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Yield and Water-Use Efficiency of Pearl Millet (*Pennisetum glaucum* (L.) R. Br.) under Deficit Irrigation with Saline Water in Arid Conditions of Southern Tunisia

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Abstract: A 2-years experiment (2005-2006) was conducted in Southern Tunisia to determine the effect of deficit irrigation regimes with saline water on soil salinity, growth, yield and water use efficiency of millet (*Pennisetum glaucum* (L.) R. Br.). Millet was grown in a commercial farm during summer season on a sandy soil and drip-irrigated with water having an ECi of 7.6 dS m^{-1} for both experiments, a complete randomized block design with four replicates was used to evaluate four irrigation regimes. Irrigation treatments consisted in water replacements of accumulated crop Evapotranspiration (ETc) at levels of 100% (100 L) 80% (80 L) 60% (60 L) and 40% (40 L), when the readily available water in the control treatment (100 L) is depleted. Findings are globally consistent between the two experiments. Results show that salinity was lowest under emitters and highest midway to the margin of wetted bands. Under emitters it increased gradually between 100 and 40 L from 2.75-6.10 dS m^{-1} in 2005, from 1.95-4.92 dS m^{-1} in 2006. Highest ECe values were found to occur at about 20 and 7 cm from emitters, respectively for 100 and 40 L. For both experiments, LAI decreased significantly as the amount of applied water decreased from 100-40% of ETc. Yields were highest under 100 L. From values of 26.70 and 27.65 q ha^{-1}, respectively for 1st and 2nd year, yields decreased almost linearly when applied water was reduced. However, reduction in quality was significantly important for 60 and 40 L. The analysis outcome of the crop sensitivity to salt indicated that threshold are close to the value calculated from published salt tolerance data (3.46 vs. 3.65 dS m^{-1}) but the slope are considerably steeper (17 vs. 6.7%), apparently because of the combined effect of salinity and water stresses. Water Use Efficiency (WUE) was found to vary significantly among treatments, where the highest (7.60 kg/ha/mm) and the lowest (6.4 kg/ha/mm) values were obtained from 60 and 100 L treatments, respectively. Finally, results support the practicality of using the 100% of ETc methodology to optimize irrigation with saline water for millet production and to control soil salinity. Under situations of water shortage, the deficit irrigation strategy (80% of ETc) is recommended as a tool to schedule irrigation of millet crop in arid regions of Tunisia.

Key words: Arid, salinity, deficit irrigation, irrigation scheduling, millet, yield, water use efficiency

INTRODUCTION

While on a global scale water resources are still ample, serious water shortages are developing in the arid and semi-arid regions as existing water resources reach full exploitation. The great challenge for the coming 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 (Fereres and Soriano, 2007). This is especially, the case in arid regions of Tunisia subject to frequent droughts and where restricted supply of good quality water is the most important factor limiting crop production. Irrigation of a wide range of crops is expanding around shallow wells having a salinity ranging from 3-9 dS m^{-1}. Therefore, innovations are needed to increase the efficiency of use of the water that is available. One way to address the issue of water shortage is to change to more efficient irrigation methods, such as drip irrigation (Bernstein and Francois, 1963; Sammis, 1980). Another way is through development of new irrigation scheduling techniques such as deficit irrigation, which are not necessarily based on full crop water requirement. Deficit irrigation is one way of maximizing Water Use Efficiency (WUE) for higher yields per unit of irrigation water applied. In this method, the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season (English, 1990; English and Raja, 1996;

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Kirda *et al*., 1999; Nagaz *et al*., 2007a, b). The expectation is that any yield reduction will be insignificant compared with the benefits gained through diverting the water saved to irrigate other crops (Eck *et al*., 1987; Bazza, 1999; Kirnak *et al*., 2002). However, the grower must have prior knowledge of the crop yield responses to deficit irrigation.

Deficit irrigation is particularly important for crops, which are frequently subject to chronic water shortages. Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is a major summer crop in the irrigated areas of Southern Tunisia and covers 13% of the irrigated agricultural land. However, productivity is usually low and irrigation with waters having an ECi >3 dS m^{-1} is commonly practiced on a routine basis without scheduling and provision drainage and it carries the danger of a rapid soil salinization because of increased salt input.

Due to chronic water shortage and soil degradation hazards in irrigated areas, there is a need to develop strategies that may help to save water and control salinity. In the absence of drainage systems and under conditions of high evaporative demand and chronic shortages of water, techniques based on irrigation restrictions during the whole growing period without substantially affecting yields seem to be reasonably appropriate. Thus, various deficit irrigation strategies have been applied to pearl millet crop considered as moderately tolerant to water stress caused by deficit irrigation or salinity (Hajor *et al*., 1996).

A 2 years study was initiated in 2005 with the objective to determine irrigation water requirements of millet crop and to make quantitative assessments of both salt accumulation in the soil and yield response to water supply in relation to different irrigation strategies in order to derive an irrigation strategy that save water in irrigated millets, reduce salt input and consequently reduce environmental degradation and improve water productivity.

MATERIALS AND METHODS

Experimental site and climate: Experiment was carried out during summer crop growing season of 2005 and 2006 in the Southern East of Tunisia in a commercial farm situated in Darghoulia near the Institut des Regions Arides de Medenine. Pearl Millet (*Pennisetum glaucum* (L.) R. Br.), native of the region, was planted on sandy soil with low organic matter content and an ECe of 2.50 and 1.74 dS m^{-1} (0-70 cm depth of soil) for 1st and 2nd year, respectively. The total soil available water calculated between field capacity and wilting point for an assumed millet root extracting depth of 0.70 m, was 62 mm.

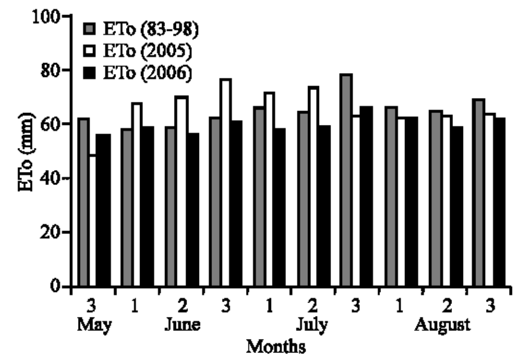

Fig. 1: Ten days reference evapotranspiration, year 2005 and 2006 and period 1983-1998

The values of 10 days reference Evapotranspiration (ETo), which define the weather conditions prevailing during the study are shown in Fig. 1. These data, which only cover the period when experiment took place are compared to the average values for the period 1983-98. The evolution of 10 days ETo was similar, though with slightly higher values for 2005, with an average of 65.4 mm as compared to 64.1 mm, whereas, the 10 days ETo during the period under experiment for 2006 was relatively lower, 59.1 mm as opposed to 64.1 mm in the period (1983-1998).

Crop management and experimental design: Planting took place on 25 May 2005 and 1 June 2006, in 50 cm rows with plants spaced 40 cm apart, in a randomized complete block design with four replicates and four irrigation treatments. The experimental area was divided into four blocks with 4 elementary plots per block. Each elementary plot consisted of ten rows. All plots were drip irrigated with water from a well having an ECi of 7.6 dS m^{-1}. Each dripper had a 4 L h^{-1} 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. Fertilizers were supplied for the cropping periods in the same amounts; before planting, soil was spread with 15 ton ha^{-1} of organic manure. Nutrient supply included N, P and K at rates of 300, 200 and 150 kg ha^{-1}, respectively, which were adopted from the local practices. The P and K fertilizers were applied as basal dose before planting. Nitrogen was divided and delivered with the irrigation water in all treatments during early vegetative growth.

Four distinct water treatments were applied: 100 L treatment irrigated when readily available water in the root zone has been depleted and plants in that treatment received 100% of accumulated crop Evapotranspiration (ETc); three additional treatments were irrigated at the same frequency as treatment 100 L, but with quantities equal to 40, 60 and 80% of accumulated ETc (40, 60 and 80 L). These treatments were identified as deficit irrigation treatments.

The crop Evapotranspiration (ETc) was estimated for daily time step by using reference Evapotranspiration (ETo) combined with a pearl millet crop coefficient (Kc). The Eto was estimated from daily climatic data collected from the Institute meteorological station, located near the experimental site by means of the FAO-56 Penman Monteith method given in Allen *et al.* (1998). The millet crop coefficient (Kc) was computed following the recently developed FAO-56 dual crop coefficient approach, the sum soil evaporation (Ke) and basal crop coefficient (Kcb) reduced by any occurrence of soil water stress (Ks) that provides for 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 100 L 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 (60% of Total Available Water in the root zone, 60% of TAW). The soil depth of the effective root zone is increased with the program from a minimum depth of 0.20 m at planting to a maximum of 0.70 m in direct proportion to the increase in the millet crop coefficient.

Measurements and water-use efficiency: Plants in an area of 1 m^2 $plot^{-1}$ were used to monitor changing in leaf area every 10-15 days starting 15 after planting. Leaf area was determined by leaf area meter and Leaf Area Index (LAI) was calculated accordingly as the total leaf area of plants in 1 m^2 divided by that area.

Millet was harvested on 20 and 26 August in the 1st and 2nd year, respectively. Twenty plants per row within each plot were harvested by hand to determine millet yield, panicle number m^{-2}, kernel number/panicle and 1000-kernel weight.

Soil samples were collected after harvest and analyzed for Ece. The soil was sampled every 15 cm to a depth of 70 cm, at four sites perpendicular to the drip line at distances of 0, 7, 15 and 25 cm from the line and at 4 sites between the emitters (0, 7, 15 and 20 cm from the emitter). Conceptually, these should be areas representing the range of salt accumulations (Bresler, 1975; Singh *et al.*, 1977).

Water Use Efficiency (WUE) is defined as the yield obtained per unit of irrigation water applied. The WUE was calculated as follow: W.U.E (kg/ha/mm) = Yield (kg ha^{-1})/total irrigation water applied (mm) from planting to harvest; an irrigation of 62 mm applied before planting is not included in the total.

Statistical analysis: Analysis of variance was performed to evaluate the statistical effect of irrigation treatments on Leaf Area Index (LAI), millet yields and components, WUE and soil salinity using STATGRAPHICS *Plus* 5.1 (www.statgraphics.com). LSD test at 5% level was used to find any significant difference between treatment means.

RESULTS AND DISCUSSION

Evapotranspiration estimates: Figure 2 shows computed Kc (KsKcb+Ke) during the cropping period in 2005 and 2006. The potential Kc values were found to have occurred following irrigation events when the soil surface layer was wetted. The Ke spikes represent increased evaporation when irrigation has wetted the soil surface and has temporarily increased ETc values (Fig. 3). The Ke spikes reach a values of 0.35-0.4 following wetting by irrigation. The evaporation spikes were lower since only fraction of the soil surface was wetted only by irrigation. The wet soil evaporation spikes decrease as the soil surface layer dries and the value of Ke became zero during the growing period when the soil surface was dried.

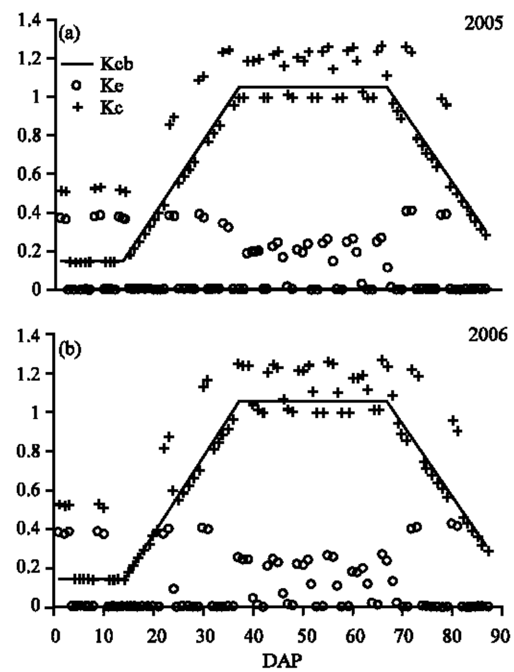

Fig. 2: FAO 56 crop coefficient curves for pearl millet crop during the cropping season

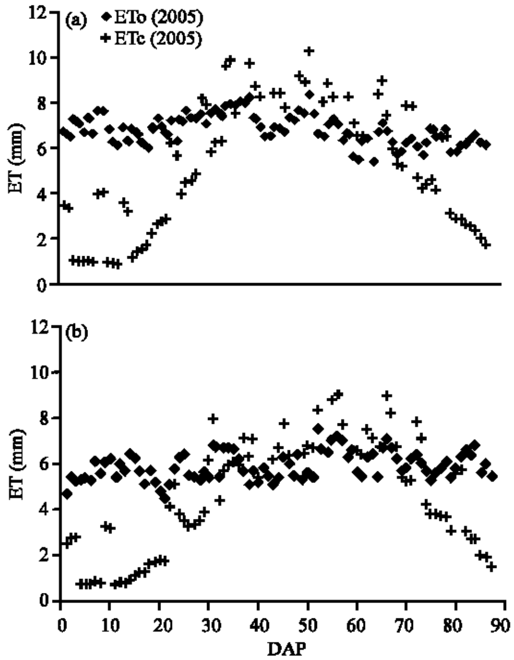

Fig. 3: Estimated daily ETc for pearl millet crop during the cropping season

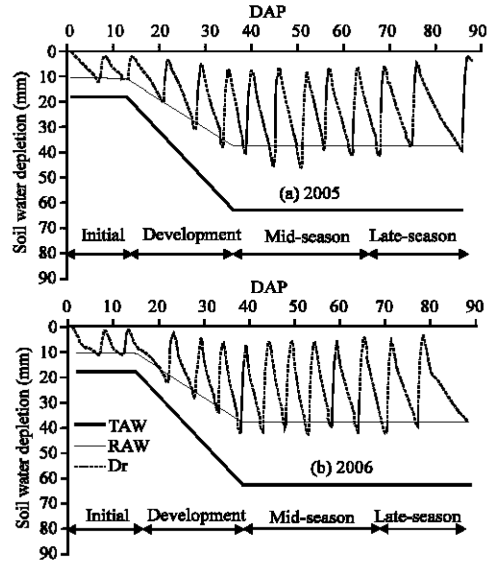

Fig. 4: Estimated daily soil water depletion for millet under 100 L irrigation treatment during the cropping season (a) 2005 and (b) 2006

Figure 3 shown the course of daily ETc relative to ETo for pearl millet crop. During the first 14 days after plantation high ETc values where observed 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 daily ETc of about 2.09 and 1.54 mm, respectively for the 1st and 2nd year. As the crop canopy grew, ETc increased and reached its highest mean value at mid-season stage (7.70 and 7.35 mm day^{-1}). The mean ETc values at the late stage were about 4.36 and 4.19 mm day^{-1}, respectively for 2005 and 2006. At the late stage, where the canopy senescence began, the high ETc values were principally attributed to the important soil evaporation induced by the frequency of irrigation and to the high evaporative demand.

Soil water balance: Figure 4 shows soil water depletion, estimated by the spreadsheet program, under 100 L treatment during the cropping period for the 1st and 2nd year. The spreadsheet program develops a water balance and supplies information on the timing and amounts of irrigation events. Figure 4 also shows 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: The final ECe values at different distances from emitter and drip line under the different irrigation treatments are presented in Fig. 5. On the row, the highest ECe values were found to have occurred at a distance of 7 and 15 cm from the emitter when 40 L treatment was used. Values of 6.10 and 4.92 dS m^{-1} were recorded below the emitter, respectively in the 1st and 2nd year. With 60 L treatment, ECe values of 4.03 and 3.33 dS m^{-1} were recorded below the emitter, respectively for 2005 and 2006 and reached the maximum at a distance of 15 cm from the emitter. Between rows, the greatest values of ECe were recorded at distances of 15 and 25 cm from drip line with 40 L treatment. With 100 L and 80 L, ECe values decreased to 2.75 and 3.14 dS m^{-1}, respectively beneath the emitter in 2005 and to 1.95 and 2.38 dS m^{-1} in 2006. The zone of highest ECe was moved out to 20 cm from the emitter. Soil salinity was highest midway between the emitters (20 cm) and towards the margin of wetted band (15-25 cm). Nagaz *et al.* (2007a), Singh *et al.* (1977) and Laosheng (2000) reported similar result.

The average ECe values under the different irrigation treatments were lower than the EC of the irrigation water

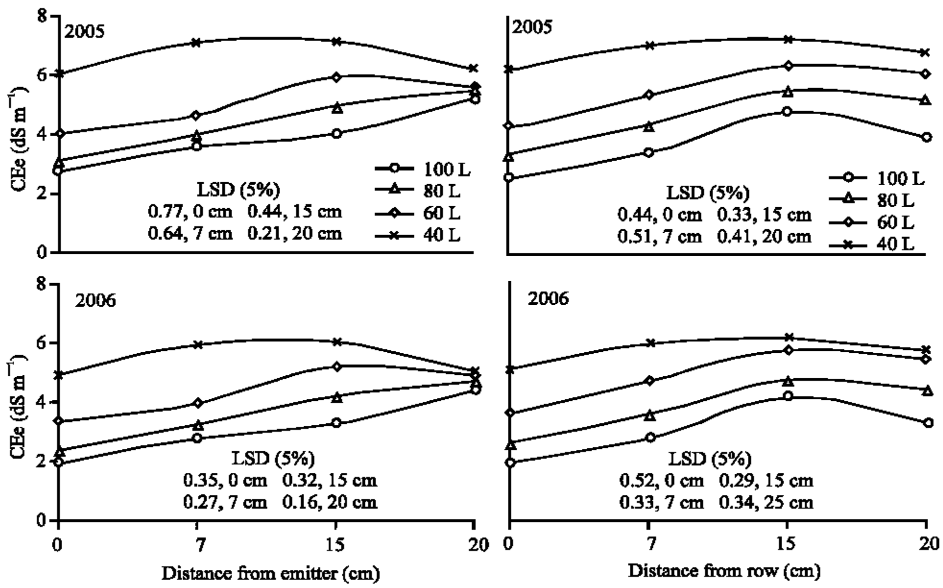

Fig. 5: Soil salinity (ECe, dS m^{-1}) under different irrigation treatments along the row and across row

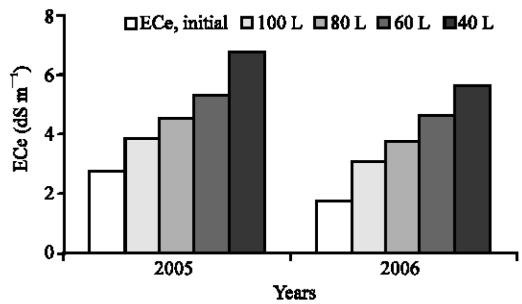

Fig. 6: Mean soil salinity values under different irrigation treatments

used (Fig. 6). Singh and Bhumbla (1968) observed that the extent of salt accumulation depended on soil texture and reported that in soils containing <10% clay the ECe values remained lower than ECiw. Low values of ECe under the prevailing climatic conditions were also due to the low initial soil salinity (2.50 and 1.74 dS m^{-1}).

Plant growth and yield: The growth of pearl millet, expressed by leaf area index, was affected by irrigation treatments (Fig. 7). The Leaf Area Index (LAI) was directly related to the amount of water applied. LAI values under deficit-irrigated treatments (40, 60 and 80 L) were lower than under100 L. In both experiments, the difference between treatments in LAI became significant 30 days after planting. These results suggest that the amount of water applied in the ulterior period of growing, which corresponds to panicle differentiation and initiation, flowering and grain filling, when most growth occurs, is particularly important for millet crop. Mahalakshmi and Bidinger (1985) and Mahalakshmi *et al*. (1988) reported that millet growth was most sensitive to water supply during these periods, although insufficient water also slowed growth at earlier stages. Millet plants receiving only 40 and 60% of their Etc requirements are not only subject to water deficit but also to a saline stress (Fig. 5 and 6). Plant growth has been shown to be reduced when the root zone is subjected to the combination of water deficit and saline stress (Devitt *et al*., 1993).

Table 1: Yield of pearl millet under different irrigation treatments

	Grain yield (q ha^{-1})			Final dry matter (q ha^{-1})		
Treatments	2005	2006	Mean	2005	2006	Mean
100 L	26.700	27.650	27.18	93.100	97.680	95.39
80 L	22.170	23.730	22.95	84.330	88.310	86.32
60 L	18.400	20.200	19.30	72.950	77.940	75.45
40 L	11.210	13.510	12.36	64.050	70.720	67.39
LSD (5%)	1.443	2.193		5.745	5.180	

For analyzing the effect of irrigation treatments on the final yield, four criteria were retained: Millet yield, panicle number/m², kernel number/panicle and 1000-kernel weight The data concerning the four parameters considered, observed for all irrigation treatments, are presented in Table 1 and 2.

The data shows that for both experiments the maximum grain yield and final dry matter production occurred in the 100 L treatment. Millet yields under the 100 L treatment were statistically different from that obtained with 80 L. A significant reduction in yields occurred with the 60 and 40 L treatments. Millet grain yields obtained with 100 L irrigation treatment were

Table 2: Yield components under different irrigation treatments

	Panicle number m^{-2}			Kernel number/panicle			1000-kernel weight (g)		
Treatments	2005	2006	Mean	2005	2006	Mean	2005	2006	Mean
100 L	68.00	69.00	69	319.00	332.00	326	12.70	12.90	12.80
80 L	64.00	68.00	66	290.00	298.00	294	12.18	12.25	12.21
60 L	60.00	64.00	62	268.00	276.00	272	11.87	11.95	11.91
40 L	51.00	55.00	53	221.00	235.00	228	11.16	11.40	11.28
LSD (5%)	7.171	7.236	-	46.148	44.390	-	0.532	0.528	-

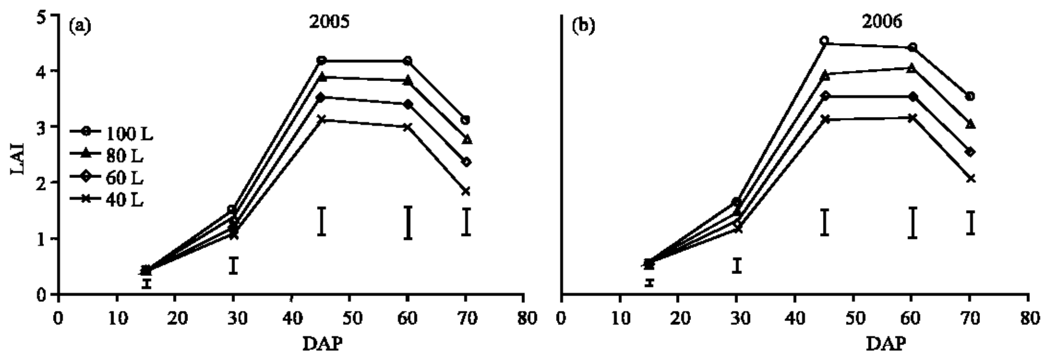

Fig. 7: Millet Leaf Area Index (LAI) under different irrigation treatments in 1st and 2nd year experiments. Bars are LSD at p = 0.05

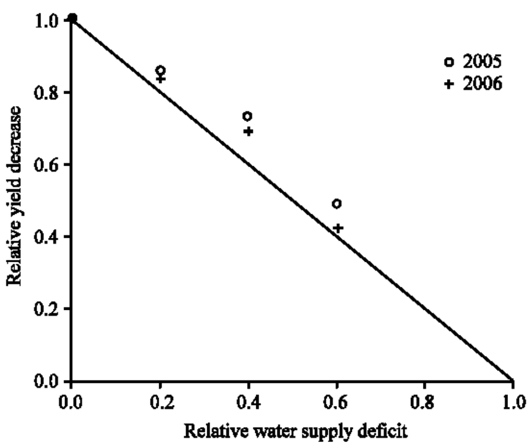

Fig. 8: Relative grain yield (Y/Y100 L) decrease in relation to relative water supply deficit

17, 31, 58% and 14, 27 and 51% greater than those obtained with 80, 60 and 40 L, respectively, for 1st and 2nd experiments (Fig. 8). The reduction in grain yield was mainly attributed to reduction in panicle number m^{-2}, kernel number/panicle and kernel weight (Table 2) as a consequence of water shortage during panicle differentiation and initiation, flowering and grain filling. Hayek and Abdelly (2004) reported similar results. Environmental factors such as available water influence yield components (Evans and Wardlaw, 1976). Millet crop productivity is most sensitive to water stress during flowering and grain filling (Hattendorf *et al*., 1988). Previous studies have shown that adequate irrigation water supply during panicle initiation, flowering and grain filling increases the panicle number and kernel number and weight (Van Oosterom *et al*., 2002; Mahalakshmi and Bidinger, 1985, 1986). Note that the deficit irrigation treatments resulted in higher salinity in the rooting zone than the full irrigation treatment (100 L) (Fig. 5 and 6). One consequence of reducing irrigation water use by deficit irrigation is the greater risk of increased soil salinity due to reduced leaching, (Schoups *et al*., 2005). A higher salinity associated with deficit irrigation caused important reductions in millet yield and its components.

There were differences between two experiments in millet yields. Yields were highest the 2nd year because of the low initial soil salinity. To assess their respective sensitivity to salt, grain yields data for each experiment were statistically analyzed with a piecewise linear response model (Van Genuchten, 1983). The model uses a non-linear least square regression to determine the slope and threshold for the salt tolerance equation. The analysis outcome indicated that thresholds were nearly the same for both experiments. Therefore, both yield sets were combined and analyzed (Fig. 9). Based on these data it can be stated that under our conditions Yr = 100-17 (ECe-3.46) for ECe >3.46 dS m^{-1} and Yr = 100 for Ece <3.46 dS m^{-1}. The threshold is close to the value calculated from published salt tolerance data (3.46 vs. 3.65) but the slope is considerably steeper (17 vs. 6.7)

Table 3: Irrigation water supplies and water use efficiency under different irrigation treatments

	Irrigation (mm)		W.U.E (kg/ha/mm)		
Treatments	2005	2006	2005	2006	Mean
100 L	431	415	6.20	6.66	6.43
80 L	345	332	6.42	7.15	6.79
60 L	260	249	7.10	8.11	7.59
40 L	172	166	6.52	8.14	7.33
LSD (5%)	-	-	0.540	0.883	-

*An irrigation of 62 mm supplied just before planting is not included in these totals

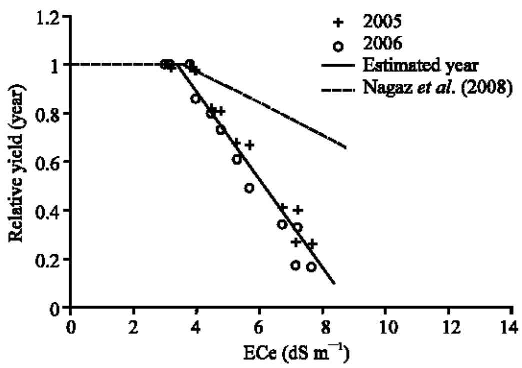

Fig. 9: Relative grain yield in relation to soil salinity (ECe, dS m^{-1})

(Nagaz *et al*., 2008), most likely because of the combined effect of salinity and water deficit for sandy soil in an arid climatic context characterized by a high evaporative demand. These results, obtained under actual farming conditions, support the practicality of using the 100 L methodology to implement an efficient use of saline water for millet production. Under severe shortage of water irrigation could be reduced voluntarily. There is a quantitative indication of the yield loss associated with deficit irrigation (Fig. 8). Irrigation water saving during the whole season of 20, 40 and 60% has resulted in the grain yield losses of 17, 31, 58% and 14, 27 and 51%, respectively, for 1st and 2nd experiments.

Water use efficiency: Amounts of irrigation water supply for each irrigation treatments are presented in Table 3. For all treatments, irrigation water supply ranged from about 165-430 mm. The amounts of irrigation water in the 2 experiments for well-watered condition were similar to those reported by Hattendorf *et al*. (1988) and Ibrahim *et al*. (1985) and less than reported by Chaudhuri and Kanemasu (1985).

The WUE expressed as the ratio of grain yield to irrigation water received from planting to harvest is presented in Table 3. The WUEs values obtained for first and second year experiments are comparable with those obtained in other field studies (Maman *et al*., 2003; Hattendorf *et al*., 1988; Chaudhuri and Kanemasu, 1985; Singh and Kanemasu, 1980) and were affected by irrigation treatments. In the 1st year, the WUE with 100 L treatment was not significantly different from those obtained with 80 and 40 L treatments but statistically different from that obtained with 60 L treatment. The difference was also significant between 60 L treatment and the 80 and 40 L treatments. These two last did not show a statistical difference between them. For 2nd year, The WUE with 100 L was not significantly different from that obtained with 80 L but statistically different from those obtained with 60 and 40 L treatments. These two last treatments did not show a statistical difference between them and were considerably higher than that obtained under 80 L treatment.

For both experiments, the WUE for grain yield was the lowest under 100 L treatment and the highest under 40 L and 60 L treatments. The irrigation treatments 40 and 60 L gave a higher WUE because grain yield reduction (31 and 58% for 2005 and 27 and 51% for 2006) was less than the irrigation water supply (40 and 60%). The relatively high yields and water use efficiencies noted in 80 L treatment in both experiments indicate an acceptable response millet crop to mild water deficit.

CONCLUSION

Results of this study indicate that the well irrigated treatments (100 L) decreased the soil salinity beneath the emitter as the zone of salt accumulation moved away from the emitter. Salts were concentrated midway between the emitters and towards the wetting front. Relatively high values of soil salinity were observed beneath the emitter for 40 and 60 L treatments; whereas, the highest soil salinity occurred at a distance of 7 and 15 cm from the emitter and 15 and 25 cm from the drip line. Millet growth expressed by Leaf Area Index (LAI) was influenced by irrigation treatments. For both experiments, LAI of deficit irrigated treatments (80, 60 and 40 L) were significantly lower than those in full irrigation treatment (100 L). The 100% of ETc treatment (100 L) produced the highest grain and final dry matter yields for both years. Treatment 80 L gave also good yields. Note that the deficit irrigation treatments gave lower yields and resulted in higher salinity in the rooting zone than the full irrigation (100 L). The higher salinity associated with the deficit irrigation treatments were sufficient to cause reduction in millet yields. The Water Use Efficiency (WUE) fro grain yield was significantly affected by irrigation treatments. The lowest values occurred under the 100 L treatment, while, the highest values were obtained under 40 and 60 L deficit irrigation treatments. Although, high efficiencies were observed for the most severe restrictions, the yield and quality obtained under these treatments do not allow opting for such important reductions.

The relatively high yields and water use efficiency values noted under full irrigation in both experiments indicate the high potential of the millet crop to valorize irrigation waters of limited quality, provided that good management is applied. In consequence, 100 L appears to be a promising irrigation strategy for millet crop under the arid climate of Southern Tunisia. In case of situations where water supply is limited, irrigation of millet could be scheduled using 80% of ETc.

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