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Soil salinity and water productivity of carrot-millet system as influenced by irrigation regimes with saline water in arid regions of Tunisia

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Abstract: Field studies were conducted for three years to determine the effects of irrigation regimes with saline water (3.6 dS/m) on soil salinity, yield and water productivity of carrot and millet under actual commercial-farming conditions in the arid region of Tunisia. Carrot and millet were grown during fall-winter and summer seasons on a sandy soil, surface and drip-irrigated with well water having an ECi of 3.6 dS/m. For three years, a complete randomized block design with four replicates was used to evaluate five irrigation regimes. Irrigation regimes consisted in water replacements of cumulated ETc at levels of 100% (SWB100, full irrigation), 80% (DI-80), 60% (DI-60), when the readily available water in SWB100 treatment is depleted, deficit irrigation during ripening stage (SWB100-DI60) and farmer method corresponding to irrigation practices implemented by the local farmers. The results showed that soil salinity was significantly affected by irrigation treatments. Higher soil salinity was maintained in the root zone with DI-60 and farmer irrigation treatments than full irrigation (SWB100). SWB100-DI60 and DI-80 treatments resulted also in low ECe values. Soil salinity was kept within acceptable limits for the growth of the crops grown in the rotation when SWB100, SWB100-DI60 and DI-80 strategies were employed. The rainfalls received during fall-winter and spring periods were effective in leaching salts from the soil profile. During the three year period, carrot and millet yields were highest for the SWB100 full treatment, (29.5, 28.7 and 26.8 t/ha for carrot and 27.2, 28.3 and 26.9 q/ha for millet) although no significant differences were observed with the regulated deficit irrigation treatment (SWB100-DI60). However, the DI-80 and DI-60 deficit irrigation treatments caused significant reductions in carrot and millet yields through a reduction in roots number and weight, panicle number, kernel number and weight in comparison with SWB100. The farmer's method caused significant reductions in yield and resulted in using 43 to 57% and 27 to 47% more water, respectively, in the carrot and millet growing seasons and increased soil salinity. For all irrigation treatments, carrot yields were higher in first than the two following years and millet yield was higher in second than first and third year. Water productivity (WP) values reflected this difference and varied, respectively, between 3.29 and 9.7 kg/m^3 and 0.35 and 0.95 kg/m^3 for carrot and millet crops. The lowest WP values occurred under the farmer's method, while the highest values were obtained under DI-60 deficit irrigation treatment. SWB100 irrigation treatment provides significant advantage on yield and WP compared to farmer's method in carrot and millet production under experimental conditions. Thus, for water-saving purposes, the SWB100 irrigation scheduling is recommended to optimize the use of saline water in carrot and millet production and to control soil salinity. Under situations of water shortage, the deficit irrigation strategies (SWB100-DI60 and DI-80) are recommended as a tool to schedule irrigation of carrot and millet crops under the arid conditions of southern Tunisia.

Keywords: salinity, deficit irrigation, irrigation scheduling, carrot, millet, yield, water productivity.

Introduction

Water scarcity represents the heart of agricultural and rural development issues in arid regions. This will be intensified by the global climate change affecting the whole North Africa region. The great challenge for the upcoming decades will therefore be the task of increasing crop production with less water, particularly in regions with limited water, land resources and inefficient water use. This is especially the case in arid regions of Tunisia characterized by a harsh climate and subject to frequent droughts and where restricted supply of good quality water is the most important factor limiting the crop production. In these regions, having underground water resources, the farmers turn into the use of low quality waters (1.7 to 5 g/l TDS and more) obtained from shallows. In these areas, sensitive and tolerant crops to water and saline stress developed but the question of the cropping systems sustainability arises.

The sustainable use of saline waters requires the adoption of specific practices by farmers. The current practices in the arid regions of Tunisia give to vegetable and cereal crops an important place in the annual crops rotations (Nagaz *et al.,* 2010). With this practice, various crops are planted over several seasons in order to reduce the soil salinization, the impact of water deficit and to optimize the use of water and manures. Thus, the farmers turn towards crops with short cycle and high economic value, trying to coincide the crops periods with the rainy season in order to increase the productivity of irrigation and rain waters and then to reduce the soil salinization. The crop rotation practices adopted by farmers can constitute a kind of adaptation to a situation of water deficit and to optimize the saline water use and the crop production. However, the irrigation water management of the cropping systems remains very empirical. The irrigation water quantities delivered by the farmers are the result of local empirical practices (Nagaz *et al.,* 2010). The "fixed amount approach" adopted by the majority of farmers leads to a water loss during the periods with low water needs and a water deficit when the needs are important. Results from experiment exploring the crop rotations in combination with four water management strategies (Bastiaanssen *et al.,* 1996) indicate that sustainable water and salinity management is possible if water is supplied according to soil characteristics and crop water requirements (CWRs).

The irrigation development in the arid region of Tunisia led to a greater use of shallow ground water where the overexploitation already starts to be felt by farmers who are already confronted with the requirement to practice deficit irrigation. Thus, to cope with scarce supplies, deficit irrigation is an important tool to achieve the goal of reducing irrigation water use (English and Raja, 1996; Lorite *et al.,* 2007; Fereres and Soriano, 2007; Geerts and Raes, 2009) and improve the crop water productivity (WP) (Ali and Talukder, 2008; Ali *et al.,* 2007; Jalota *et al.,* 2006; Zhang *et al.,* 2004; Oweis *et al.,* 2000; Talukder *et al.,* 1999). While deficit irrigation is practiced by farmers for a number of reasons - from inadequate network design to excessive irrigation expansion relative to catchment's supplies - it has not received sufficient attention in research. The irrigation from individual shallow wells constitutes an advantage for the farmers in the region. They have the possibility of controlling the water amounts with more flexibility, without the constraints and the risks related to the variable intervals and water practiced in the public perimeters (Smith 1985). Therefore, the capacity to decide moment and water amounts of irrigation could facilitate the development and management of deficit irrigation program in the private perimeters under the arid conditions of Tunisia.

At present, farmers grow millet (*Pennisetum glaucum* (L.) R. Br.) in rotation with carrot (*Daucus carota* L.) in only 11.5% of the total cultivated area in the majority of the private farms with fixed irrigations approach to each crop through surface and drip irrigation methods. For this region, Nagaz *et al.* (2009, 2010) have conducted some field experiments to study the effects of different irrigation regimes on millet yield but information about crop water productivity (WP), which is calculated as yield over actual water use and its potential enhancement for millet and carrot crops grown in a rotation, is lacking. To estimate yield response and WP in relation to deficit irrigation, adequate observations for a number of years are required to achieve an accurate management advice. To enhance WP through deficit irrigation, as suggested by other researchers (Kijne *et al.,* 2003), quantitative specific information for arid regions on yield and water use of carrot and millet crops in rotation under different irrigation water regimes needs to be developed. The present work, initiated in 2008 aims at determining irrigation water requirements of millet-carrot crops 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 derive an irrigation strategy that save water in irrigated carrots and millets, reduce soil salinity and improve water productivity in carrot-millet cropping system under the arid conditions of southern Tunisia.

Materials and methods

Field experiments were carried out during the fall-winter carrot and summer millet growing seasons over three years (2007/2008), (2008/2009), and (2009/2010) in a commercial farm situated in the Southern East of Tunisia (33°22' N latitude, 9°06' E longitude; 45 m a.s.l. Altitude). The climate is typical of arid areas. Climatic data (TemperaturE, relative humidity & ETo-PM) relative to the growing seasons of the period 2007-2010 are presented in Tables 1and 2.The rainfall during the growing seasons of carrot-millet rotation for 3 years is reported in Figure 1. During the first year of the study in 2007/2008, fall-winter precipitation was relatively low during the entire growing season, reaching 57 mm by the end of the season (Figure 1). The 2008/2009 field season, however, was considerably drier than the previous year, with only 25.5 mm of rain falling during September and January. Throughout the 2009/2010 season, there was only 28.5 mm of precipitation, most of which fell the beginning of the season (September and October). No rainfall was received during the cropping period of millet over the three years. Reference evapotranspiration (ETo-PM) over each carrot and millet growing season was, respectively, 438.7 and 502.2 mm in 2007/2008, 443.1 and 490.5 mm in 2008/2009, and 440 and 510 mm in 2009/2010.

The soil is a sandy soil with low organic matter content. The electrical conductivity (ECe) values measured before planting are, respectively, 3.74, 3.20 and 3.70 dS/m, and 2.80, 2.00 and 3.50 dS/m for first, second and third year of carrot and millet crops. The total soil available water calculated between field capacity (FC) and permanent wilting point (WP) for an assumed carrot and millet root extracting depth of 0.80 m, was 100.5 mm.

Fertilizers were supplied for the cropping periods in the same amounts for 3 years successively with a cropping rotation of carrot (*Daucus carota* L.) - millet (*Pennisetum glaucum* (L.) R. Br.) every year; before planting, soil was spread with 16 and 15 t/ha of organic manure. Nutrient supply included N, P and K at rates of 200, 200 and 150 kg/ha for carrot crop and 300, 200 and 150 kg/ha for millet crop, which were adopted from the local practices. The P and K fertilizers were applied as basal dose before

Table 1 - Monthly climatic data of carrot growing season for the three years of field experiment.

	September	October	November	December	January	February
			Air temperature (°C)			
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 (%)			
2007/2008	54	60	59	67	64	60
2008/2009	55	67	64	65	64	54
2009/2010	63	58	65	73	61	66
			ETo-PM (mm)			
2007/2008	166	129	69	67	80	85
2008/2009	162	131	76	66	75	90
2009/2010	165	128	77	67	74	86

Table 2 - Monthly climatic data of millet growing season for the three years of field experiment.

	May	June	July	August
		Air temperature (°C)		
2007/2008	23.5	26.0	28.5	29.5
2008/2009	24.0	27.5	29.0	28.5
2009/2010	25.0	28.0	29.5	31.0
		Relative humidity (%)		
2007/2008	64	61	62	65
2008/2009	57	60	61	63
2009/2010	64	62	62	67
		ETo-PM (mm)		
2007/2008	151	162	191	182
2008/2009	147	156	181	171
2009/2010	155	164	190	183

planting. Nitrogen was divided and delivered with the irrigation water in all treatments during early vegetative growth.

Carrot and Pearl Millet, natives of the region, were planted every year on 15 September for carrot, in 8 x 10 m plots separated from each other; and on 25 May, in 50 cm rows with plants spaced 40 cm apart for millet, in a randomized complete block design with four replicates and five irrigation treatments. The same experimental area was used for both crops and was divided into four blocks with four elementary plots per block. Each elementary plot consisted of fifteen rows for both carrot and millet. Carrot and millet crops rotation for 3 years were surface and drip irrigated with water

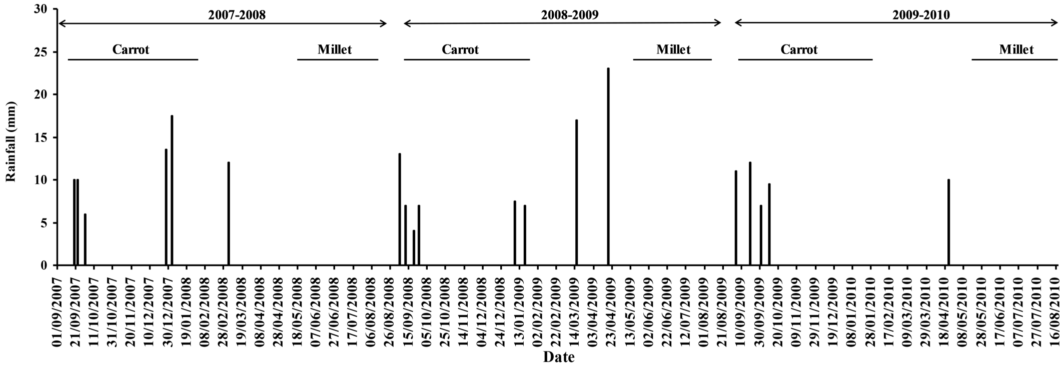

Figure 1 - The rainfall received during the cropping periods of carrot-millet rotation for 3 years.

from a well having an ECi of 3.60 dS/m. Each dripper had a 4 l/h flow rate. Water for each block passed through a water meter, gate valve, before passing through laterals placed in every millet row. A control mini-valve in the lateral permits use or non-use of the dripper line. For carrot, each plot was feed individually. Measured amounts of water were delivered to the plots using a hosepipe and water meters.

Five irrigation treatments were used for 3 years in carrot-millet system. These were SWB100, DI-80, DI-60, SWB100-DI60 referring and farmer's method. The SWB100 treatment was used when readily available water in the root zone has been depleted; plants with this treatment, received 100% of accumulated crop evapotranspiration (full irrigation treatment). Two additional treatments were used at the same frequency as treatment SWB100, but with quantities equal to 60 and 80% of accumulated ETc (DI-60 and DI-80). These treatments were identified as continuous deficit irrigation treatments. In the fourth treatment (SWB100-DI60), water was applied from planting to the mid-season stage, to supply fully the ETc. After that stage, only 60% of ETc was applied till harvest (regulated deficit irrigation). A fifth irrigation treatment consisted of applying the farmer's method corresponding to irrigation practices traditionally implemented by the local farmers i.e. a fixed amount of water (25 and 30 mm) is supplied every 7 and 5 days from planting till harvest, for both crops.

The crop evapotranspiration (ETc) was estimated, on daily basis, using reference evapotranspiration (ETo) combined with carrot and millet crop coefficient (Kc). The ETo-PM was estimated from daily climatic data collected from the meteorological station, located at Médenine, Tunisia (33°35' N latitude, 10°48' E longitude; 76 m a.s.l. Altitude) by means of the FAO-56 Penman-Monteith method (Allen *et al.*, 1998). The carrot and millet crop coefficient (Kc) was computed following the recently developed FAO-56, single and dual crop coefficient approach. The dual crop coefficient, the sum soil evaporation (Ke) and basal crop coefficient (Kcb) reduced by any occurrence of soil water stress (Ks), provides separate calculations for transpiration and soil evaporation (Kc=KsKcb+Ke).

For irrigation scheduling, the method used was the water balance, by means of a spreadsheet program for Excel, developed according to the methodology formulated by Allen *et al.* (1998). The spreadsheet program estimates the day when the target soil water depletion (readily available water, RAW) for the treatment SWB-100 would be reached and the amount of irrigation water needed to replenish the soil profile to field capacity. The program calculates the soil water depletion on daily basis using the soil water balance and projects the next irrigation event based on the target depletion: 35 and 60% of TAW for both crops. The soil depth of the effective root zone of carrot and millet is increased with the program from a minimum depth of 0.15 and 0.20 m at planting to a maximum of 0.80 m in direct proportion to the increase in the carrot and millet crop coefficient.

At physiological maturity, carrot and millet yields were obtained. Forty and fifteen plants per row within each plot were harvested every year by hand, to determine millet yield, panicle number/m, kernel number/panicle and 1.000-kernel weight, and carrot fresh root yield, root number/m and root weight.

Every year, soil samples were collected after harvest and analyzed for ECe. For millet crop, the soil was sampled with a 4 cm auger every 20 cm to a depth of 80 cm, at three sites perpendicular to the drip line and at three sites between the emitters. Conceptually, these should be areas representing the range of salt accumulations (Bresler, 1975; Singh *et al.*, 1977). For carrot, each elementary plot was sampled at two points within homogeneous areas from four depths (0-0.20; 0.20-0.40; 0.40-0.60; 0.60-0.80 m in depth).

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 date is not included in the total amount.

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

Results and discussion

Evapotranspiration estimation and soil water balance

Figure 2 illustrates the course of mean daily ETc relative to ETo for three years during the periods of carrot and millet crops. During the first 30 days after plantation of carrot, high ETc values where observed when the wetting of the soil surface by

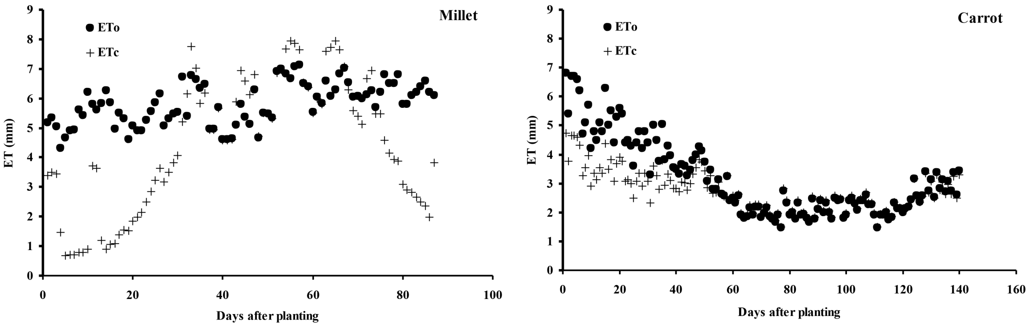

Figure 2 - Mean values of daily ETo and ETc during the cropping periods of carrot-millet rotation for 3 years (2008-2010).

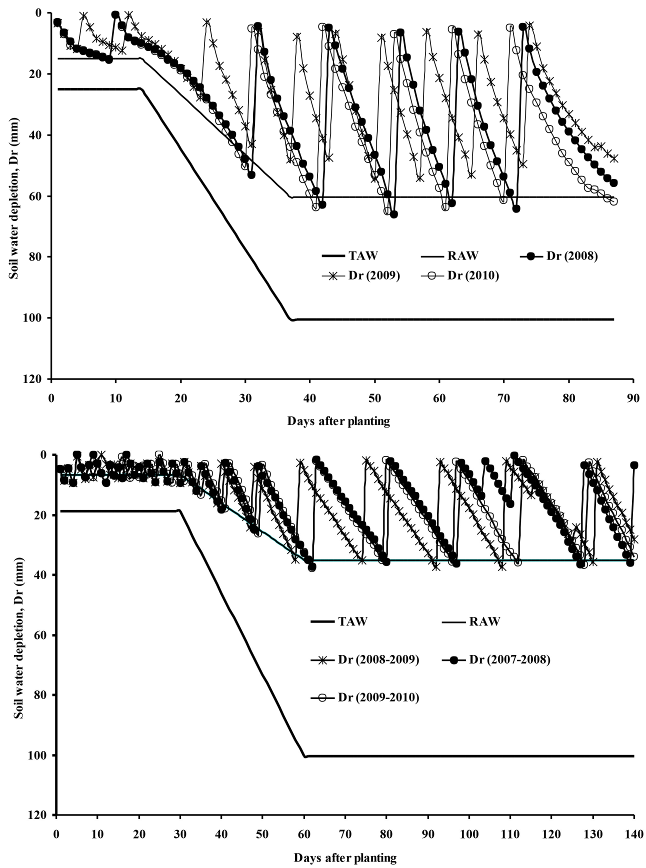

Figure 3 - Estimated daily soil water depletion under SWB100 irrigation treatment during the cropping seasons of carrot-millet rotation for 3 years.

irrigation or precipitation coincides with high evaporative demand. The potential ETc values in the first 14 days after plantation of millet where recorded when the soil surface layer was wetted by irrigation. Most of the daily crop ET consisted of soil evaporation, controlled mainly by soil hydraulic properties and solar radiation. This period is characterized by mean values of ETc of about 3.60 and 1.84 mm/day, respectively, for both crops. As the crop canopy grew, ETc of millet increased and reached values of 3.60 mm/day at development stage and 6.40 mm/day at mid- season stage. For carrot crop, lower ETc 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 values at the late stage were about 4.28 and 2.50 mm/day, respectively, for millet and carrot crops. During the late stage, the relatively high ETc values of carrot and millet crops were principally attributed to the warmer conditions corresponding to the end of winter season and to the important soil evaporation induced by the frequency of irrigation and to the high evaporative demand at the end of summer season.

Figure 3 illustrates soil water depletion, estimated by the spreadsheet program, under SWB-100 treatment during the cropping seasons of carrot and millet for 3 years. The spreadsheet program develops a water balance and supplies information about the timing and amounts of irrigation events. This figure illustrates also 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 not applied in the spreadsheet until the soil water depletion at the end of the previous day is greater than or equal to the readily available water, occasionally plants could be subject to a slight stress on the day prior to irrigation.

Soil salinity

Figure 4 shows the soil salinity during the field trials at planting and after harvest of carrot-millet rotation for 3 years. The soil salinity (ECe) at the time of planting (September, 2007) was 3.74 dS/m. Soil salinity after carrot harvest (February 2008) decreased in all treatments as compared to ECe at planting. The ECe values were 2.4, 2.7, 3.1, 2.5 and 3.4 dS/m in SWB100, DI-80, DI-60, SWB100-DI60 and farmer's treatments, respectively. The decrease of ECe values were due to the leaching of soluble salts with the received rainfall (57 mm) (Figure 1). The soil salinity measured at harvest of millet crop (August, 2008) was higher than the initial ECe for all irrigation treatments. The ECe values were about 3.8, 4.3, 4.7, 4.0 and 5.9 dS/m, respectively, for SWB100, DI-80, DI-60, SWB100-DI60 and farmer's treatments. The reason for the higher soil salinity obtained for all treatments may be attributed to the relatively high

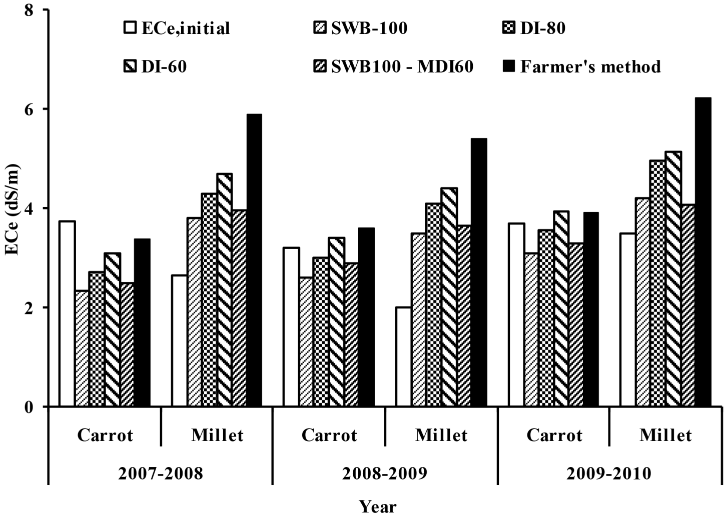

Figure 4 - Soil salinity (ECe, dS/m) under different irrigation treatments of carrot-millet rotation for 3 years.

initial soil salinity (ECe~2.8 dS/m) and high evaporative demand during the periods when the soil samples were taken and since no rainfall was received during the cropping period and, since water was applied mainly by irrigation, little leaching of the soil is expected.

A major portion of the salts accumulated in the soil profile during irrigation of millet (Figure 4) was leached by rains (20 mm) before planting of the second carrot (September, 2008) and by the pre-irrigation (100.5 mm). The salinity in the root zone (0-80 cm) at the sowing date of second carrot crop was 3.2 dS/m. The results show a reduction in soil salinity measured after second carrot harvest (February, 2009), the ECe for the treatments SWB100, DI-80 and SWB100-DI60 decreases from 3.2 at plantation in September to 2.6, 3 and 2.9 dS/m at carrot harvest (Figure 4). The soil salinity was comparable with the initial ECe for DI-80 and farmer's method. The ECe values were about 3.8 and 3.6 dS/m, respectively, for both treatments. The soil salinity values for all irrigation treatments have been reduced by leaching due to rainfall received (25.5 mm) during the carrot growing period (Figure 1).

The salts accumulated in the soil profile during irrigation of second carrot in different treatments were leached out again by 40 mm rainfall received during March and April 2009 (Figure 1). The adequate leaching of accumulated salts by rains reduces the soil salinity at the sowing date of the second millet crop (May, 2009). The ECe at millet planting was about 2 dS/m. The soil salinity after millet harvest (August, 2009) also increased in different treatments. The ECe of the soil from 0-80 cm depth increased to 3.5, 4.1, 4.4, 3.6 and 5.4 dS/m in SWB100, DI-80, DI-60, SWB100-DI60 and farmer's treatments, respectively. The soil salinity values in all treatments were relatively lower in 2009 because of the low initial ECe at second millet planting (Figure 4).

At the sowing date of the third carrot crop (September, 2009), soil ECe was about 3.7 dS/m. The ECe value is relatively high in spite of the rains received before the third carrot planting date (11 mm) which caused a leaching of the salts accumulated in the soil profile during irrigation of the second millet. At harvest (February, 2010), the average salinity of 80-cm soil layer for SWB100, DI-80, DI-60, SWB100-DI60 and farmer's treatments was 3.1, 3.6, 4.0, 3.3 and 3.9 dS/m, respectively. The average soil salinity trend for all treatments during the third carrot crop was almost similar to that of 2008-2009. Again, the rainfall received during the carrot period (28.5 mm) leached the salts from the profile.

The soil salinity measured at harvest of the third millet crop (August, 2010) was higher than the ECe at planting (May, 2010) for all irrigation treatments. The ECe obtained SWB100, DI-80, DI-60, SWB100-DI60 and farmer's treatments increases from 3.5 dS/m at sowing to 4.2, 4.9, 5.1, 4.1 and 6.2 dS/m, respectively, after the millet harvest. The soil salinity values in all treatments were higher in 2010 because of the residual salinity of the previous carrot season and leaching had not occurred during spring period of 2010. The reason for the higher soil salinity obtained for millet crop may be attributed to high evaporative demand conditions during the millet cropping period and irrigation with saline water under these conditions would result in higher direct evaporation rates leading to an increase in salt accumulation in the soil.

Over the three years study, the ECe data indicates that leaching had occurred during fall-winter and spring periods each year. In treatment SWB100, the average soil salinity varied between 2.4 and 4.2 dS/m in the period from Fall 2007 to summer 2010, with ECe in farmer's method, which received more irrigation water (ECi~3.6 dS/m), the average soil salinity increased from 3.4 dS/m in 2007-2008 to 6.2 dS/m by the summer of 2010. The salinity data for all treatments (Figure 4) shows that in the individual seasons the soil salinity can be controlled during fall-winter carrot periods by rainfall (Figure 1). Increases in soil ECe during the entire rotation occurred on plots that had been cultivated by millet crop during summer season where leaching by rains was absent. Thus, the rainfalls received during fall-winter and spring periods were effective in leaching salts from the soil profile. Manchanda and Chawla (1981) and Sharma *et al.* (1994) while reporting on the use of highly saline waters in light textured soils, also observed that salt accumulated in the preceding crop season were leached out by rains.

Comparison between ECe data (Figure 4) shows that within a season there were decreases in the ECe in full irrigation treatment (SWB100). SWB100-DI60 and DI-80 irrigation treatments resulted also in low ECe values. The ECe values are similar to the ECe for SWB100. A further increase in ECe values occurred with the DI-60 irrigation treatment. The higher soil salinity obtained under DI-60 irrigation treatment may be attributed to little leaching of the soil expected under deficit irrigation conditions. Schoups et al. (2005) 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 found to have occurred when farmer method was used. In this case, 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. These data demonstrate that soil salinity was kept within acceptable limits for the growth of the crops grown in the rotation when SWB100, SWB100-DI60 and DI-80 strategies were employed. These results obtained under actual farming conditions support the practicality of these strategies to facilitate the use of saline waters for irrigation.

Crop yield

The data concerning the yields of carrot and millet crops, observed for all irrigation treatments, are presented in Figure 5. The data show that for both crops the maximum yield occurred in the full treatment (SWB100). However, yields dropped significantly with the DI-80 and DI-60 treatments during the three years of the study. Carrot and millet yields were significantly different between the DI-80 and DI-60 treatments (Figure 5). Lower yields were observed for the farmer's method and DI-60. These two last treatments did not show a statistical difference between them and were significantly lower than that obtained under SWB100 treatment. No significant reduction in carrot and millet grain yield was observed in SWB100-DI60 treatment in 2007-2008, 2008-2009 and 2009-2010.

The farmer's and DI-60 irrigation treatments produced a similar carrot root and millet grain yields, but the first saved 40% irrigation water. Moreover, DI-80 treatment produces more yield than farmer' method. Carrot and millet yield components (Tables 3 and 4) were affected by the irrigation treatments. The root weight and number, the panicle number and kernel number and weight for farmer's method was lowest while SWB100 and SWB100-DI60 irrigation treatments did not differ significantly from each other.

The decreased root and grain yields in the DI-80, DI-60 irrigation treatments and farmer's method compared to the SWB100 were associated with lower root number/m² and root weight and panicle number, kernel number and weight (Tables 3 and 4) as a consequence of water shortage during panicle initiation, flowering and millet grain filling and between fruit-set and harvest of carrot crop. Therefore, the yield increase under SWB100, SWB100-DI60 and DI-80 treatments was attributed to enhanced growth and yield components due to water supply. These results are in agreement with the results reported by other researchers (van Oosterom *et al*., 2002); Mahalakshmi and Bidinger 1986; Parabhakar *et al*., 1991; Imtiyaz et *al*., 2000; Paradiso

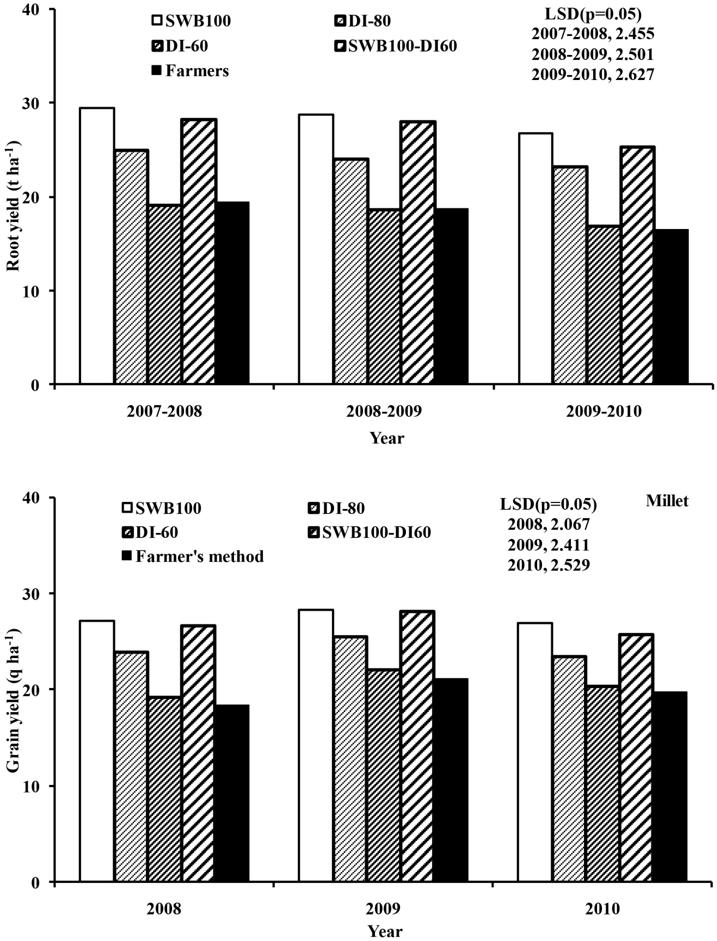

Figure 5 - Yields of carrot (t/ha) and millet (q/ha) for 3 years under different irrigation treatments.

et al., 2002) who obtained higher marketable yields of carrot and millet, root and kernel weight and number with full irrigation treatment. Thus, water stress should be avoided between fruit-set and harvest of carrot, during panicle initiation, flowering and grain filling, the most critical periods of carrot and millet for irrigation.

There were differences between experiments in carrot and millet yields. Carrot yields were highest in the first year because of the low soil salinity and the higher amount of rainfall received (57 mm). However, millet yields were highest the second year because of the low initial soil salinity. There was a reduction in carrot and millet yields in the third year as compared to those obtained in first and second years for all irrigation treatments. This yield reduction was caused by the residual salts

Table 3 - Yield components of carrot under different irrigation treatments.

Treatment	Yield component/Year					
	Root number/m			Root weight (g/root)		
	2007-2008	2008-2009	2009-2010	2007-2008	2008-2009	2009-2010
SWB100	71	70	67	41.3	41	40.0
DI-80	64	59	59	35.4	40.7	39.3
DI-60	60	55	52	24.2	33.9	32.6
SWB100-DI60	70	68	63	36.2	41.2	40.2
Farmer's method	62	57	52	23.7	32.8	31.6
LSD (p=0.05)	4.3	5.2	5.0	3.60	2.77	3.11

Table 4 - Yield components of millet under different irrigation treatments.

Treatment	Yield component/Year								
	Panicle number/m²			1000-kernel weight (g)			Kernel number/panicle		
	2008	2009	2010	2008	2009	2010	2008	2009	2010
SWB100	69	71	70	12.80	12.95	12.72	326	308	302
DI-80	66	69	67	12.21	12.43	12.13	294	298	290
DI-60	62	65	62	11.91	12.07	11.92	272	282	276
SWB100 -DI60	68	69	67	12.72	12.81	12.69	317	318	303
Farmer's method	53	60	55	11.28	11.74	11.71	228	285	279
LSD (p=0.05)	6.074	5.775	7.112	0.613	0.577	0.601	34.222	31.077	33.442

accumulated in the soil during irrigation of the previous millet and carrot seasons and thus relatively high soil salinity at planting of the two crops. During the experimental periods the differences in yield and its components under SWB100 and SWB100-DI60 treatments were not significant. Due to its effect of reducing the soil salinity the SWB100-DI60 treatment resulted in carrot and millet yields comparable with those obtained under SWB100 treatment. Water supply restriction after mid-season stage by 40% (SWB100-DI60) seems to have low impact on soil salinity and yield of carrot and millet crops as compared to SWB100 full irrigation treatment.

Note that the deficit irrigation and farmer's treatments results in higher salinity in the rooting zone than the SWB100 and SWB100-DI60 (Figure 4). The higher salinity associated with the deficit irrigation and farmer's strategies were sufficient to cause reduction in yield of carrot and millet. These results support the use of the SWB100 strategy to facilitate the use of saline water for irrigation. Several reports indicate that the SWB approach is the one to be adopted under conditions described in this paper (Smith, 1985; Raes *et al*., 2002; Nagaz *et al*., 2007). Carrot and millet can be also grown with acceptable yield using saline water, if irrigation management practices maintain the fraction of ETc applied above the value of 80% (DI-80).

The reason for the lower yields obtained for farmer's treatment may be attributed to the fact that the farmer apply water to the crop without regard to whether the plant needs water or not. Farmer seems to relate irrigation occurrences to days after planting rather than to crop growth stages progress. The SWB irrigation scheduling based on crop water requirements and soil characteristics results in varying water application and intervals, and then allows for applying irrigation water when needed by the crop over the growing season. Accurate irrigation scheduling is only possible when water supply and irrigation amounts can be managed independently by farmer. For a single farm with an independent water source, as in arid regions of Tunisia where carrots and millets are cultivated mainly on shallow wells in private farms, this could be manageable and is essential to optimize water supply to crop.

Water productivity

The amounts of water applied for the carrot ad millet crops from planting to harvest over the three-year periods of carrot and millet are given in Table 5. Irrigation water applied before planting of carrot and millet (100 mm) each year is not included in the total. Total rainfall amounts for the three growing seasons of carrot were 57, 25.5 and 28.5 mm in 2007/2008, 2008/2009 and 2009/2010, respectively. No rainfall was received during the cropping period of millet over the three years.

When the carrot and millet crops were irrigated at 100% ETc (SWB100), irrigation amounts were, respectively, 328 and 336 mm in 2007/2008, 330 and 395 mm in 2008/2009, and 328 and 395 mm in 2009/2010. Compared to the SWB100 treatment, 31-39, 15-49 and 29.5-49 mm of water were saved by irrigation treatment SWB100-DI60, respectively, in first, second and third year for carrot and millet. Similarly, the water savings by DI-80 and DI-60 treatments were 66 and 131 mm for carrot and 67 and 134, 79 and 158 mm compared to the SWB100 treatment in first, second and third year. The amount of irrigation water for SWB100 irrigation treatment was comparable to that reported by Parabhakar *et al.* (1991), Paradiso *et al.* (2002), Hattendorf *et al.* (1988) and Ibrahim *et al.* (1985).

Water productivity (WP) based on fresh root and grain production was expressed as the ratio of root and grain yields at final harvest to the water supply (Table 6). For all years, the total water productivity for millet grain yield was not calculated since no rainfall was received during the growing period of millet. The WP values reported in this study were similar to those reported for carrot and millet by others (Parabhakar *et al.*, 1991; Imtiyaz *et al.*, 2000; Maman *et al.*, 2003; Kanemasu *et al.*, 1982) and were affected by irrigation treatments. There is also a variation in WP values between years. For all irrigation treatments, carrot yield was higher in first than the two following

Table 5 - Water supply under different irrigation treatments during the growing periods of carrot and millet for 3 years.

Year	Crop	Rainfall (mm)	Irrigation water (mm)				
			SWB100	DI-80	DI-60	SWB100-DI60	Farmers
2007-2008	Carrot	57	328	262	197	297	509
	Millet	-	336	269	202	297	493
2008-2009	Carrot	25.5	330	264	198	315	518
	Millet	-	395	316	237	346	522
2009-2010	Carrot	28.5	328,5	263	197	299	471
	Millet	-	395	316	237	346	502

years and millet yield was higher in second than the first and third years (Figure 5). IWP values reflect this difference: it varied typically around 3.8-9.7, 3.6-9.4 and 3.5-8.8 kg/m^3 for carrot and 0.37-0.95, 0.38-0.93 and 0.35-0.86 kg/m^3 for millet, respectively, in first, second and third year.

For all experiments, the WP for carrot root yield with SWB100 treatment was not significantly different from those obtained with DI-80 and SWB100-DI60 treatments but statistically different from that obtained with DI-60 and farmer treatments. WP with farmer's method was statistically different from those obtained with DI-80 and DI-60 treatments ($P < 0.05$). These two last treatments did not show a statistical difference between them. The WP for millet grain yield with SWB100 treatment was significantly different from those obtained with DI-80, DI-60 and SWB100-DI60 treatments and farmer's method ($P < 0.05$). The difference was also significant between DI-60 treatment and the DI-80 and SWB100-DI60 treatments ($P < 0.05$). These two last did not show a statistical difference between them ($p < 0.05$) and were considerably higher than that obtained under farmer's treatment. WP with farmer's treatment was significantly different from that obtained with DI-60 ($P < 0.05$). Maximum IWP for carrot and millet averaging, respectively, 9.701 and 0.955 kg/m was obtained in DI-60 treatment, followed by DI-80, SWB100-MDI60 and SWB-100 treatments with 9.523-0.890, 9.512-0.899 and 8.994-0.809 kg/m^3 in 2007-2008. Minimum IWP was obtained from the farmer's treatment as 3.811 and 0.372 kg/m^3 for the first experimental year. In 2008-2009 and 2009-2010, similar to the previous year, maximum IWP was obtained from the DI-60 treatment as 9.414-0.932 and 8.604-0.862 kg/m^3 and followed by DI-80, SWB100-MDI60 and SWB-100 treatments with IWP of 9.109-0.811, 8.905-0.814 and 8.697-0.716 kg/m^3 versus 8.821-0.745, 8.462-0.745 and 8.158-0.621 kg/m^3, respectively. As in the first year, minimum IWP were obtained from the farmer's treatment with 3.610-0.385 kg/m^3 for the second experimental year and 3.49-0.356 kg/m^3 for the third year. The low WP for the farmer's method during all experiments can be attributed to reduced yields but also to higher irrigation water use.

Table 6 - Water productivity (WP, kg/m³) under different irrigation treatments during the growing periods of carrot and millet for 3 years.

Treatment	IWP		TWP	
	Carrot	Millet	Carrot	Millet
		2007-2008		
SWB100	8.994	0.809	7.662	-
DI-80	9.523	0.890	7.821	-
DI-60	9.701	0.955	7.524	-
SWB100-DI60	9.512	0.899	7.986	-
Farmer's method	3.811	0.372	3.428	-
LSD (p=0.05)	0.787	0.065	0.542	
		2008-2009		
SWB100	8.697	0.716	8.073	-
DI-80	9.109	0.811	8.307	-
DI-60	9.414	0.932	8.340	-
SWB100-DI60	8.905	0.814	8.238	-
Farmer's method	3.610	0.385	3.441	-
LSD (p=0.05)	0.624	0.094	0.399	
		2009-2010		
SWB100	8.158	0.681	7.507	-
DI-80	8.821	0.745	7.959	-
DI-60	8.604	0.862	7.517	-
SWB100-DI60	8.462	0.745	7.725	-
Farmer's method	3.490	0.356	3.291	-
LSD (p=0.05)	0.509	0.062	0.411	

Conclusions

This three-year field study showed that carrot and millet grown over fall-winter and summer periods required, respectively, 328-330 and 336-395 mm of irrigation water under well irrigated conditions (SWB100) and indicates also that the irrigation requirements could be decreased by adopt regulated (SWB100-DI60) and moderate (DI-80) deficit irrigation. Full (SWB100) and deficit irrigation treatments (SWB100-DI60 and DI-80) decreased the soil salinity. Higher soil salinity was maintained in the root zone with DI-60 deficit irrigation treatment and farmer's method. For all treatments, increases in ECe values during carrot-millet rotation for 3 years occurred on plots cultivated by millet crop during summer season where leaching by rains was not occurred. However, rainfall received during fall and/or winter periods corresponding to carrot growing and spring period when the field remained fallow seems to be effective in removing salts accumulated in the root zone.

Carrot and millet yields were influenced by irrigation treatments. Carrot and millet yields of DI-60 and DI-80 deficit irrigated treatments were significantly lower than those in SWB100 treatment. Treatment SWB100-DI60 gave also good yields. Note that the deficit irrigation treatments gave lower yields and resulted in higher soil salinity than the SWB100 full irrigation. Farmer's method was least efficient and caused higher salinity in the rooting zone. This method gave the lowest carrot root and millet grain yields with more irrigation water applied. The data show that factors such as root number/m² and root weight and panicle number, kernel number and weight are significant for carrot and millet yield. The higher salinity associated with the farmer's method and deficit irrigation treatments were sufficient to cause reduction in carrot and millet yield and yield components.

The water productivity (WP) for root and grain yield was significantly affected by irrigation treatments. The lowest values occurred under the farmer's method, while the highest values were obtained under DI-60 deficit irrigation treatment. Although high WP values were observed for the most severe restricted treatment (DI-60), the yield and quality obtained under this treatment do not allow opting for such important reduction. The relatively high yields and WP values noted under DI-80 and SWB100-DI60 treatments indicate the high potential of the carrot and millet crops to valorize saline waters in irrigation under moderate water deficit conditions.

Based on results, it can be concluded that the full irrigation (SWB-100) and deficit irrigation (SWB100-MDI60 and DI-80) strategies offer significant advantage for both carrot yields and WP and reduce the soil salinity compared to the DI-60 and farmer's irrigation practices in carrot production under arid conditions. The results of the field experiments were demonstrated to the local farmers where the yield increase and savings in irrigation water was fully understood. As a result of this research, full irrigation scheduling technique (SWB100) is recommended for irrigation of carrot and millet crops under the arid conditions of southern Tunisia. In case of situations where water supply is limited, irrigation of carrot and millet could be scheduled using DI-80 and SWB100-DI60 deficit irrigation strategies (DI). The deficit irrigation presents a great potential to improve the water productivity and the control of soil salinization by exploiting the natural leaching of salts by the rain. Future studies should be undertaken to evaluate the efficiency of the fall-winter rains for natural leaching.

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