans and carrots is expanding around shallow wells having a TDS ranging from 1.7 to 5 g/l and more. Sustainability of production systems based on crops that are not specifically tolerant to salinity could not be met without proper management of both water and salt.

Good irrigation management practices are required in order to improve farmers practices and water use. Many studies have reported substantial increases in crop yields as a result of suitable irrigation management, including studies under saline conditions (Batra, 1990; Ayars et al., 1991; Parabhakar et al., 1991; Pasternak and De Malach, 1995; Minhas, 1996; Paradiso et al., 2002; Bustan et al., 2004; Zhang et al., 2004; Malash et al. 2005; Jalota et al., 2006; Ali et al., 2007; Nagaz et al., 2007a,b, 2008). It has been demonstrated that optimal irrigation scheduling requires accurate estimates of crop evapotranspiration (ETc) (Doorenbos and Pruitt, 1977). Determination of ETc during the initial stage before complete cover is reached requires considering soil evaporation and crop transpiration separately (Ritchie, 1972).

In the absence of sufficient rainfall events used elsewhere for natural leaching, irrigated farming in arid lands is exposed to accumulation of salts in the soils. Therefore, good management should take into consideration the effect of irrigation on the crop yield and at the same time on the environment, particularly the risk of soil salinization. Both quantity and quality of water to be used and their effects on the farm productivity need to be precisely known. Considerable research has been directed towards defining the effects of salts on crop growth and development (Maas, 1990; Shalhevet, 1994; Shannon and Grieve, 1999). The existing body of information is impressive but should be adapted to the local environment. For instance carrot (*Daucus carota* L.) is an important short duration root vegetable grown for fresh market food but it is considered as relatively susceptible to salinity (Bernstein et al., 1974). This crop is grown in arid regions of Tunisia during autumn and winter, considered as the 'rainy' season, in individual plantings usually not exceeding 1 ha and irrigated with water from shallow wells. Because carrot crop has is high economic value, the irrigation management strategy seeks maximum yield by supplying all requirement of the crop. However, under local practices, irrigation is typically applied on a routine basis without scheduling and supply often exceeds crop requirements. Considering the prevailing low farmers' performances, it seemed possible to significantly increase the total production using the same amount of water.

The impact of irrigation scheduling and deficit irrigation with saline water on carrot yield and quality has not been studied in arid regions of Tunisia. The present work, initiated in 2007 aims at determining irrigation water requirements of carrot crop and to make quantitative assessments of both salt accumulation in the soil and yield response to water supply under full and deficit irrigation strategies with saline water. The objective is to identify best irrigation strategy that allow water saving with reduced effect on soil salinity and crop productivity under the arid Mediterranean conditions of southern Tunisia. With the expectation to promote appropriate irrigation scheduling and deficit irrigation methods among farmers communities, all field work was conducted within local farms and with farmer's participation.

2. Materials and methods

Field experiment was conducted during the fall-winter seasons over three years (2007/2008), (2008/2009), and (2009/2010) in a commercial farm situated in the Southern East of Tunisia

Table 1 Monthly climatic data of the growing season for the period (1979–2002) and for the three years of field experiment.

	September	October	November	December	January	February
Air temperature (°C)						
Long term	23.0	21.5	19.5	10.5	10.5	12.0
2007/2008	25.5	22.5	22.9	11.0	11.5	12.7
2008/2009	27.5	24.9	23.8	12.0	12.5	13.3
2009/2010	26.5	24.0	23.1	11.5	12.1	13.0
Relative humidity (%)						
1979–2002	54	57	63	66	66	60
2007/2008	54	60	59	67	64	60
2008/2009	55	67	64	65	64	54
2009/2010	63	58	65	73	61	66
Rainfall (mm)						
Long term	17	27	19	25	21	18
2007/2008	20	6	0	13	17	0
2008/2009	11	0	0	0	14	0
2009/2010	12	16	0	0	0	0
ETo-PM (mm)						
Long term	141	109	70	53	55	68
2007/2008	166	129	69	67	80	85
2008/2009	162	131	76	66	75	90
2009/2010	165	128	77	67	74	86

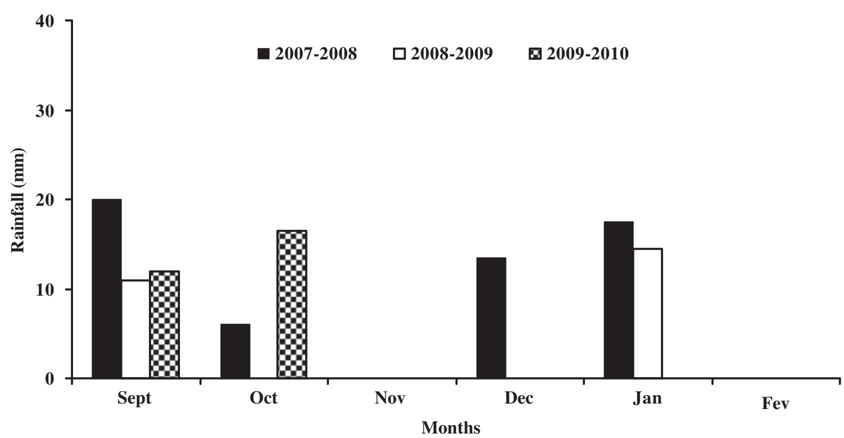

Figure 1 The rainfall received during the carrot cropping periods (2007–2010).

(33°22' N, 9°06' E; altitude 45 m) in the region of Médenine. The climate is typical of arid areas.

Long-term mean monthly climatic data (1979–2002) and climatic data relative to the growing seasons of the period 2007–2010 are presented in Table 1. Average value of precipitation at the site during the full-winter growing season from September to February was 129 mm, which means that irrigation may be required to optimize growth of carrot during the fall-winter months, particularly during dry years. During the first year of the study (2007/2008), fall-winter precipitation was relatively low throughout the entire growing season, totalizing 57 mm by the end of the season (Fig. 1). The year 2008/2009 was considerably drier than the previous year, with only 25.5 mm of rain falling during September and January. During 2009/2010 there was only 28.5 mm of precipitation, most of which fell early in the season (September–October). Reference evapotranspiration (ETo-PM) over each growing season was 438 mm in 2007/2008, 443 mm in 2008/2009, and 440 mm in 2009/2010.

The soil of the experimental area is sandy soil with 87.9% sand, 8.9% silt and 3.9% clay. Average values in the 80 cm topsoil of field capacity (0.33 bar, pF 2.5) and permanent wilting point (15 bar, pF4.2), determined by the membrane method, are respectively 12.0% and 3.6% and organic matter concentration is 6.6 g/kg. The bulk density of soil was 1.49 g/cm^3. The total soil available water calculated between field capacity and wilting point for an assumed carrot root extracting depth of 0.80 m, was 100.5 mm. The electrical conductivity (ECe) values measured before planting of carrot are, respectively, 3.7, 3.2, and 3.7 dS/m for the first, second, and third year.

Fertilizers were supplied during the three years with the same amounts; before planting of carrot crop, soil was spread with 16 t/ha of organic manure. Nutrient supply followed local practices consisting of giving N in the form of ammonium nitrate, P_2O_5 and K_2O at rates of 200, 200, and 150 kg/ha respectively. The P_2O_5 and K_2O fertilizers were applied as basal dose before planting. Nitrogen was divided and delivered

Table 2 Chemical composition of irrigation waters (meq/l).

ECi (dS/m)	$Ca^{2+} + Mg^{2+}$	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	$CO_3^{2-} + HCO_3^{-}$	SARiw
3.6	25.60	9.45	0.95	8.50	23.00	4.50	2.64

with the irrigation water in all treatments during early vegetative growth.

Carrot, native of the region, was planted every year on 15 September, in 8×10 m plots separated from each other in a randomized complete block design with four replicates and five irrigation treatments. The same experimental area was used for the 3 years and was divided into four blocks with five elementary plots per block. Each elementary plot consisted of fifteen rows. Carrot was surface irrigated with water from a well having an ECi of 3.6 dS/m and chemical analysis given in Table 2. Water is delivered to each plot using a hosepipe equipped with a gate valve and a water meter used to control irrigation amounts.

Five irrigation treatments were applied: The FI-100 treatment considered as full irrigation consists of giving 100% ETc when readily available water in the root zone is depleted. Two deficit irrigation treatments were irrigated at the same frequency as treatment FI-100 but irrigation amount covered 60% and 80% of cumulated ETc (DI-60 and DI-80). These treatments were identified as continuous deficit irrigation treatments. In the fourth treatment (FI-DI60), considered as regulated deficit irrigation regime, water was applied as FI-100 during the planting-mid-season period and restricted to 60% of ETc afterwards, until harvest. A fifth irrigation treatment consisted of applying the traditional irrigation practices adopted by local farmers where fixed amount of water (25 mm) are supplied to the crop every 7 days from planting till harvest.

The crop evapotranspiration (ETc) was estimated for daily time step by using reference evapotranspiration (ETo) combined with carrot crop coefficient (Kc) using the single crop coefficient approach. ETo is estimated using daily climatic data collected from the meteorological station, located at Médenine, Tunisia and the FAO-56 Penman-Monteith method (ETo-PM) given in Allen et al. (1998). The Penman–Monteith method considers hypothetic grass reference crop with a crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23.

For irrigation scheduling, the method used was the water balance developed according to the methodology formulated by Allen et al. (1998) and implemented in an Excel spreadsheet program. The program estimates the day when the target soil water depletion (readily available water, RAW) for the treatment FI-100 would be reached and the amount of irrigation water needed to replenish the soil profile to field capacity. The program calculates on daily basis the soil water depletion using the soil water balance and estimates the next irrigation date considering a depletion limit of 35% of total available water in the root zone (TAW). Soil depth of the effective root zone is automatically increased linearly with carrot crop coefficient from a minimum of 0.15 m at planting to a maximum of 0.80 m.

At physiological maturity carrot yield is determined for each treatment. Forty plants per row within each plot are harvested by hand in the first week of February to determine fresh root yield (t/ha), root number/m^2 and average root weight (g/root).

Every year, soil samples are taken before planting and after harvest, from two points within homogeneous areas in each elementary plot. Soil is sampled with a 4 cm auger from four depths (0–0.20; 0.20–0.40; 0.40–0.60; 0.60–0.80 m in depth), it is air-dried and ground to pass a mesh of 2 mm size and then analyzed for ECe.

Water productivity (WP) is generally defined as marketable yield/ET, but economists and farmers are most concerned about the yield per unit of irrigation water applied. Thus, The WP was calculated as follow: WP (kg/m^3) = Yield (kg/ha)/irrigation water (m^3/ha) from planting to harvest; an irrigation of 100.5 mm applied before planting is not included in the total.

Analysis of variance was performed to evaluate effect of irrigation treatments on carrot yields and components, WP and soil salinity using the STATGRAPHICS *Plus* 5.1 (www.statgraphics.com). LSD test at 5% level was used to test for any significant difference between treatment means.

3. Results and discussion

3.1. Evapotranspiration estimates and soil water balance

Fig. 2 illustrates the course of mean daily ETc relative to ETo for three years during the growing periods of carrot crop. During the first 30 days after planting high ETo values resulted in high ETc despite the low crop cover. Frequent wetting of the soil surface by irrigation or precipitation increased soil evaporation, controlled mainly by soil hydraulic properties and solar radiation. This period is characterized by mean values of ETc of about 3.6 mm/day. Lower values were observed at development and mid-season stages with, respectively, 3.0 and 2.1 mm/day following the decrease in evaporative demand in winter. The ETc value at the late stage increased slightly to about 2.50 mm/day as a result of the warmer conditions corresponding to the end of winter season.

The spreadsheet program uses water balance equation and gives estimations of the date and amounts of irrigation based on cumulative soil water depletion. Fig. 3 illustrates soil water depletion, estimated by the program, under FI-100 treatment for the cropping period of carrot for 3 years. This figure illustrates the effect of an increasing root zone on the readily available water. The rate of root zone depletion at a particular moment in the season is given by the net irrigation requirement for that period. Each time the irrigation water is applied, the root zone is replenished to field capacity. Because irrigation is applied only when soil water depletion at the end of the previous day exceeds to the readily available water, plants may suffer a slight stress on the day prior to irrigation.

3.2. Soil salinity

The initial and final average ECe values in the 0–80 cm soil layer under the different irrigation treatments are presented in Fig. 4. Initial soil salinity values determined at planting were, respectively, 3.7, 3.2 and 3.7 dS/m in the first, second and third year. The results show that during the three years,

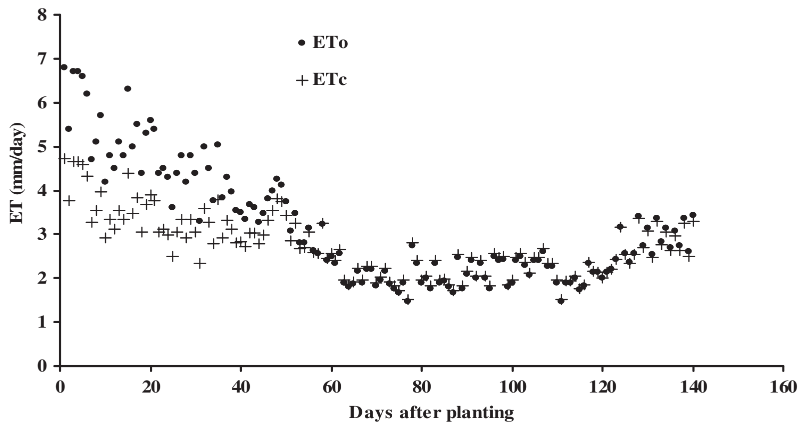

Figure 2 Mean values of daily ETo and ETc during the cropping period of carrot (2007–2010).

a decrease in ECe values measured at harvest is observed under all irrigation treatments compared to initial soil salinity. The decrease of ECe values is attributed to the leaching of soluble salts by fall and winter rains (57 mm) (Fig. 1). In 2009 and 2010, ECe decreased only for treatments FI-100, DI-80 and FI-DI60 while its value was relatively higher at harvest than the initial ECe for DI-60 and farmer's method despite fall and winter rains. The capacity of fall-winter rainfall to leach salts in the region is variable and depends on the total amount and distribution of rainfall events. This is illustrated by the lowest ECe values observed in the first year which corresponds to the highest amount of total rainfall during carrot growing season (Fig. 1) that seemed to be effective in removing salts accumulated in the root zone.

ECe data (Fig. 4) shows a decrease in ECe values between planting and harvest for full irrigation treatment (FI-100). FI-DI60 irrigation treatment resulted also in low ECe values at harvest without significant difference with FI-100 during the three years. However, higher soil salinity levels were observed for deficit irrigation regimes. ECe values were, in a decreasing order, DI-60 > DI-80 > FI-100. The reason for the higher soil salinity obtained for deficit irrigation treatments is attributed to absence of substantial leaching under deficit irrigation conditions. Schoups et al. (2005), Kaman et al. (2006) and Geerts et al. (2008) reported that one consequence of reducing irrigation water use by deficit irrigation is the greater risk of increased soil salinity due to reduced leaching. The highest ECe values were observed for farmer's irrigation method where more water is applied without adequate scheduling and the high frequency of application during the first stage seem to concentrate salts in the root zone.

ECe values under the different irrigation treatments were generally lower than or equal to the EC of irrigation water used. Singh and Bhumbla (1968) observed that the extent of salt accumulation depends on soil texture and reported that in soils containing less than 10% clay the ECe values remains lower than ECiw. Low values of ECe under the prevailing climatic conditions were due to the natural leaching of soluble salts by rainfall that occurred during fall and/or winter periods (Fig. 1). Thus, under actual farming conditions, the use of saline waters for irrigation of short-cycle crops during the rainy season seems to have low impact on soil salinization as salts added by irrigation are removed from the root zone by natural leaching.

3.3. Crop yield

Results on yield during the three years of experimentation are presented in Fig. 5 and Table 3. Carrot yields of DI-80 and DI-60 treatments were significantly different and lowest yields were observed for the farmer's method and DI-60. These two last treatments did not show a statistical difference between them and have much lower yields than those obtained under FI-100 regime. Although yield observed under FI-100 is numerically higher than FI-DI60 difference was not statistically different during the three years. However, yields decreased significantly for DI-80 and DI-60 treatments during the three years of the study.

DI-60 and farmer's irrigation treatments had similar root yields, but 40% less irrigation water than full irrigation regime is used in the first while the farmer used more than 40% water than FI-100. Also, with 20% less water DI-80 treatment resulted in 22–29% more yield than farmer' method. Roots number/m^2 and average root weight (Table 3) were affected by the irrigation regime. The root weight and number obtained under farmer's method were the lowest while the highest were obtained for FI-100 and FI-DI60 irrigation treatments.

The relatively low levels of root yields obtained under farmer's and DI-60 irrigation treatments compared to the full treatment (FI-100) were associated with lower root number/m^2 and root weight (Table 3) as a consequence of water stress during the period between fruit-set and harvest. Thus, the better yields obtained under FI-100, FI-DI60 and DI-80 treatments are attributed to better growth and yield components due to appropriate water supply. Results are in agreement with the results reported by Hartmann et al. (1986), Parabhakar et al. (1991), Imtiyaz et al. (2000) and Paradiso et al. (2002), who obtained higher total marketable, root size and number with 100% ETc, full irrigation treatment. It seems that, water stress should be avoided between fruit-set and harvest, the most critical period of carrot for irrigation.

Yields were highest in the first year because of the low soil salinity and the higher amount of rainfall (57 mm). During the experimental periods the differences in yield and its components under FI-100 and FI-DI60 treatments were not significant. Reduction of water supply after mid-season stage by 40% (FI-DI60) seems to have low impact on soil salinity and yield of carrot crop as compared to full irrigation regime.

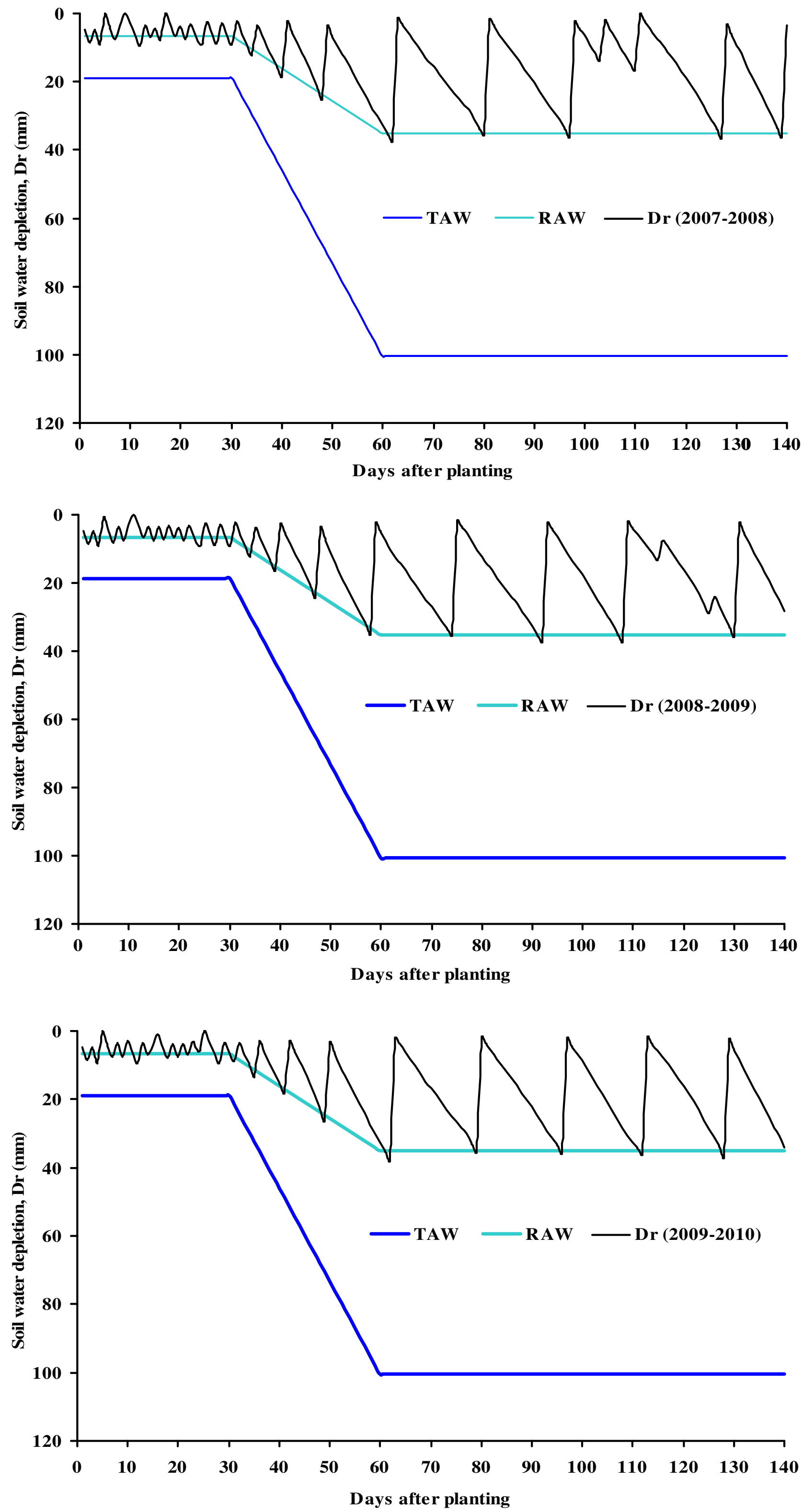

Figure 3 Estimated daily soil water depletion under FI-100 irrigation treatment during the cropping season of carrot (2007–2010).

The use of SWB strategy for managing irrigation water resulted in better yields than the method using fixed frequency and amounts practiced by local farmers. Deficit irrigation and farmer's strategies results in higher salinity in the rooting zone than the FI-100 and FI-DI60 (Fig. 4). The higher soil salinity levels associated with the deficit irrigation and farmer's strategies induced substantial yield reduction of carrot. These results, obtained under actual farming conditions, support

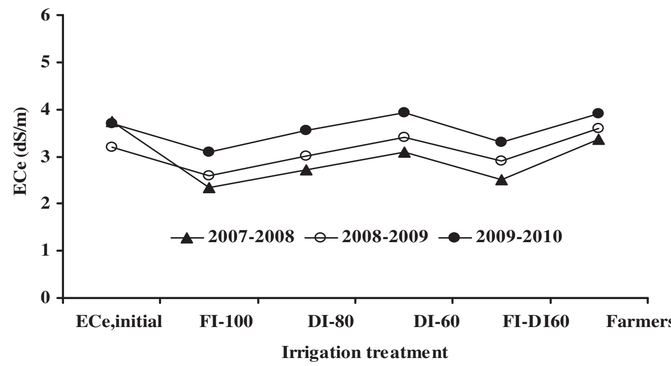

Figure 4 Soil salinity (ECe, dS/m) under different irrigation treatments of carrot.

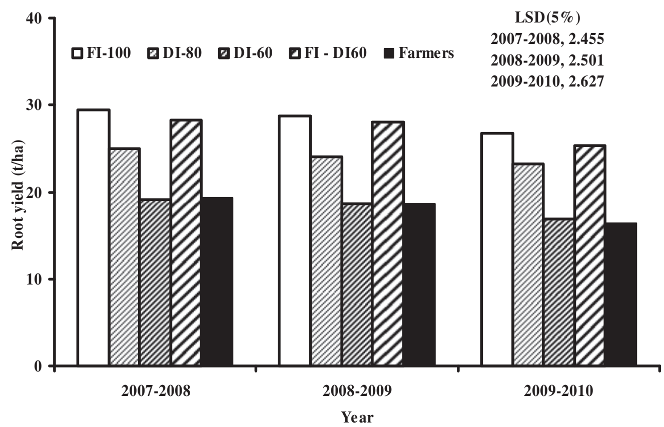

Figure 5 Yields of carrot under different irrigation treatments grown during the 2007/2008, 2008/2009 and 2009/2010 fall-winter field seasons.

Table 3 Yield components of carrot under different irrigation treatments for the three years of the study (2007–2010).

Treatment	Yield component/Year					
	Root number/m^2			Average root weight (g/root)		
	2007–2008	2008–2009	2009–2010	2007–2008	2008–2009	2009–2010
FI-100	71	70	67	41.3	41.0	40.0
DI-80	64	59	59	35.4	40.7	39.3
DI-60	60	55	52	24.2	33.9	32.6
FI-DI60	70	68	63	36.2	41.2	40.2
Farmers	62	57	52	23.7	32.8	31.6
LSD (5%)	4.3	5.2	5.0	3.60	2.77	3.11

the use of SWB strategy for irrigation with saline water. Numerous reports recommend the use of SWB strategy for conditions similar to those of the present paper (Smith, 1985; Raes et al., 2002; Nagaz et al., 2007b). Carrot crop seems to give acceptable yield with saline water, if irrigation management practices maintain a deficit under 20% of ETc (DI-80).

The yield is greatly dependant of timing, amount and frequency of irrigation applied. Lower yields obtained under farmer's method may be attributed to the fact that the farmer applies water to the crop regardless of the effective plant needs. He seems to relate irrigation occurrences to days after planting rather than to crop growth stages progress. The corresponding irrigation applications are often characterized by periods of over- and under-irrigation. Raes et al, (2002) reported that excess watering in saline conditions may cause loss of valuable nutrients out of the root zone and soil salinization, especially during crop sensitive periods, which results in limited growth and reduction in crop yield.

The SWB irrigation scheduling based on crop water requirements and soil characteristics resulted in water amounts and intervals adapted to the crop requirement change during the growing season. Smith (1985) reported that accurate or optimal irrigation scheduling is only possible when water supply and irrigation amounts can be managed independently by farmer. For a small surface farms with an independent water source, as in arid regions of Tunisia where irrigation use

Table 4 Water supply, irrigation and total water productivity under different irrigation treatments during the growing period of carrot for 3 years.

Treatment	Irrigation water (mm)	Rainfall (mm)	I + R (mm)	IWP (kg/m^3)	TWP (kg/m^3)
2007–2008					
FI-100	328	57	385	8.9	7.6
DI-80	262	57	319	9.5	7.8
DI-60	197	57	254	9.7	7.5
FI-DI60	297	57	354	9.5	7.9
Farmers	509	57	566	3.8	3.4
LSD (5%)	–	–	–	0.78	0.54
2008–2009					
FI-100	330	25	355	8.6	8.0
DI-80	264	25	289	9.1	8.3
DI-60	198	25	223	9.4	8.3
FI-DI60	315	25	340	8.9	8.2
Farmers	518	25	543	3.6	3.4
LSD (5%)	–	–	–	0.62	0.39
2009–2010					
FI-100	328	28	357	8.1	7.5
DI-80	263	28	291	8.8	7.9
DI-60	197	28	225	8.6	7.5
FI-DI60	299	28	327	8.4	7.7
Farmers	471	28	499	3.4	3.2
LSD (5%)	–	–	–	0.50	0.41

shallow well waters, accurate scheduling is manageable and therefore there is high chances to optimize water supply to crops.

3.4. Water productivity

The amounts of water applied for the carrot from planting to harvest over the three-year period are given in Table 4. Irrigation water applied before planting of carrot (100 mm) each year is not included in the total. Total rainfall amounts for the three growing seasons were 57, 25 and 28 mm in 2007/2008, 2008/2009 and 2009/2010, respectively. Cumulative ETo over the growing season for the three year study were 438, 443 and 440 mm, respectively.

For FI-100 treatment, giving 100% ETc, irrigation amounts of the three years were quite similar with 328 mm in 2007/2008, 330 mm in 2008/2009, and 328 mm in 2009/2010. These amounts are comparable to those reported by Parabhakar et al. (1991) and Paradiso et al. (2002).

Using the FI-DI60 strategy, 31, 15, and 29 mm of water were saved respectively, in the first, second and third year. Similarly, the water savings achieved from the 80% and 60% of ETc approach (DI-80 and DI-60) were 66 and 131 mm compared to the FI-100 treatment.

Water productivity based on fresh root production was expressed as the ratio of root yield at harvest to the water supply (Table 4). The WP values obtained in this study were similar to those reported for carrot by others (Parabhakar et al., 1991; Imtiyaz et al., 2000) and were affected by irrigation treatments. There is also a variation in WP values between years. For all irrigation treatments, yield was higher in the first year compared to the two following years. Values of water productivity of irrigation (IWP) reflect this difference, they varied typically around 3.8–9.7, 3.6–9.4 and 3.4–8.8 kg/m^3, respectively, in the first, second and third year.

For all experiments, the WP values obtained with FI-100 treatment were not significantly different from those obtained with DI-80 and FI-DI60 treatments but were statistically different from those obtained with DI-60 and farmer's treatments. WP obtained using farmer's method was statistically different from those obtained with DI-80 and DI-60 treatments. These two last treatments did not show a statistical difference between them.

Highest IWP are obtained in 2007–2008 with 9.7 kg/m^3 for DI-60 treatment, followed by DI-80, FI-DI60 and FI-100 treatments with respectively 9.5, 9.5 and 8.9 kg/m^3. Minimum IWP of 3.8 kg/m^3 was obtained for farmer's treatment during the first experimental year. Values were in the same range in the following years 2008–2009 and 2009–2010. The low IWP for the farmer method during the two experiments can be attributed to reduced yields but also to higher irrigation water use.

4. Conclusions

Results obtained over 3 years of field experiment using five irrigation regimes with saline water show that in the arid condition of southern Tunisia full-irrigated carrot grown over fall-winter period used 328–330 mm of irrigation water. Evidence from the study indicates that irrigation amount can be reduced by adopting regulated and moderate deficit irrigation (FI-DI60 and DI-80). Full irrigation (FI-100) and deficit irrigation treatments (FI-DI60 and DI-80) maintained low level of soil salinity while higher soil salinity levels in the root zone were observed with DI-60 deficit irrigation strategy and farmer's method. Carrot yields were affected by irrigation treatments. Root yields of deficit irrigated treatments (DI-60 and DI-80) were significantly lower than those obtained under full irrigation (FI-100) and regulated deficit irrigation (FI-DI60). Deficit irrigation treatments DI-60 resulted in lower yields and in higher salinity in the root zone than full irrigation regime (FI-100). The "fixed amount approach" used by the farmer gave the lowest root yields i.e. 34–38% less than FI-100 with 43–57 % more water and resulted in higher salinity in the rooting zone.

The water productivity of carrots irrigated with saline water was significantly affected by irrigation regime. The lowest values are observed for the farmer's method, while the highest values were obtained under DI-60 deficit irrigation treatment. High efficiencies observed for the most severe restricted regime (DI-60) is therefore counterbalanced by reduced yield and quality. The relatively high yields and water use efficiency values obtained under DI-80 and FI-DI60 treatments indicate the high potential of the carrot crop to valorize irrigation waters of limited quality under mild water deficit conditions.

As a conclusion it seems the full irrigation (FI-100) and deficit irrigation (FI-DI60 and DI-80) strategies offer significant advantages for both yields and WP of carrot crop and reduce the build-up of salinity in the root zone (0–80 cm) compared to the DI-60 and farmer's irrigation practices. Full irrigation scheduling technique FI-100 could be recommended for irrigation of carrot crop under the arid climate of southern Tunisia with the possibility to reduce supply up to 20% in case of limited water availability (DI-80 and FI-DI60). Deficit irrigation offers a potential way to improve water productivity and to control soil salinization when it can benefit from the leaching capacity of rains. Investigation should focus on this issue and evaluate the efficiency of the small amounts of rain that occur in fall-winter for natural leaching. Conducting the field experiment on a commercial farm with the contribution of the farmer will facilitate the extension as the results are fully accessible to the local farmers.

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