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The consequences of saline irrigation treatments on soil physicochemical characteristics

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Abstract

When saline water is used to irrigate crops in arid environments, appropriate irrigation management should be applied to avoid negatively impacting soil characteristics. In this study, the effects of irrigating date palms with saline water (2.24 g l^{-1}) on soil physicochemical characteristics such as the electrical conductivity (EC_e), the pH of the saturated soil paste (pH_e), the concentrations of soluble cations (Ca^{2+}, Mg^{2+}, Na^+), the sodium adsorption ratio (SAR), the saturated soil hydraulic conductivity (K_s), and the volumetric water content of the soil (θ_v) were evaluated in a Tunisian Saharan cropland, the Dergine Oasis, during a 4-year period (2012–2015). The effects of three different irrigation treatments of date palms on soil properties were investigated: low treatment (90% of the net irrigation requirement (NIR) of date palms was applied); medium treatment (100% of NIR was applied), and high treatment (110% of NIR was applied). The results showed that the application of saline water for irrigation inevitably has a negative impact on the physicochemical properties of the soil. Irrigation with saline water was observed to have severe negative impacts on the soil characteristics, especially EC_e, Na^+, K_s, and θ_v. However, among the three irrigation treatments applied, statistical analysis (Duncan's multiple range test) indicated that the high treatment significantly $(p < 0.05)$ minimized the degradation of soil characteristics by the saline water; this treatment decreased EC_e, Na^+, and SAR and increased the water content, θ_v, of the studied soil.

Keywords Irrigation treatment · Soil characteristics · Saline water · Arid environments · Oasis

Introduction

In arid regions, meager rainfall (annual amounts vary between 100 and 300 mm; FAO 1989) coupled with an extreme shortage of fresh groundwater necessitate the use of saline groundwater to satisfy the water demands of the agricultural sector (Kolsi et al. 2013; Zaidi and Kassem 2012). This saline groundwater arises through processes known as primary and secondary salinization. Primary salinization occurs naturally in groundwater where there is naturally occurring salt (e.g., halite and gypsum) in the parent aquifer material or lateral flow from adjacent saline aquifers. Secondary salinization arises through human activities, primarily land-use changes, development, and agricultural activities such as increased crop production resulting from the intensive use of agrochemicals (Knapp and Baerenklau 2006). During the past few decades, a rapid increase in irrigated lands and the climatic conditions of the Saharan environment have together caused major salinization of the groundwater resources in this region; consequently, intensive exploitation of saline groundwater has led to severe degradation of agricultural soil (King and Thomas David 2014). Indeed, soil salinization is considered the main reason for cropland degradation in these areas. Hamdy (2005) reported that the soil salinization process has negatively affected about 30% of the irrigated lands in the Sahara.

As demonstrated by numerous researchers (e.g., Amézketa 1999; Tedeschi and Dell'Aquila 2005; Al-Zu'bi Y 2007; Huang et al. 2011; Askri et al. 2014), frequent irrigation with saline water can accelerate the soil salinization process, significantly degrading the quality of agricultural soil in various ways. A high concentration of salt, especially sodium salt, in the soil can cause physicochemical deterioration of the soil. This can lead to structural damage to the

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soil due to the dispersion of clay particles, decreased soil hydraulic conductivity, soil instability due to the clogging of soil pores, and the formation of a thin crust at the surface of the soil, which reduces the rate of infiltration of irrigation water into the soil profile. Physicochemical deterioration of the soil also leads to a severe reduction in soil productivity, hence degrading soil fertility (Al-Zu'bi 2007).

The appropriate management of saline water and the soil to ensure sustainable agriculture in Saharan croplands by avoiding or minimizing the adverse effects of saline water on agricultural soil is therefore an extremely important issue. Key to achieving sustainable agricultural management is a good understanding of the processes behind the degradation of soil physicochemical characteristics by the saline irrigation water (Tedeschi et al. 2007). Particular attention needs to be paid to agricultural soils that receive large amounts of water through surface irrigation, considering the complexity involved in maintaining a safe level of salinity within the soil (Huang et al. 2011). In the Saharan croplands, the considerable water requirements of date palms *Phoenix dactylifera* (Sperling et al. 2014) lead to the application of enormous volumes of saline water during the irrigation process (Tripler et al. 2011). A number of studies have addressed the effect of saline irrigation water on soil physicochemical characteristics (e.g., Al-Zu'bi 2007; Huang et al. 2011; Singh et al. 2011), but very few studies have studied this effect for soil in which date palms are growing. The primary objectives of the work reported in the present paper were therefore to assess the effects of four years of irrigation of date palms with saline water on the characteristics of the soil, and to identify the appropriate irrigation treatment (i.e., the appropriate volume of saline water) that will minimize the degradation of soil physicochemical characteristics.

Materials and methods

The Dergine Oasis

Field work was performed during a 4-year period between January 2012 and December 2015 in the Dergine Oasis (Fig. 1), a modern Saharan irrigated oasis located in southwestern Tunisia, where environmental conditions (De Grenade 2013) favor the growth of date palms. The climate of the study area is arid (the average yearly rainfall rarely exceeds 90 mm) and hot (exceeding 40 °C in the summer months). In contrast, the average annual potential evapotranspiration reaches 1800 mm. The average monthly relative humidity varies between 62 and 32% in December and August, respectively (El-Fahem 2003). In 2003, the Dergine Oasis, 88 ha in area, was completely planted with the date palm *Phoenix dactylifera* to a density of 120 palms per hectare. These trees receive surface irrigation with saline water (3.5 dS m^{-1} ≈ 2.24 g l^{-1}) supplied by a deep artesian well with a depth of 175 m. Chemical and physical properties of the applied irrigation water are given in Table 1. The soil texture is loamy sand and gypsum is present throughout the oasis (depth concentration: 1 m; average gypsum distribution: 6%). The extensive application of saline water to irrigate the palm trees as well as the unsuitable agricultural soil (loamy-sand soil with a high infiltration rate) have led to the creation of a shallow saline groundwater layer at an average depth of less than 2 m in the studied oasis (Askri and Bouhlila 2010). To prevent the potential for this shallow groundwater layer to cause irrigated soil salinization, the oasis was protected with a subsurface drainage system (buried pipe drains) installed at a depth of 1.5 m. The drainage system is designed to stop the water table from rising to a critical

Fig. 1 Location of the Dergine Oasis in the town of Douz, Kebili, southwestern Tunisia
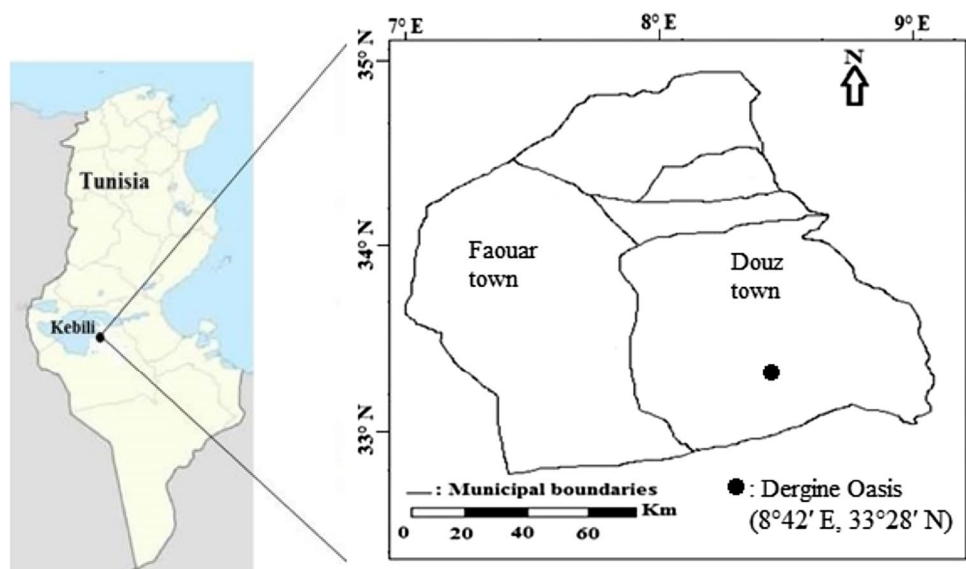
Table 1 Chemical and physical properties of the saline irrigation water applied in the Dergine Oasis (data based on the analysis of 12 samples taken in the year 2012, i.e., one sample per month)

Parameter	Minimum	Maximum	Average
EC_{iw} (dS m^{-1})	3.40	3.62	3.51
SAR	4.70	6.10	5.80
pH_e (−)	7.83	7.92	7.87
Na^+ (meq L^{-1})	12.50	18.50	16.6
Ca^{2+} (meq L^{-1})	7.20	09.36	8.40
Mg^{2+} (meq L^{-1})	6.62	8.75	7.80
K^+ (meq L^{-1})	0.25	0.32	0.30
Cl^- (meq L^{-1})	12.17	14.20	13.3
SO_4^{2-} (meq L^{-1})	10.12	11.19	10.8
HCO_3^- (meq L^{-1})	2.10	3.30	2.80
Na (%)	24.0	28.0	27.0

soil depth of 1.5 m (defined based on the agroclimatic and soil conditions in the oasis; Ben Aissa et al. 2013; Bouarfa et al. 2009).

Experimental design and monitored plots

The main objective of the present work was to investigate the effect of saline water quantity (irrigation treatment) on soil physicochemical characteristics. To achieve this aim, the soil characteristics observed following the application of different quantities of saline water were investigated. Three irrigation treatments (Table 2) were applied in three different plots (Fig. 2) located in the Dergine Oasis during the studied period (2012–2015). These plots were selected largely on the basis of their location within the Dergine Oasis (Fig. 2). The

Table 2 Properties of the monitored plots and the irrigation treatments applied to them

Plot	Surface area (ha)	Soil texture[a]	Irrigation frequency[b] (days)	Number of irrigation events[b]	Palm density (palms ha^{-1})	Water quantity	Irrigation treatment type
Plot 1	0.5	Loamy-sand	15	96	120	90% of NIR[c]	Low treatment
Plot 2	0.5	Loamy-sand	15	96	120	100% of NIR	Medium treatment
Plot 3	0.5	Loamy-sand	15	96	120	110% of NIR	High treatment

[a]Determined using the sedimentation method (Gee and Bauder 1986)

[b]Applied during the studied period (2012–2015)

[c]NIR is the net irrigation requirement of date palms (NIR = actual evapotranspiration (ET_a) + leaching requirement (LR))

Fig. 2 Irrigation system topology in the Dergine Oasis and locations of the three monitored plots (plots 1, 2, and 3)
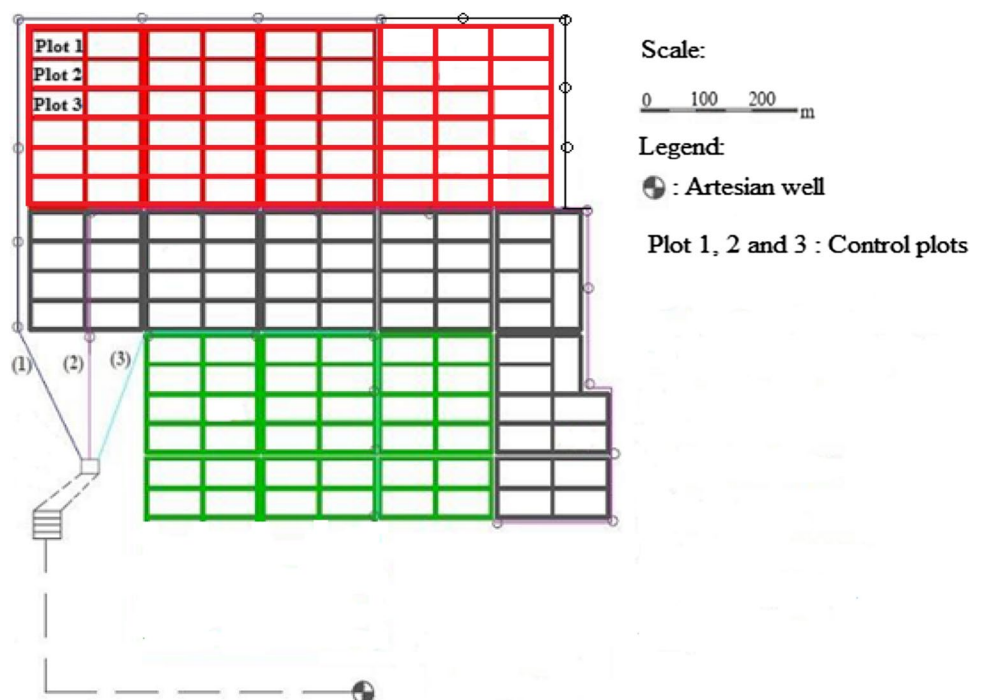
selected plots (the three in the top left corner in the figure) were the most elevated plots, so they did not receive lateral shallow groundwater flow from neighboring irrigated plots. In other words, we eliminated the possibility that lateral flow from neighboring plots could influence the properties of the soil in each plot of interest. No significant rainfall was recorded during the study period, meaning that the soil in the studied plots mainly received moisture from irrigation. Whereas palm trees were planted in the other plots in the Dergine Oasis in 2003, the palms in the monitored plots were planted in January 2012 (at the beginning of the studied period) and were surface irrigated using available saline water (Table 1). The quantity of saline water applied to each plot over the studied period is presented in Table 3. It should be mentioned that regular and adequate drainage was observed in all monitored plots.

Soil sampling

The soil properties of all monitored plots (plots 1–3) were investigated by analyzing the first 90 cm of the soil profile in each plot (90 cm is the maximum depth of the root zone for planted date palms). In the soil profile, three soil horizons were identified: 0–30, 30–60, and 60–90 cm. The variations in the properties of the soil within those horizons were determined. Throughout the studied period (2012–2015), 96 irrigation events were recorded for each plot (Table 2). Soil samples were collected from each plot at the three depth intervals 24 h after each irrigation event. A truck-mounted hydraulic push probe (Giddings Machine Company, Fort Collins, CO, USA) was used to collect intact soil samples. This allowed 288 soil samples to be collected from each plot (96 irrigation events $\times$ 3 soil layers), or 864 samples in total (96 irrigation events $\times$ 3 soil layers $\times$ 3 plots). The collected soil samples were subject to careful physical and chemical analyses carried out via standard methods (Page et al. 1982). Before the analyses, all of the collected soil samples were dried for 24 h, crushed, and sieved using a screen with a grid size of 2 mm and then stored for further analyses.

Chemical analyses of the collected soil samples included the pH of the saturated soil paste (pH_e), the electrical conductivity (EC_e), soluble cation concentrations (Ca^{2+}, Mg^{2+},

Table 3 Total amount of water applied (in mm) to each of the monitored plots during the studied period (2012–2015)

Years	Plot 1 (low treatment)	Plot 2 (medium treatment)	Plot 3 (high treatment)
2012	1245	1386	1464
2013	1278	1398	1481
2014	1288	1409	1492
2015	1293	1422	1518

Na^+), and the sodium adsorption ratio (SAR). The cation concentrations and the SAR were measured for a saturated extract, whereas pH_e and EC_e were measured in a 1:5-diluted extract ("1 soil/5 water"). Physical analyses of the collected soil samples included the saturated soil hydraulic conductivity (K) and the volumetric water content of the soil (θ_v). Each soil property was measured in four replicates to check the consistency of the results. Furthermore, for each plot, the effect of the local heterogeneity on the soil physicochemical property measurements was neglected due to the size of the investigated plot (0.5 ha) as well as the homogeneity of the texture of the soil (loamy sand).

Electrical conductivity of the saturated soil paste (EC_e)

This parameter was measured to evaluate the level of soil salinization. A high soil salinization level, especially around the roots of the crop, imposes ion toxicity, osmotic stress, nutrient deficiency, and oxidative stress on crops and limits their uptake of water from the soil, decreasing crop production (Shrivastava and Kumar 2015). High soil salinity can also negatively affect many soil physicochemical characteristics such as soil structure and soil porosity (Huang et al. 2011).

Following the method proposed by Rhoades (1996), a filtrate was first extracted from a 1 soil/5 water mixture to measure the electrical conductivity of the 1:5-diluted extract ($EC_{1/5}$). The extraction process was performed through a Buchner funnel. A linear regression equation was then derived for each soil layer (Eqs. 2.1, 2.2, and 2.3 below) to convert the $EC_{1/5}$ values into electrical conductivity values of the saturated soil paste (EC_e). The 864 soil samples collected from the Dergine Oasis (96 samples from each soil layer) were used to establish the relationships between $EC_{1/5}$ and EC_e (regression coefficients $R^2 > 0.95$). The measured EC_e was expressed in dS m^{-1}.

$$EC_e = 1.89 + 1.11 \times EC_{1/5} \left(0 - 30 \text{ cm}; R^2 = 0.98\right) \quad (2.1)$$

$$EC_e = 1.63 + 1.16 \times EC_{1/5} \left(30 - 60 \text{ cm}; R^2 = 0.97\right) \quad (2.2)$$

$$EC_e = 1.59 + 1.27 \times EC_{1/5} \left(60 - 90 \text{ cm}; R^2 = 0.95\right) \quad (2.3)$$

pH of the saturated soil paste (pH_e)

This parameter is considered a key influence on the physicochemical condition of the soil and on plant growth (Roy et al. 2006). The filtrate used for $EC_{1/5}$ measurements was also employed to conduct pH measurements with a glass-electrode pH meter. The obtained values ($pH_{1/5}$) were transformed into the pH of the saturated soil paste (pH_e) based on

established relationships between $pH_{1/5}$ and pH_e for the three soil layers (Eqs. 2.4, 2.5, and 2.6 below). The soil samples collected for each layer (80 samples) in the Dergine Oasis were used to establish the relationship between $pH_{1/5}$ and pH_e for each layer.

$$pH_e = 0.21 + 1.02 \times pH_{1/5} \left(0 - 30 \text{ cm}; R^2 = 0.96\right) \quad (2.4)$$

$$pH_e = 0.18 + 1.13 \times pH_{1/5} \left(30 - 60 \text{ cm}; R^2 = 0.94\right) \quad (2.5)$$

$$pH_e = 0.11 + 1.22 \times pH_{1/5} \left(60 - 90 \text{ cm}; R^2 = 0.97\right) \quad (2.6)$$

Soluble cation concentrations (Ca^{2+}, Mg^{2+}, and Na^+)

The sodium cation (Na^+) concentration was measured using a flame photometer (model 410, Corning Inc., Corning, NY, USA). The calcium (Ca^{2+}) and magnesium (Mg^{2+}) cation concentrations were measured with an atomic absorption spectrophotometer (model SP3, Pye Unicam, Cambridge, UK). The guideline proposed by Page et al. (1982) was followed when measuring the Ca^{2+}, Mg^{2+}, and Na^+ concentrations.

Sodium adsorption ratio (SAR)

This parameter was analyzed to probe the potential for soil properties, especially the soil structure, to be degraded by high sodium concentrations (with respect to the calcium and magnesium concentrations) in the irrigation water. The measured Ca^{2+}, Mg^{2+}, and Na^+ concentrations were used to calculate the sodium adsorption ratio (SAR) using Eq. 2.7 below (Oster and Sposito 1980):

$$SAR = \frac{(Na^+)}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}}, \quad (2.7)$$

where ionic concentrations are expressed in meq L^{-1}.

Soil hydraulic conductivity (K_s)

The saturated hydraulic conductivity (K_s) of each soil core sample was determined based on the constant-head method described by Blake and Hartge (1986). For this purpose, the collected intact soil cores (8.2 cm in length and 6.2 cm in diameter) from the studied plots and soil layers were saturated in the laboratory. The saturated hydraulic conductivity (K_s) values of the samples were then measured using a constant-head permeameter. We strictly followed the guideline for K_s measurements produced by Gholizadeh-Sarabi and Sepaskhah (2013) regarding the laboratory materials

required, the measurement steps to perform, and the calculation method to use. K_s was calculated using the following equation and expressed in cm day^{-1}:

$$K_s = \frac{\Delta V}{\Delta T \times i \times A}, \quad (2.8)$$

where ΔV is the volume of the inflow or outflow, ΔT is the time step, i is the hydraulic gradient, and A is the cross-sectional area of the soil column (for more details, see Gholizadeh-Sarabi and Sepaskhah 2013).

Volumetric water content (θ_v)

In each of the three monitored plots, the volumetric soil water content (θ_v) in each soil layer (0–30, 30–60, and 60–90 cm) was measured 24 h after each irrigation event (to ensure that the soil conditions had stabilized after irrigation). The θ_v measurements were performed in situ using a time-domain reflectometry (TDR) probe (TRASE 6050X1, Soil Moisture Corporation Company, Goleta, CA, USA). The TDR probe was calibrated according to the method reported in Hamouda et al. (2005). As recommended by Cichota et al. (2008), the direct measurement of θ_v by TDR is an appropriate technique for soil with a high potential salt concentration. The values of θ_v were expressed in cm^3 cm^{-3}.

Statistical analysis

The data collected, i.e., the measurements of soil properties in the three monitored plots obtained during 2012–2015, were analyzed using a standard statistical approach. Differences between the soil property values obtained under the three irrigation treatments (low, medium, and high; Table 2) were detected using analysis of variance (ANOVA). Duncan's multiple range (DMR) test at a significance level of 0.05 (Duncan 1955) was conducted to identify which of the values differed significantly among the three irrigation treatments. The SPSS software package (Kinnear and Gray 2000) was used to perform this statistical analysis. The DMR test is very useful for distinguishing the impacts of various treatments on soil properties and for identifying the best amount of saline irrigation water to apply to minimize the degradation of soil physicochemical characteristics.

Results and discussion

During the studied period, the shallow groundwater did not rise to the critical soil depth (2 m) after each irrigation event. For this reason, we ignored any contribution of the groundwater to the deterioration in soil properties. Therefore, the main focus of the present study was to assess the impact of the saline irrigation water on the soil characteristics.

In the following section, we present the soil properties recorded for plot 2 before irrigation (i.e., just before the first irrigation event in the first year) and after irrigation (i.e., just after the last irrigation event in the fourth year). This is because a normal irrigation treatment (i.e., 100% of the net irrigation requirements of date palms) was applied to plot 2 during the studied period. We also compare the impacts of the different treatments in the three monitored plots on the soil physicochemical properties.

Effect of saline irrigation water on soil characteristics

We now present a comparison of the soil physicochemical characteristics before (January 2012) and after (December 2015) the application of saline water for irrigation to plot 2 (a medium irrigation treatment was applied in this plot). It is apparent from the results presented in Table 4 that the application of saline water for irrigation (2.24 g l^{-1} salinity) significantly ($p < 0.05$) changed the soil physicochemical

characteristics in all three soil layers. As presented in Table 4, pH$_e$ decreased from neutral (7.2–6.9) in January 2012 to slightly acidic (6.5–6.1) by the end of the studied period. As reported by Roy et al. (2006), microbial activity and nutrient efficiency are maximized in neutral to slightly acidic soil, thus facilitating optimal crop growth. Also, the density of palm roots in the deep (60–90 cm) soil layer increases over time (Zaid and Jiménez 2002), which increases the amount of organic acid in this layer (i.e., the pH decreased with soil depth). This may be another reason for the increase in the observed soil acidity following three years of the saline water irrigation treatment.

Regarding the effects of the applied saline irrigation water on the soluble cation concentrations (Ca^{2+}, Mg^{2+}, and Na$^+$) in plot 2, the following findings should be noted. First, the saline irrigation water decreased the calcium (Ca^{2+}) concentration in the studied soil. The acidity level of the irrigated soil may be the main reason for this noticeable decrease (Fig. 3). Good irrigation management by the farmers during the studied period (i.e., a strategy to reduce the gypsum

Table 4 Comparison of soil properties before (January 2012) and after (December 2015) irrigation treatment in monitored plot 2

| Parameter	Soil layer: 0–30 cm		Soil layer: 30–60 cm		Soil layer: 60–90 cm	
	Before irrigation	After irrigation	Before irrigation	After irrigation	Before irrigation	After irrigation
EC$_e$ (dS m^{-1})	6.20	8.62	5.81	9.84	4.71	11.81
pH$_e$ (−)	7.20	6.50	7.10	6.40	6.90	6.10
Na$^+$ (meq L^{-1})	34.50	44.50	32.50	42.60	30.50	40.30
Ca^{2+} (meq L^{-1})	36.20	28.36	34.4	26.4	32.4	25.4
Mg^{2+} (meq L^{-1})	17.62	13.75	14.8	12.8	13.8	11.8
SAR (−)	6.60	9.70	6.50	9.60	6.40	9.50
K_s (cm day^{-1})	99.32	81.25	91.22	76.31	85.31	72.13
θ_v (cm^3 cm^{-3})	0.064	0.032	0.082	0.041	0.098	0.044
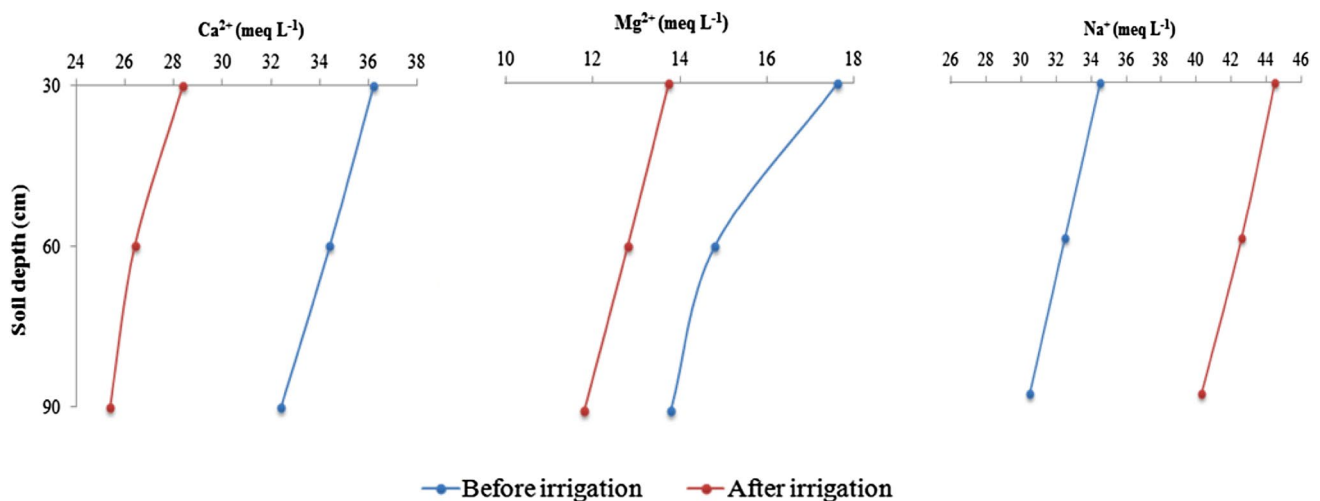
Fig. 3 Comparison of the soluble cation (Ca^{2+}, Mg^{2+}, and Na$^+$) concentrations observed before and after irrigation

concentration) could be another reason for this decrease. Second, a significant decrease in the magnesium (Mg^{2+}) concentration was also observed at the end of the studied period (Fig. 3). A low Mg^{2+} concentration in the irrigated soil hinders the growth of planted trees, as Mg^{2+} deficiency leads to leaf yellowing with brilliant tints (Roy et al. 2006). This was observed in the date palms planted in the Dergine Oasis after applying saline water for irrigation. Third, in contrast to the Ca^{2+} and Mg^{2+} concentrations, a significant increase in the Na^+ concentration was noted after the irrigation period (Fig. 3). This is most likely due to the high Na^+ concentration in the applied irrigation water (the Na^+ level in the irrigation water is presented in Table 1). Generally, the three common cations in the studied soil can be listed as follows in order of how negatively their concentrations were impacted by the saline irrigation water: $Na^+ > Ca^{2+} > Mg^{2+}$.

The observed decreases in Ca^{2+} and Mg^{2+} concentrations and the increase in Na^+ concentration were employed to calculate the sodium adsorption ratio (SAR) using Eq. 2.7. The result showed that there was a major increase in the SAR over the studied period (Fig. 4). Al-Rasbi (2010) suggest that a continuous increase in the SAR in irrigated soil could degrade date palm growth characteristics such as plant height, plant girth, and leaf length. Hence, it is very important to reduce the SAR level in the irrigated soil.

After four years of irrigation with saline water, a significant increase in the electrical conductivity (EC_e) of the irrigated soil was observed (Fig. 5). This implied a progressive accumulation of salt in the soil profile during the studied period. As seen in Fig. 5, the EC_e of the irrigated soil exceeded the desired EC_e level of the date palm (< 4 dS m^{-1}; Maas and Hoffman 1977). A similar salinization trend has been noted for irrigated soil in many other Tunisian Saharan oases (e.g., Askri and Bouhlila 2010; Haj-Amor et al. 2016). It appears that the climatic conditions of Tunisian Saharan oases (rainfall < 80 mm year^{-1} and evapotranspiration
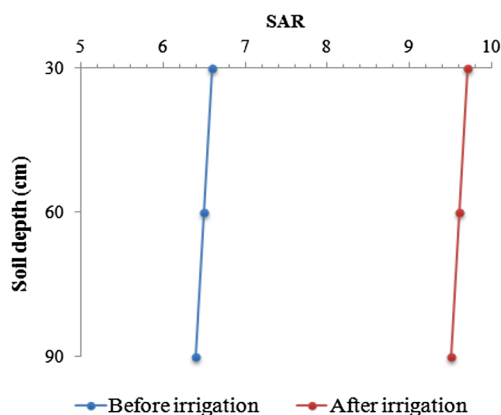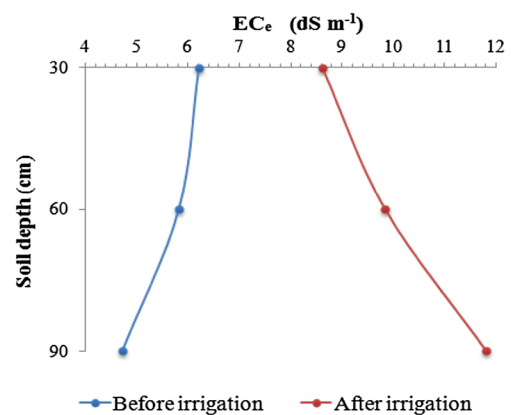
Fig. 5 Measured soil electrical conductivity (EC_e) distributions before and after irrigation

> 1500 mm year^{-1}) and the extensive application of saline water (Sperling et al. 2014) are the main drivers of the major salinization observed in the irrigated areas of various Tunisian Saharan oases (Askri et al. 2014).

The changes in EC_e with soil depth (Fig. 5) showed a slight increase in EC_e in the topsoil layer (0–30 cm), whereas a substantial increase in EC_e was noted for the bottom layer (60–90 cm, the high root density zone; Zaid and Jiménez 2002). Therefore, there is a high risk of decreasing crop production due to the impact of soil salinization on the root zone (Huang et al. 2011). The variations in EC_e throughout the soil profile revealed that the leaching effect of the irrigation water (i.e., salt removal from soil) was significantly higher for the topsoil than for the deeper soil layers. This could be the main factor in the large difference between the EC_e of the topsoil and that of the deep soil layer. As reported in many studies (e.g., El-Haddad and Noaman 2001; Mostafazadeh-Fard et al. 2007), accurate estimation of the leaching requirement is key to reducing soil desalinization. To calculate this, it is important to take into account the depth of the soil profile (to prevent soluble salt from being deposited in the deeper soil layers), the salinity threshold of the crop (4 dS m^{-1} for the date palm), and the salinity level of the applied water. As stated by Mostafazadeh-Fard et al. (2007), the accurate estimation of the leaching requirement, the application of irrigation water of a suitable salinity, and the use of a well-designed drainage system represent an effective overall approach to managing soil salinization in arid lands.

Regarding the physical properties of the studied soil, the hydraulic conductivity (K_s) of the irrigated soil decreased from 99.3 to 81.2 cm day^{-1} and from 85.3 to 72.1 cm day^{-1} in the 0–30 cm and 60–90 cm soil layers, respectively (Fig. 6). The major decrease in K_s over the studied period can be directly related to the observed increase in soil salinization. Increasing the water-soluble salt concentration in the soil can suppress soil dispersion, leading to a decrease in
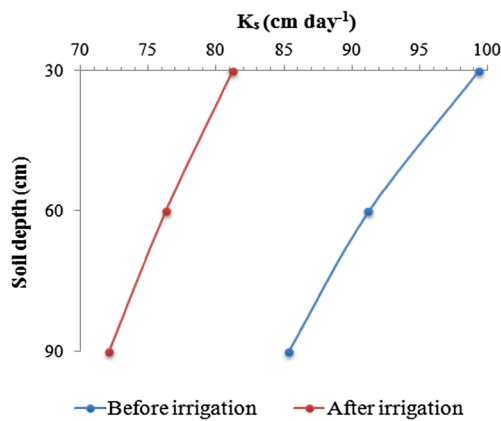
Fig. 4 Comparison of the sodium adsorption ratio (SAR) before and after irrigation

Fig. 6 Measured saturated soil hydraulic conductivity (K_s) values before and after irrigation at different soil depths
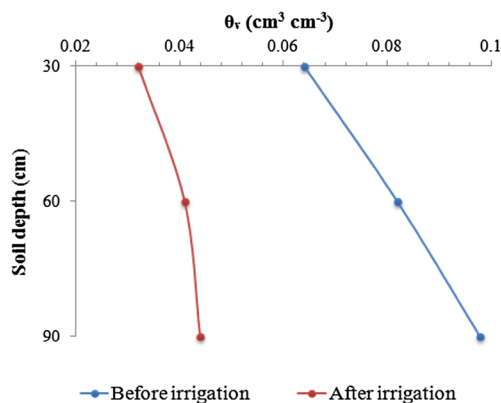

Fig. 7 Comparison between the volumetric water content (θ_v) after the first irrigation event (January 2012) and that after the last irrigation event (December 2015)

hydraulic conductivity (Singh et al. 2011; Adhikari et al. 2014; Hanson et al. 1999). The observed decrease in K_s has a negative effect on the soil water content by decreasing the infiltration rate of the irrigation water into the soil profile. This argument is supported by measurements of the volumetric soil water content (θ_v), as shown in Fig. 7.

θ_v was measured after each irrigation event. The results revealed that for all soil layers, and assuming that the same amount of irrigation water was applied at each event, θ_v generally decreased over the studied period. It appears that the decrease in θ_v was primarily due to the long-term (four-year) application of saline groundwater to irrigate the palm trees in the studied oasis.

In summary, the results show that the evaluated physicochemical properties of the soil (EC_e, pH_e, Ca^{2+}, Mg^{2+}, Na^+, SAR, K_s, and θ_v) are interdependent; for example, an increase in EC_e could cause a major increase in K_s. Therefore, all of these soil properties should be taken into consideration when devising an appropriate soil and water

management plan that has the potential to minimize the impact of saline water on irrigated soil.

Effects of the irrigation treatments on the soil characteristics

In this section, we present the effects of the different irrigation treatments applied to the three monitored plots (Table 2) on their soil properties. Duncan's multiple range (DMR) test at a significance level of 0.05 was utilized to compare the results of the three treatments. Based on the measurements obtained and the results of the statistical test, we were able to identify the irrigation treatment that minimized the negative effects of the saline water treatment on the soil physicochemical characteristics, thus optimizing plant growth and productivity. Table 5 summarizes the effects of the different irrigation treatments on the soil properties of each layer.

Effect on soil electrical conductivity (EC_e)

The results presented in Table 5 show a significant (p value < 0.05) difference in soil electrical conductivity (EC_e) between the three irrigation treatments (T_1, T_2, and T_3) for each soil layer. Figure 8 shows the average value of EC_e recorded during the studied period for each irrigation treatment. According to the figure, it is evident that EC_e built up to levels that exceeded the salt tolerance of date palms, estimated at 4 dS m^{-1} (Maas and Hoffman 1977). The main causes of this soil salinization are the high salinity of the irrigation water ($EC_{iw} = 3.51$ dS m^{-1}), the climatic conditions (especially the aridity and very low rainfall), and the soil properties (texture, salinity, etc.). However, a remarkable effect of the irrigation treatment on EC_e was noted. For example, for the 0–30 cm soil layer, it was observed that the average EC_e of the soil under treatment T_3 was 47.2% lower than the average EC_e of the soil under treatment T_2. Comparison of the EC_e values of the top layer under treatments T_3 and T_1 revealed that the EC_e was 52.1% lower under treatment T_3. Thus, the high irrigation treatment substantially contributed to reducing soil salinity. As shown in Fig. 8, the observed decrease in EC_e with the high treatment helped to reduce salinization stress by keeping the electrical conductivity of the soil close to the tolerance level (salinity threshold) of the date palm, which is about 4 dS m^{-1} (Maas and Hoffman 1977).

Effect on soil water content (θ_v)

A significant difference (p value < 0.05, Table 5) in soil water content (θ_v) was observed between the different irrigation treatments. As shown in Fig. 9, a positive effect on θ_v of increasing the amount of irrigation water applied was noted. As can be seen in the figure, for the 60–90 cm soil layer

Table 5 Effects of the irrigation treatments [low (T_1), medium (T_2), and high (T_3) treatments] on soil properties (mean ± S.D. values are shown, as are significance levels)

| Soil layer (cm)	Soil property	Irrigation treatment			Significance levels		
		T_1	T_2	T_3	Between T_1 and T_2	Between T_1 and T_3	Between T_2 and T_3
0–30	EC_e (dS m^{-1})	9.2 ± 1.7	7.41 ± 1.1	4.21 ± 1.2	0.039	0.031	0.035
	pH_e (−)	6.5 ± 0.4	6.85 ± 0.6	6.71 ± 0.7	n.s.	n.s.	n.s.
	Na$^+$ (meq L^{-1})	38.9 ± 0.3	39.5 ± 3.2	32.5 ± 3.1	n.s.	0.029	0.026
	Ca^{2+} (meq L^{-1})	27.2 ± 1.3	32.2 ± 2.3	29.2 ± 2.6	n.s.	n.s.	n.s.
	Mg^{2+} (meq L^{-1})	12.7 ± 0.8	15.6 ± 1.3	14.8 ± 1.1	n.s.	n.s.	n.s.
	SAR (−)	10.4 ± 1.5	8.1 ± 0.6	6.6 ± 0.8	0.036	0.033	0.037
	K_s (cm day^{-1})	92.2 ± 0.6	90.2 ± 0.8	91.2 ± 0.5	n.s.	n.s.	n.s.
	θ_v (cm^3 cm^{-3})	0.034 ± 0.003	0.048 ± 0.002	0.055 ± 0.001	0.022	0.021	0.045
30–60	EC_e (dS m^{-1})	9.9 ± 0.7	7.8 ± 0.9	4.4 ± 1.3	0.041	0.033	0.037
	pH_e (−)	6.4 ± 0.4	6.7 ± 0.5	6.6 ± 0.2	n.s.	n.s.	n.s.
	Na$^+$ (meq L^{-1})	37.1 ± 0.3	37.5 ± 1.8	31.1 ± 0.5	n.s.	0.031	0.028
	Ca^{2+} (meq L^{-1})	25.2 ± 1.1	30.4 ± 1.9	28.2 ± 1.2	n.s.	n.s.	n.s.
	Mg^{2+} (meq L^{-1})	11.5 ± 0.8	13.8 ± 0.9	13.6 ± 0.3	n.s.	n.s.	n.s.
	SAR (−)	10.3 ± 1.5	8.1 ± 06	6.4 ± 0.5	0.038	0.035	0.039
	K_s (cm day^{-1})	84.2 ± 0.6	83.7 ± 0.9	84.8 ± 0.4	n.s.	n.s.	n.s.
	θ_v (cm^3 cm^{-3})	0.048 ± 0.002	0.061 ± 0.003	0.068 ± 0.003	0.024	0.023	0.047
60–90	EC_e (dS m^{-1})	12.4 ± 1.7	8.26 ± 0.6	4.7 ± 0.3	0.040	0.034	0.038
	pH_e (−)	6.1 ± 0.4	6.5 ± 0.4	6.3 ± 0.2	n.s.	n.s.	n.s.
	Na$^+$ (meq L^{-1})	36.1 ± 0.6	35.4 ± 2.4	30.7 ± 0.1	n.s.	0.033	0.029
	Ca^{2+} (meq L^{-1})	23.2 ± 1.2	28.9 ± 1.2	25.2 ± 1.5	n.s.	n.s.	n.s.
	Mg^{2+} (meq L^{-1})	11.2 ± 0.9	12.8 ± 1.3	13.1 ± 0.3	n.s.	n.s.	n.s.
	SAR (−)	10.1 ± 1.5	7.95 ± 0.8	6.1 ± 0.5	0.039	0.037	0.038
	K_s (cm day^{-1})	79.25 ± 0.6	78.72 ± 0.6	79.81 ± 0.4	n.s.	n.s.	n.s.
	θ_v (cm^3 cm^{-3})	0.055 ± 0.002	0.071 ± 0.001	0.075 ± 0.003	0.026	0.025	0.044

n.s. not significant at the 0.05 level

Fig. 8 Average soil electrical conductivities (EC_e) in the three soil layers under various irrigation treatments (T_1, T_2, and T_3)
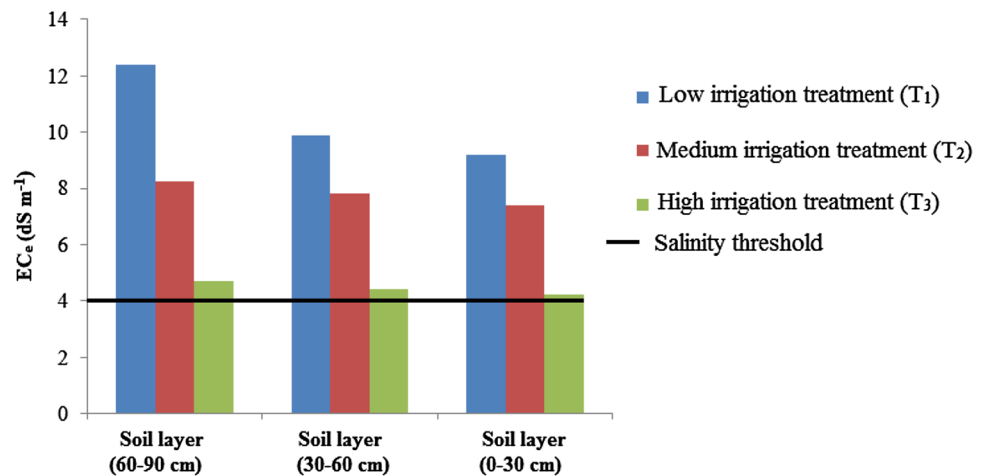
(the high root density zone), the average θ_v was 24.7 and 14.1% higher under the treatment T_3 than under treatments T_1 and T_2, respectively (Fig. 9). These large decreases and increases in EC_e and θ_v, respectively, were directly related to the application of T_3 during the studied period. As reported by many scholars (e.g., Haj-Amor et al. 2016; Askri et al.

Fig. 9 Average soil water contents (θ_v) of the three soil layers under various irrigation treatments (T_1, T_2, and T_3)
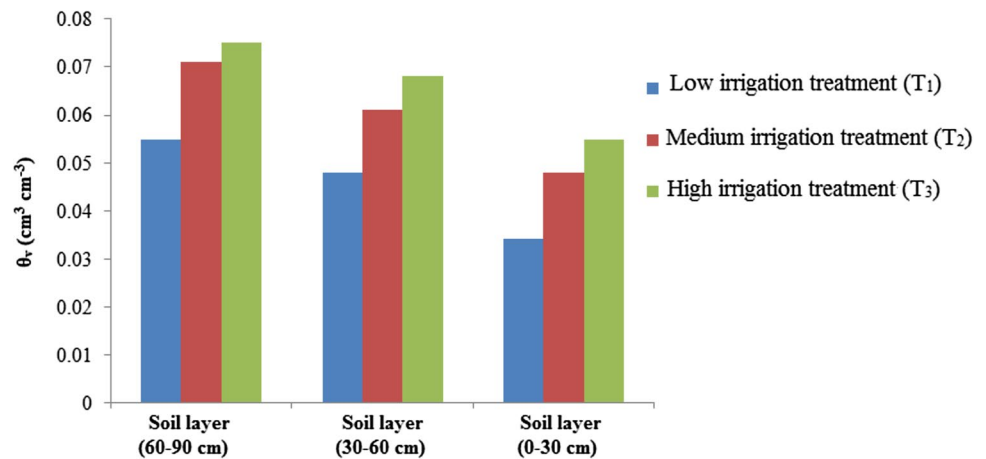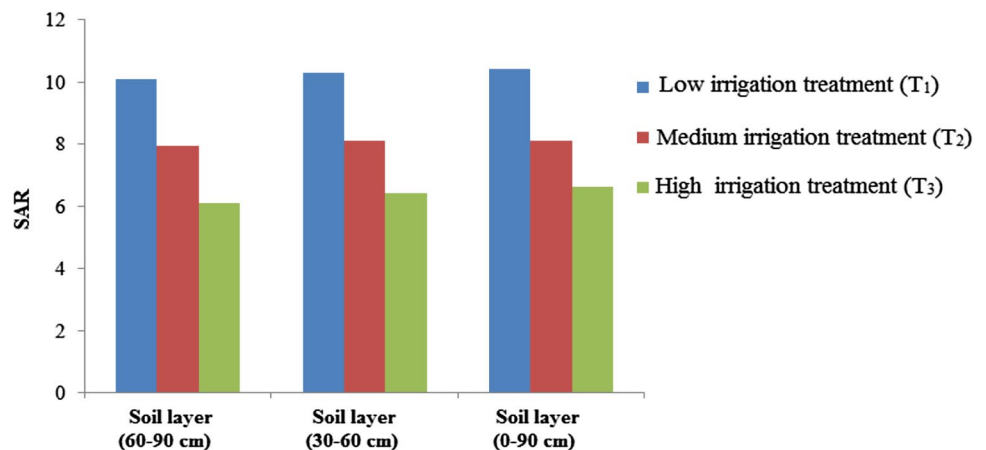

2014), improved knowledge of the EC_e and θ_v values of irrigated soil permits more accurate irrigation scheduling, thus reducing the negative effects of saline irrigation water on the agricultural soil.

Effects on the Ca^{2+}, Mg^{2+}, and Na^+ concentrations and the SAR

A comparison of the effects of the different irrigation treatments on the Ca^{2+}, Mg^{2+}, and Na^+ concentrations is provided in Table 5. As can be seen in the table, for all three investigated soil layers, the concentrations of Ca^{2+} and Mg^{2+} did not vary significantly with the irrigation treatment applied. However, the Na^+ concentration was significantly ($p < 0.05$) lower for treatment T_3 (relative to the Na^+ concentrations for T_1 and T_2). The decrease in Na^+ concentration under the high irrigation treatment could help to enhance date palm growth. As depicted in Fig. 10, for all soil layers, the lowest average value of the sodium adsorption ratio (SAR) was obtained with the high irrigation treatment. This is directly related to the significant decrease in Na^+ concentration under T_3 (Fig. 10).

Effect on pH_e

The results presented in Table 5 suggest that pH_e and K_s were not significantly influenced by the treatment applied during the studied period. The pH_e measured in each plot was in good agreement with the results of the study conducted by Rahil et al. (2013), who showed that the pH of the irrigated soil was not affected by the amount of saline irrigation water applied. This study revealed that the pH is a function of the quality (especially the salinity level) of the irrigation water, not the quantity of irrigation water used.

Effect on K_s

The hydraulic conductivity (K_s) of the soil also did not differ significantly between the three monitored plots (i.e., did not vary with the irrigation treatment applied; see Table 5). This can be explained by the fact that K_s is mainly dependent on the quality of the irrigation water (Bardhan et al. 2007).

As discussed above, it is evident that when the date palms were irrigated frequently (every 15 days over the 4-year period) with saline water (2.24 g l^{-1}), the high irrigation

Fig. 10 Average sodium adsorption ratios (SAR) for the three soil layers of interest under various irrigation treatments (T_1, T_2, and T_3)

treatment (i.e., applying 110% of the net irrigation requirement of date palms) was the best irrigation strategy for maintaining the appropriate properties of the irrigated soil and thus achieving the highest potential yield of planted trees. Such an approach requires continuous control of the irrigation water and soil properties (Bouksila et al. 2013), and considerable effort must be made to educate farmers about the tremendous benefits of the high irrigation treatment for soil productivity. Therefore, as stated by Ghazouani et al. (2009), special attention should be paid to improving farmers' awareness of the effects of irrigation strategy, particularly the combined influence of water quantity and quality, on soil characteristics. Our understanding of the water management strategy currently employed in the studied oasis and the findings of Ghazouani et al. (2009) both suggest that the farmers' perceptions of water conservation and their application of a low irrigation treatment have degraded the studied region's soil productivity. Therefore, the farmers should be educated about the need to ensure sustainable agricultural activity in the studied oasis by applying the appropriate long-term strategy for irrigating with saline water. On the other hand, a similar study has shown that the farmers have the ability to adapt and reduce the problems caused by soil salinization due to their long-term practical experience (Omrani and Dieter 2012).

Conclusion

We monitored the characteristics of the soil in three plots in the Dergine Oasis that were irrigated with different quantities of saline water (3.5 dS m^{-1}) over a period of four years (2012–2015), and observed that irrigation of the plots with the saline water had severe effects on the chemical and physical properties of the soil. The soil properties investigated included its electrical conductivity (EC_e), the pH of the saturated soil paste (pH_e), the concentrations of various soluble cations (Ca^{2+}, Mg^{2+}, Na^+), the sodium adsorption ratio (SAR), the soil hydraulic conductivity (K_s), and the volumetric water content of the soil (θ_v). Soil property values measured before the start of each irrigation treatment (in January 2012) were compared with those measured at the end of the studied period (December 2015). Analysis of the resulting data revealed that there was a high risk of soil quality deterioration in terms of EC_e, SAR, and K_s in the near future unless an appropriate irrigation water and soil management strategy is established in the studied Saharan oasis. Among the three irrigation treatments applied to the plots, i.e., a low treatment (90% of NIR), a medium treatment (100% of NIR), and a high treatment (110% of NIR), the high treatment strategy yielded the best results, as it suppressed the soil salinization process through leaching. The findings of this study could be applied to other typical

Saharan oases that are irrigated with saline water in order to optimally manage the salinization process and potentially prevent further soil deterioration in Saharan croplands.

Compliance with ethical standards

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