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RESEARCH ARTICLE

Saline soil reclamation by agroforestry species under Kalaât Landelous conditions and irrigation with treated wastewater in Tunisia

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Abstract

Irrigation with treated waste water (TWW) in combination with plantation of agroforest species was tested in the Kalaât Landelous region for the reclamation of salt affected soils. Five species (*Atriplex nummularia, Eucalyptus gomphocephala, Acacia cyanophylla, Casuarina glauca, Pinus halepensis*) were cultivated in saline soils that are affected by shallow, saline groundwater and were irrigated with TWW during the summer season. The results after 4 years of experimentation show a distinct decrease in soil pH and salinity accompanied by a decrease in Cl and Na concentrations. Irrigation decreased the heavy metal concentrations in the topsoil but an increase in deeper layers indicate to leaching due to TWW irrigation. The investigated plant species were differently affected in growth performance by salinity and TWW irrigation. *Atriplex nummularia* appeared to be the most resistant species and *Pinus halepensis* the most sensitive one to hydro-pedological conditions of the Kalaât Landelous plot. In conclusion, salt-tolerant plant species seem to be good candidates for the reclamation of salt-affected, waterlogged sites in combination with TWW irrigation, as the adaptations of such species seem to operate under different abiotic stress conditions.

Keywords Forest species · Heavy metals · Salinity · Soil · TWW · Waterlogging

Introduction

In Tunisia, scarcity of water has become the most crucial problem, especially in agricultural production. In addition, it is estimated that the excessive use of domestic and industrial water may cause a further decrease in the volume of available water resources for Tunisian agriculture in the future. Therefore, the concept to use alternative sources to support agricultural water security and to find new resources of water for irrigation is crucial for Tunisian agriculture. Treated wastewater (TWW) reuse has become one promising solution and the main option to develop sustainable water resource management. According to the National Sanitation Utility (ONAS 2017), the TWW is derived from 119 wastewater treatment plants (WWTPs) in Tunisia, which are located close to the cities and the secondary treatment is used in most of them.

The usage of TWW for irrigation has been part of a national strategy to mobilize and increase the water supply. The reuse of TWW aims to conserve water resources with good quality. This strategy contributes to the protection of the environment, to a reliable water supply to farmers, to the sustainability of agricultural production, and to the reduction of saline water intrusion in coastal areas through groundwater recharge. In addition, the reuse of TWW for irrigation provides essential plants nutrients, such as N, P, K, and micronutrients (Rusan et al. 2007; Bedbabis et al. 2015; Etchebarne et al. 2019).

Wastewater is derived essentially from households; industrial areas contribute only a small percentage. The estimated TWW volume was about 260 million cubic meters (Mm^3) in 2017 (about 5% of the mobilized water resources) in Tunisia.

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The exploitation of treated water is still weak as about 71% of the wastewater is released into the sea or valleys. The rest is used for various purposes including agriculture, golf and green areas, and recharge of groundwater. Exploitation capacity was developed in agriculture whenever the TWW conform to health and environmental standards established for this purpose. The Tunisian TWW needs to meet the NT 106.02 standard (revised, JORT 2018) before being released into natural environments. Reuse of TWW in agriculture is regulated by the 1975 Water Code, the NT 106.03 standard (INNORPI 1989), a list of crops which are allowed to be irrigated with secondary effluents and by the list of requirements for agricultural wastewater reuse projects.

High salt and heavy metal concentrations contained in the TWW are the two major constraints related to the secondary effluent and can cause potential contamination of agricultural soils (Qadir et al. 2010; Tarchouna et al. 2010a; Abd-Elwahed 2018). There are concerns that the long-term soil application of TWW will negatively affect the fields and pose a toxicity threat to human beings (Sachan et al. 2007; Khan et al. 2012; Brahim et al. 2014). Several investigations have shown changes in nutrient contents and in physical or chemical properties of wastewater irrigated soils (Tarchouna et al. 2010a; Mechri et al. 2011; Singh et al. 2009; Abegunrin et al. 2013 ; Bedbabis et al. 2014; Khaskhoussy et al. 2015; Abd-Elwahed 2018). Irrigation with TWW can provide macronutrients such as phosphorus (P) and organic matter to the soils (Mohammad and Mazahreh 2011) but there is also a risk to accumulate heavy metals such as Cd, Pb, Zn, Fe, Mn, and Cu (Brahim et al. 2014). Furthermore, many studies proved that the accumulation of heavy metals was significantly higher in vegetables grown on wastewater-irrigated fields in comparison to vegetables grown on reference soils (Singh et al. 2009). Therefore, by reusing TWW for irrigation purposes, soils can be enriched with useful nutrients but also with harmful salts or various other compounds and heavy metals.

In Tunisia, the low quality of irrigation water and the presence of a shallow saline water table, which can carry salts from subsurface to surface layers, are the major factors causing soil salinization. In total, about 10% of the Tunisian soils are affected by salinity (about 1.5 million hectares) (Hachicha 2007). Besides soil salinity, waterlogging is a second major problem, which is negatively affecting Tunisian agricultural soils and the agricultural yield potential. Effects of salinity on plant growth are well documented (Munns and Tester 2008; Negrao et al. 2017; Rahneshan et al. 2018). However, waterlogging and interactions between salinity and waterlogging are not fully understood. Forest plantations can contribute to site reclamation by a reduction in dryland salinization (Sharma et al., 2014). Saline and waterlogged soils can be transformed into agroforestry systems by using species which are tolerant to these conditions (Dagar 2014). This would provide an opportunity to recultivate degraded soils and increase the reuse of TWW in agriculture.

The reuse of TWW to produce forest plantations represents one of the most promising alternatives to get a stable vegetation cover on soils affected by high salinity and/or waterlogging. To get a deeper insight into this context, we chose the soil of Kalaât Landelous, known as a site, which is affected by high salinity as well as by waterlogged conditions. Different plant species were tested, which are typically grown trees and shrubs in Tunisia on the one hand and which are partly known to be adapted to high salinity. We focused on the growth potential and survival of the selected plants and their development and adaptation to the environmental stress conditions.

Materials and methods

Study area and experimental plot

The study was carried out from July 2012 to December 2015 in a plot (37° 02′ 36.81″ N. 10° 07′ 37.43″ E) near the city of Kalaât Landelous in the northern part of Tunisia (35 km north of the capital Tunis). The area has a Mediterranean semi-arid climate with an annual rainfall close to 470 mm, which occurs mainly in autumn and winter, and an average annual potential evaporation of 1400 mm. The soil has a fine texture, silty clay to clay, a very low organic matter content (about 0.7%), and a high total carbonate content (43%) and is rich in calcareous fraction (between 25 and 50% $CaCO_3$). The soil is very saline (see Tables 1 and 2). In 2012, an experimental plot (60 m × 40 m) has been elevated 1 m by putting soil from the same region onto the plot. This way, the plot was

Table 1 Variation of the depth, pH, salinity, and ionic composition of the groundwater (July 2012–December 2015)

	NB	Average ± SD	Range
Depth (cm)	69	118.8 ± 42.8	50.0-206.0
pH	69	7.5 ± 0.3	6.2-8.2
EC(dS/m)	69	51.8 ± 20.4	18.0-98.5
Mineral composition (mM)			
Cl	45	546.8 ± 319.3	50.8-1235.5
SO_4	45	56.2 ± 48.5	5.4-192.15
HCO_3	45	8.2 ± 3.8	0.9-20.5
Na	45	595.5 ± 406.9	62.2-1358.7
Mg	45	32.0 ± 47.4	0.05-122.5
Ca	45	17.3 ± 10.4	4.5-30.5
K	45	7.1 ± 6.9	1.14-32.5

Table 2 Variation of the pH and the EC in the different soil layers before and after the irrigation cycles (July 2012–December 2015) at the experimental site in Kalaât Landelous, Tunisia

	Before irrigation cycle	After irrigation cycle
pH		
0–30 cm	8.4 a	8.0 a
30–60 cm	8.3 ab	7.9 a
60–90 cm	8.3 ab	8.0 a
90–120 cm	8.0 b	7.9 a
ECe (dS/m)		
0–30 cm	19.5 a	15.1 b
30–60 cm	19.9 a	14.7 b
60–90 cm	22.4 a	17.9 ab
90–120 cm	22.7 a	21.9 a

Data represent the mean. For each parameter and each irrigation cycle, significant differences between layers are indicated by different letters according to Tukey's test ($p < 0.05$)

no longer affected by the shallow and saline groundwater. The experiment was set up in a randomized block design consisting of three blocks, which were provided with three piezometers in 2-m depth from the soil surface to follow the variation of the groundwater characteristics. In July 2012, 2-year-old plants of five forest species were planted. These plants were *Atriplex nummularia* (20 plants), *Eucalyptus gomphocephala* (31 plants), *Acacia cyanophylla* (27 plants), *Casuarina glauca* (31 plants), and *Pinus halepensis* (16 plants). The selected plants were randomly cultivated in 3 rows with 14 plants each. The plants have been irrigated during the summer season, with the secondary TWW provided by the WWTP of Kalaât Landelous treating industrial and domestic wastewater by aerated lagoons. An aerated lagoon is a treatment pond associated with high intensity of artificial aeration to promote the biological oxidation of wastewaters. In the lagoon, wastewater receives treatment through a combination of physical, chemical, and biological processes. The lagoon system was shown to be effective for the decontamination of heavy metals present in the wastewater with removal rates ranging from 32 to 79 % (Hannah et al. 1986; El-Shenawy et al. 2010). The removal efficiency depends on various parameters, such as the initial metal concentration, type of heavy metals, season, and temperature (El-Shenawy et al. 2010).

About 15 summer irrigation events per year, from June to September, were performed with an average dose of 50 mm per block (6 m × 10 m).

The TWW was basic (pH 8.3) with moderate salinity, indicated by electrical conductivity (EC) of about 4.2 dS/m. The irrigation water contained essentially Na and Cl. The contents of metallic trace elements (MTE) allowed the reuse of TWW in agriculture according to the Tunisian standard (NT 106.03).

Monitoring and analysis

Irrigation water and groundwater analysis

During the experiment, water samples (TWW and groundwater samples) were collected and groundwater depth was recorded. The pH and the EC of the effluent samples were measured weekly using a pH meter (InoLab pH 7110) and a conductivity meter (WTW InoLab Cond Level 2), respectively.

Soluble ions and heavy metals in the TWW and groundwater samples were analyzed monthly. Quantification of Cl and HCO_3 ions was performed by titration using silver nitrate solution ($AgNO_3$) and hydrochloric acid (HCl), respectively. The SO_4 ions were measured according to the nephelometric method and the concentration of Ca and Mg by complexometric titration. Na and K ions were determined by flame spectrophotometry (Jenway, PFP7). The heavy metal (Co, Cu, Mn, Fe, Zn, Ni, Cd, and Pb) concentrations were determined using atomic absorption spectrometry (Perkin Elmer).

Soil sampling and analysis

Soil samples were collected before starting the experiment (July 2012) and at the end of the experiment (December 2015), from the three experimental blocks of the Kalaât Landelous plot. Samples from 0–30, 30–60, 60–90, and 90–120cm soil depth were collected from the plots using a Dutch auger by combining 9 sub-samples taken over the plots. Soil samples were air-dried and sieved through a 2-mm mesh and transferred to the laboratory for physico-chemical analyses. The soil pH was determined in a soil-water mixture (20 g soil + 50 mL distilled water) and measured after 4 h. The EC of the saturated paste extract (ECe) was measured with a conductivity meter (WTW InoLab Cond Level 2) based on the method outlined by the US Salinity Laboratory Staff (1954). Cl, SO_4, HCO_3, Na, Mg, Ca, and K contents were determined from the saturated paste extract according to methods used for the water sample analyses, while heavy metals (Co, Cu, Mn, Fe, Zn, Ni, Cd, and Pb) in soil samples were measured by atomic absorption spectrophotometry (ISO 14869-1 l). The method based on acid digestion induced by microwave energy was optimized to measure the total heavy metal contents in soils. One gram of soil was put into a Teflon vessel (100 mL) with HF (10 mL) and $HClO_4$ (5 mL) and was, then, digested in a microwave oven. Seventy milliliters of perchloric acid was added to the mixture. Samples were, then, filtered and transferred into 100 mL volumetric flasks and brought to a volume of 100 mL by addition of distilled water.

Growth characteristics and chemical composition of plants irrigated by TWW

For each plant species, the percentage of growth was determined for all individual plants and the mortality was monitored. After a growth period of four years, one plant of each species per plot was harvested (*Atriplex nummularia, Eucalyptus gomphocephala, Acacia cyanophyllia*, and *Casuarina glauca*) and divided into leaves, stems, and roots. From *Pinus halepensis*, no samples could be collected as all plants died off. The biomass of the different plant parts was determined. All samples were immediately washed in tap water and rinsed with distilled water. Samples were dried in an oven at 60 °C until constancy of weight. After drying, the samples were weighed again and ground to pass through a 2mm sieve. The finely ground plant material was used to determine the chemical composition in the different plant organs. Mineral analysis was carried out after dry-ashing and digestion of the ashes with 1 M of HNO_3 at room temperature for 48 h. The essential (Co, Cu, Mn, Fe, Zn, and Ni) and toxic heavy metals (Cd and Pb) were extracted from dry matter by HNO_3 at room temperature for 48 h. They were determined by atomic absorption spectrophotometry. N was determined by the Kjeldahl method (NF T 90-110) (Martin 1987) in which 0.5 g of plant material was decomposed and oxidized by an excess of concentrated sulfuric acid (20 mL) using a catalyzed digestion ($CuSO_4$ + K_2SO_4) at 350 °C for 3 h. The amount of generated NH_4 was determined by using a programmable type distiller Vapodest Gerhardt 30s allowing the distillation of the mineral deposit by steam stripping. P, K, Na, and Cl were determined by X-ray spectroscopy (Tiger S8, Softwarepackage Spectra^{Plus}, Bruker).

Statistical analysis

The results presented are the means (± standard deviation (SD) in the case of the groundwater table) obtained from at least 5 replicates. Means were compared by Tukey's test at the 0.05 confidence level using the SPSS program (IBM SPSS statistics, v20). Heavy metals concentrations in the soils and plants were compared with ranges that can be observed frequently according to Adriano (2001) and Kabata-Pendias (2000).

Results

Changes in groundwater characteristics

The average groundwater depth was 118.8 cm (Table 1). During the rainy season, the groundwater table rose to 50.0 cm below the soil surface in October 2013. Contrarily, during the dry season, the groundwater table was lower and reached a maximum depth of 206 cm below the surface in August 2014. The groundwater was characterized by a slightly basic pH (7.5) and high salinity exceeding 51.8 dS/m. The EC varied from one season to another. A value of 18.0 dS/m was recorded in June 2013 and 98.5 dS/m in October 2015. The salinity was caused by Cl and Na ions (Table 1).

Effect of irrigation with TWW on soil parameters

Soil pH

The soil pH was found to be slightly decreased from 8.4–8.0 before to 8.0–7.9 after irrigation (Table 2). The soil was more basic in the top layer (0–30 cm). The lowest values were noticed at the deepest layer (90–120 cm).

Soil salinity

Results showed that, before and after irrigation with TWW, the EC increased slightly with soil depth (Table 2). Before irrigation, the soil was very strongly saline and salinity ranged from 19.5 to 22.7 dS/m with no significant differences in relation to soil depths. After irrigation, the soil was still strongly to very strongly saline with values ranging from 14.7 to 21.9 dS/m but at that time the salinity was significantly lower at the soil surface and increased with soil depth.

Major element composition

Cl, SO_4, HCO_3, Na, Mg, Ca, and K concentrations in the soil profiles were higher in the soil samples before irrigation started than after irrigation but the differences were not

Table 3 Ionic composition of different soil layers of the experimental plot in Kalaât Landelous before and after irrigation with TWW

	Ionic composition (mM)						
	Cl	SO_4	HCO_3	Na	Mg	Ca	K
Before irrigation cycle							
0–30 cm	190.6 a	18.5 a	5.6 a	188.5 a	8.1 a	7.6 a	0.7 a
30–60 cm	260.3 a	16.5 a	6.6 a	203.0 a	8.5 a	7.2 a	0.8 a
60–90 cm	267.9 a	18.0 a	6.4 a	247.7 a	8.3 a	15.2 a	0.8 a
90–120 cm	293.8 a	26.1 a	6.8 a	216.5 a	11.4 a	7.6 a	0.8 a
After irrigation cycle							
0–30 cm	169.8 a	14.0 a	3.8 a	166.2 a	5.8 a	0.4 a	9.6 a
30–60 cm	203.6 a	13.8 a	3.8 a	202.2 a	6.2 a	0.5 a	8.4 a
60–90 cm	217.5 a	13.0 a	3.5 a	206.1 a	7.8 a	0.5 a	10.6 a
90–120 cm	212.0 a	19.9 a	3.2 a	201.0 a	8.2 a	0.6 a	9.8 a

Data represent the mean. For each element and each irrigation cycle, significant differences between layers are indicated by different letters according to Tukey's test ($p < 0.05$)

statistically significant (Table 3). The highest concentrations were determined for Cl and Na, ions influencing the salinity of the soil.

Heavy metal concentrations in the soil

Kalaât Landelous soil was analyzed for the content of essential (Co, Cu, Mn, Fe, Zn, and Ni) and non-essential (Cd and Pb) metals in the different soil layers (Fig. 1). Before irrigation, most of the tested elements (except Co) decreased by trend progressively with soil depth. Significant differences between the topsoil and the deepest layer were found for Cu and Ni.

After irrigation with TWW, the levels of Mn, Fe, Zn, and Ni increased in the soil and those of Co, Cu, and Cd, contrarily, decreased when compared with their initial concentrations. Pb decreased in the upper soil layers up to 60 cm with irrigation but increased in the depths.

In general, summer irrigation accumulated Fe, Ni, and Pb in deeper soil layers (90–120 cm), while Co, Cu, Mn, and Zn

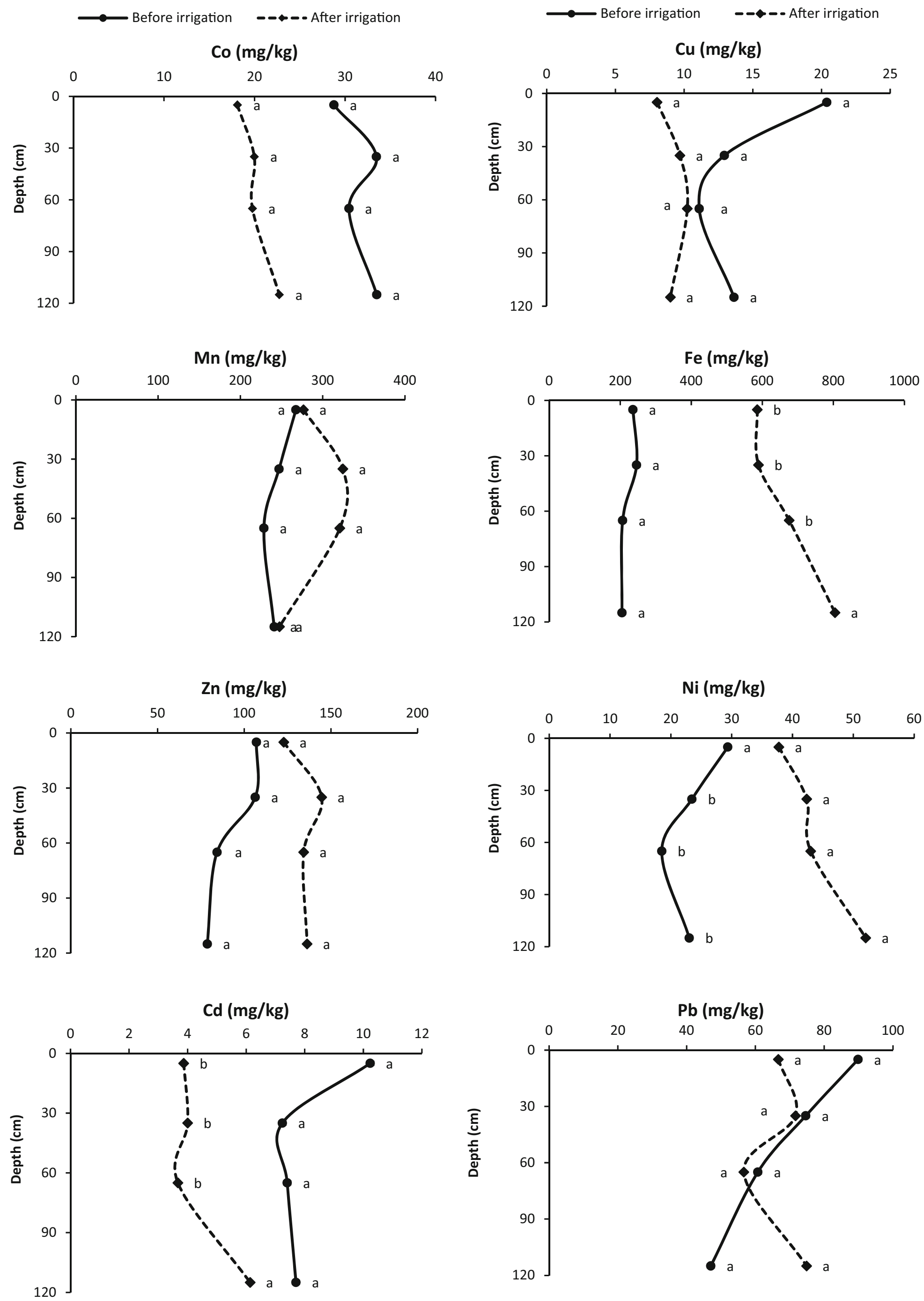

Fig. 1 Heavy metal concentrations in the different layers of the Kalaât Landelous soils before and after the irrigation cycle with TWW

showed no remarkable changes in their concentrations with soil depth. The Cd concentration also increased with soil depth but as the concentration was lower after irrigation than before the increase is not caused by irrigation but by changing soil conditions, which promote Cd accumulation.

Effect of treated wastewater on plant growth and chemical composition

Growth parameters

The plants mortality was recorded during the experimental time (Fig. 2a). After four years of experimentation, mortality reached 100% in case of *Pinus halepensis*. For *Eucalyptus gomphocephala*, *Acacia cyanophyllia,* and *Casuarina glauca*, on average, the mortality was 60.5%, 53.1%, and 40.0%, respectively. The lowest mortality of 21.0% was recorded for *Atriplex nummularia* where only 7 plants died from the 20 that were cultivated.

Generally, there was an increase in plant height and diameter in all plants grown from July 2012 to December 2015 (Fig. 2b). *Eucalyptus gomphocephala* showed the largest increase in height (71.6%) compared with the height at plantation time. Plants reached 163 cm in height at the end of the experiment. However, *Atriplex nummularia* showed the largest increase in stem diameter compared with all other cultivated plants (89.6%).

Distribution of mineral elements in plant parts

Results for the distribution of N, P, K, Na, and Cl in the different plant organs are depicted in Table 4. For all the investigated plant species, N, P, and K contents were higher in leaves than in stems or roots. The highest contents were found in *Acacia cyanopyllia*. Concentrations of Na and Cl were higher in roots. The highest concentrations of the latter elements were found in roots of *Atriplex numularia*, where values of 28.5 and 60.3 mg/g DW for Na and Cl, were accumulated, respectively.

Distribution of heavy metals in plant parts

The heavy metal contents in leaves, stems, and roots of the different plant species are shown in Table 5. The concentrations of some essential elements (Co, Fe, Zn, Ni) and some toxic (Cd and Pb) were above the ranges reported by Adriano

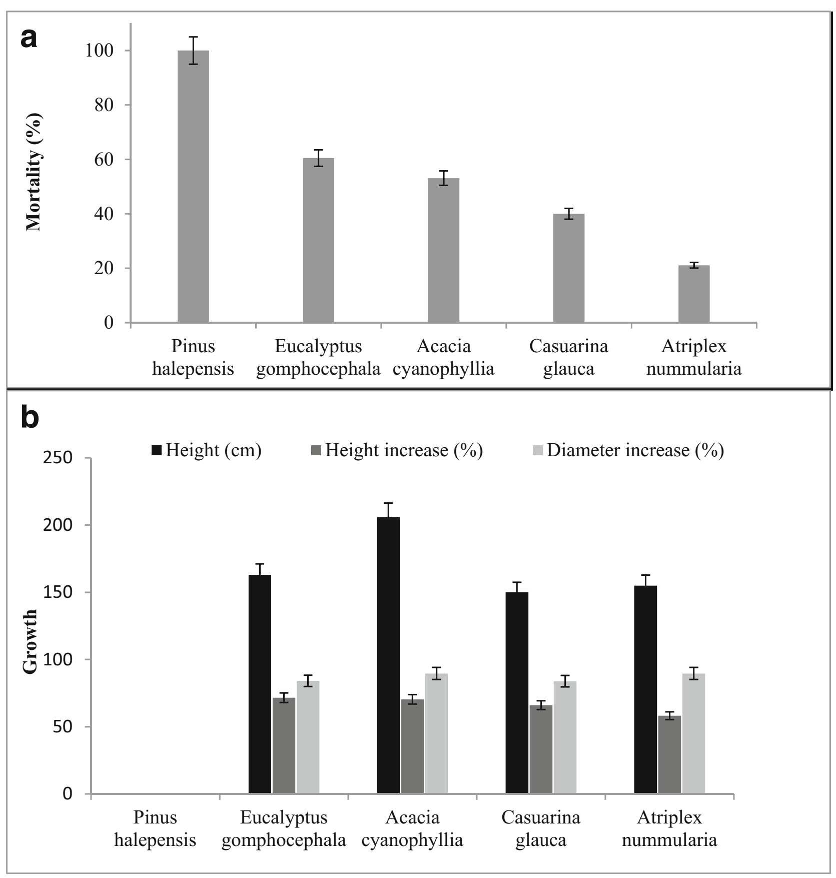

Fig. 2 Mortality recorded at the end of the experiment (**a**) and growth increase (July 2012–December 2015) (**b**) of different plant species grown in the Kalaât Landelous plot and irrigated with the TWW

Table 4 Mineral Composition (mg/g DW) in different tissues of tree species that were grown in Kalaât Landelous and irrigated with TWW (December 2015)

	N	P	K	Na	Cl
Atriplex nummularia					
Leaves	55.0 a	2.4 a	0.6 a	9.3 b	20.3 b
Stems	31.0 b	2.3 a	0.4 b	5.4 b	12.3 b
Roots	29.1 c	1.6 b	0.4 b	28.5 a	60.3 a
Acacia cyanophyllia					
Leaves	72.1 a	2.4 a	0.5 a	7.4 b	16.3 b
Stems	33.1 b	2.2 a	0.3 b	4.8 b	11.0 b
Roots	31.0 b	1.5 b	0.3 b	25.7 a	54.4 a
Eucalyptus gomphocephala					
Leaves	66.0 a	2.1 a	0.4 a	7.1 b	15.7 b
Stems	18.2 b	1.5 b	0.3 b	4.9 b	11.3 b
Roots	23.0 b	1.4 b	0.3 b	16.7 a	35.6 a
Casuarina glauca					
Leaves	41.8 a	2.2 a	0.5 a	6.6 b	14.7 b
Stems	36.1 a	1.1 b	0.2 b	4.8 b	10.3 b
Roots	25.0 b	1.4 b	0.2 b	16.7 a	34.6 a

Data represent the mean. For each element and each specie, significant differences between organs are indicated by different letters according to Tukey's test ($p < 0.05$)

(2001) and Kabata-Pendias (2000). Heavy metals were, preferentially, accumulated in root tissues, except Mn with higher contents in leaves. *Atriplex* roots embodied the highest levels of Cu, Zn, and Cd, while *Casuarina* contained the highest concentrations of Co and Pb.

Discussion

Our research was conducted over a period of 4 years to give the five selected plant species the chance to grow and get established in soils affected by salinity and by shallow saline groundwater. The TWW used for irrigation was basic (pH 8.3) with moderate salinity (4.2 dS/m) and met the Tunisian standard for trace elements which allowed reuse in agriculture (TN 106.03). The groundwater depth varied between 50 and 206 cm and the groundwater was slightly basic (7.5) with high salinity (exceeding 51.8 dS/m) mainly caused by high Na and Cl concentrations. The groundwater depth varied according to the season: the groundwater table was close to the surface in the rainy season and deeper during the dry season in summer.

In Tunisia, waterlogging, salinity, and water shortage represent serious threats to the sustainability of irrigated agriculture (Hachicha and Ben Aissa 2014). To overcome the problem of waterlogging, the experimental plot was redesigned in blocks. It was shown that elevation by 1 m above the surface reduced the effect of salinity in the topsoil but the soil remained very strongly saline in the deeper layers. The results of this study clearly revealed that irrigation with TWW can help to reduce salinity in the topsoil as well as water shortage during the dry season but the special situation in Tunisia with

Table 5 Heavy metals contents (mg/kg DW) in the leaves, stems and roots of plants grown in Kalaât Landelous and irrigated with the TWW (December 2015)

	Co	Cu	Mn	Fe	Zn	Ni	Cd	Pb
Atriplex nummularia								
Leaves	0.7 a	8.2 b	32.4 a	214.3 c	42.0 a	2.1 b	0.9 a	0.5 a
Stems	0.8 a	6.7 b	27.7 a	397.1 b	53.0 a	2.3 b	1.2 a	0.6 a
Roots	1.1 a	15.2 a	18.0 a	539.7 a	89.5 a	3.8 a	1.9 a	0.9 a
Acacia cyanophyllia								
Leaves	0.5 c	5.4 b	29.1 a	143.2 b	57.6 ab	1.5 c	0.8 a	0.4 c
Stems	0.6 b	7.8 ab	27.8 a	407.5 a	54.5 b	1.8 b	1.2 a	0.6 b
Roots	0.7 a	11.0 a	14.8 a	487.8 a	75.5 a	2.4 a	1.2 a	0.8 a
Eucalyptus gomphocephala								
Leaves	0.5 a	6.2 b	83.2 a	371.0 a	42.0 b	1.3 b	0.6 b	0.6 b
Stems	0.5 a	9.4 ab	37.0 b	498.9 a	45.9 b	2.7 a	0.8 ab	0.7 b
Roots	0.6 a	11.1 a	28.5 b	555.3 a	71.6 a	3.0 a	1.3 a	1.1 a
Casuarina glauca								
Leaves	0.4 a	7.6 a	91.9 a	379.5 ab	29.3 b	2.0 a	0.5 b	0.5 a
Stems	0.5 a	5.2 a	36.2 b	216.4 b	40.1 ab	2.5 a	1.0 ab	0.6 a
Roots	0.6 a	12.2 a	36.5 b	546.4 a	60.4 b	3.3 a	1.3 a	0.9 a
*Ranges	0.02–0.5	3.0–12	20–400	50–200	20–100	0.2–2.0	0.05–0.5	0.1–0.5

Data represent the mean. For each element and each plant, significant differences between organs are indicated by different letters according to Tukey's test ($p < 0.05$). *Ranges: typical trace element contents that can be observed frequently for vegetative aboveground plant organs according to Adriano (2001) and Kabata-Pendias (2000) high saline groundwater will result in salinity in the soils again, when the groundwater rises close to the surface in the wet season. Therefore, irrigation could help to diminish the problem of salinity but not to solve the problem at all.

A highly significant difference was found after four years of irrigation with TWW between the different soil layers (Table 2) with a lower salinity in the top layer, in comparison to the deepest layer (90–120 cm). This was caused by the transport and accumulation of salts in deeper layers after irrigation with TWW. These results are in accordance with Bedbabis et al. (2014) who reported that, after 4 years of irrigation with TWW, soil salinity was reduced close to the soil surface (20–40 cm) in comparison to deeper layers (60–80 cm). Moreover, our results coincide with that of Shojaei (2016) who investigated the effects of wastewater irrigation in different soil depths. The authors concluded that EC decreased in wastewater-irrigated soils. This decrease may be explained by leaching and displacement of salt after irrigation and partly by rainfall as well. Nevertheless, during our experiment, the soil remained strongly saline to very strongly saline (ECe > 14.0 dS/m).

Irrigation with TWW seems to decrease Cl, SO_4 HCO, Na, Mg, Ca, and K contents in soils in comparison to samples taken before the irrigation cycle. In general, the major element contents increased with increasing soil depths before and after irrigation. These results are in accordance with Shojaei (2014) who showed that, in comparison to control soils, the EC, dissolved Na content, total soluble Ca, Mg, and K were reduced in wastewater-irrigated soils. Shojaei (2016) revealed that irrigation with wastewater decreased the dissolved Cl content in the soil by 12.26% in 0–30-cm depth. This reduction could be a result of leaching into deeper soil layers or of plant uptake. Tarchouna et al. (2010a) found that Cl is, generally, not adsorbed or held back by soils but it moved readily with soil water.

Soil pH is well-known as one of the most important parameters acting on the concentration of metals in soil solution and increasing their mobility and availability to plants (Fijałkowski et al. 2012). The average pH values at the beginning of the experimental period ranged from 8.4 to 8.0. Irrigation with TWW only slightly reduced the pH to 8.0–7.9 and led to a decrease of soil pH with depth. In fact, this reduction is low, the soil pH value changed from moderately to slightly alkaline, according to the USDA classification (Soil Survey Division Staff 1993). Therefore, in this study, no change in trace element mobility and plant availability can be expected due to changes in pH. Some studies showed that irrigation with wastewater decreased the soil's pH. This decrease was probably caused by the decomposition of organic matter and production of organic acids, absorption of ammonia ions by plant and leaching of basic cations (Tarchouna et al. 2010a).

The low changes in pH were accompanied by variations of the heavy metal concentrations, which depend on the sampling date (before or after TWW irrigation) and soil depth (upper or deeper layers). In general, the concentrations of essential soil elements (Cu, Mn, Fe, Zn, and Ni) before and after the irrigation cycle were in the ranges reported by Adriano et al. (2001) and Kabata-Pendias (2000), while the levels of Co and toxic elements (Cd and Pb) were above these ranges.

Before TWW irrigation, the concentration of the majority of elements was different between layers with a general trend to be higher in the topsoil and decreasing progressively with depth. Such results may be related to the soil disturbance after its redesign in blocks and the low leaching of heavy metals, by either rainfall or TWW. After the irrigation cycle and despite the acceptable quality of the Kalaât Landelous TWW, the levels of Mn, Fe, Zn, and Ni increased while those of Co, Cu, and Cd decreased in the different soil layers in comparison to their initial soil concentrations. Our results were in agreement with other studies emphasizing the effect of the TWW on soil enrichment with some heavy metals. Many of these studies showed increases of the heavy metal concentrations in the wastewater irrigated areas compared with control soils (Tarchouna et al. 2010b; Galavi et al. 2010; Yintao et al. 2014), while others revealed, contrarily, lower concentrations of heavy metals in soils subjected to TWW irrigation when compared with geochemical background soils (Klay et al. 2010).

With depth, Fe, Ni, Cd, and Pb were preferentially accumulated in the deepest layers (90–120 cm), while Co, Cu, Mn, and Zn show lower variations (Fig. 1). Many authors (e.g. Klay et al. 2010; Tarchouna et al. 2010b) investigated the influence of irrigation on heavy metal leaching and accumulation in the soil profile. Element mobility is determined by specific characteristics, such as atomic radius or charge, that affect adsorption behavior, precipitation, and leaching (Serpaud et al. 1994; Lomander and Johansson 2001; Lu et al. 2009; Klay et al. 2010). Moreover, soil conditions play an important role in the mobility and adsorption of heavy metals. In this context, it has been reported that in well-aerated acid soils, several metals (especially Cd and Zn) are more mobile and bioavailable, while in poorly aerated neutral or alkaline soils, metals are substantially less available (Tack and Verloo 1995; Wilson et al. 2006). Additionally, the organic carbon content, the percentage of the clay fraction, the Fe and Mn oxide contents, and the irrigation time is influencing the accumulation of heavy metals in different soil depths as reported by Klay et al. (2010). Heavy metals were also sensitive to rainfalls, which induced leaching or a change of the metal speciation (Tarchouna et al. 2010b). In our case, the heavy metal distribution, which either accumulated in deeper layers or was more or less equally distributed throughout the soil profiles may be related to soil alkalinity (low variation of pH), the low organic matter content (low, 0.7 %), the high clay content (silty clay soil), or leaching caused by TWW and rainfall.

Kalaât Landelous soils are critical sites with respect to cultivation and economic usage. Therefore, it is an important task to develop and investigate cultivation strategies, which help to get an economic value out of these sites and preserve them from further soil degradation that will take place when there is no vegetation cover. Research efforts have greatly enhanced the understanding of the biology and management of forestry plantations on salt-affected soils (Lieth and al Masoom 1993; Singh et al. 1993; Dagar et al. 2001; Dagar and Singh 2003, Tomar et al. 2003; Singh and Dagar 2005; Dagar 2014; Sharma et al. 2014).

Therefore, to understand aspects of salt tolerance, physiology of halophytes and especially of those species with high economic value and salt tolerance (Yamaguchi and Blumwald 2005; Yan et al. 2013) is of high importance to help solve those problems in agricultural soils.

With the intention to discover suitable plant species that can be cultivated on degraded soils and can be irrigated by TWW, five different forest plant species were selected and tested in the experimental plot of Kalaât Landelous. After approximately 4 years of experimentation, some differences, regarding the mortality and growth, were noticed among the studied species. Sixty among 125 cultivated plants were able to survive. Similar mortality rates were noticed by other authors on such critical sites (Marcar et al. 1991; Marcar and Crawford 2004; Forrester et al. 2010; Isla et al. 2014). Despite the imposed salinity and waterlogging, *Atriplex nummularia* was the most tolerant among the five studied species and the growth of this plant was successful under the climate and soil conditions of the plot. *Atriplex nummularia* is a halophyte well adapted to arid, semi-arid, and salt-affected areas (Bajji et al. 1998). Our results were in agreement with Asad (2001) who observed a morphological adaptation of this plant to waterlogged and saline conditions. Several studies focused on the effects of salinity on *Atriplex nummularia* (Ramos et al. 2004; de Sandro et al. 2006; Bazihizina et al. 2009; Bazihizina et al. 2012; Souza et al. 2014). *Atriplex* showed a stimulation of growth under NaCl concentrations, which are, contrarily, a growth inhibitor for non-halophytes (Osmond et al. 1980). In the same context, Bazihizina et al. (2012) showed a growth stimulation of *Atriplex* under 10 to 450 mM NaCl. *Acacia cyanophyllia* has been also tested in Kalaât Landelous and was chosen because of its ability to survive in a diverse range of habitats and environments. Our results showed a significant increase in height and diameter of *Acacia cyanophyllia*. However, only 47% of the planted species survived during the experiment despite the fact that several studies showed a high tolerance of different species of *Acacia* to abiotic stress (Bui et al. 2014; Chandrasekaran et al. 2014; Arnold et al. 2014; Abbas et al. 2016). *Acacia* has been reported to be tolerant to waterlogging and salinity up to 40 dS/m, and has been suggested for the rehabilitation of damaged arid areas (Tomar et al. 1998; Cherifi et al. 2016).

In the present study, *Eucalyptus gomphocephala* had shown excellent growth despite the high mortality of 60.5%. Studies based on the response of *Eucalyptus* to salinity and/or waterlogging showed contradictory results. Some authors considered *Eucalyptus* as an attractive species due to its relatively high tolerances to salinity (Donaldson et al. 1983; Marcar et al. 1991) and waterlogging (Marcar 1993; Van der Moezel et al. 1988; Sarvade et al. 2017). Others observed a satisfactory growth of this species only when soil salinity was below 10 dS/m (Tomar et al. 1998).

Casuarina glauca was able to survive in the plot of Kalaât Landelous to a high proportion (60%) but its growth was a little bit smaller than that observed for the other species. Isla et al. (2014) found that *Casuarina glauca* could survive under both salinity and waterlogged environments. It was reported in a study that was conducted over 6 to 9 years, that *Casuarina glauca* was able to grow under 10–20 dS/m of salinity (Tomar and Gupta 1984–1994; Tomar and Minhas 1998; Tomar et al. 1994, Tomar et al. 1998).

Among the selected species, *Pinus halepensis* was the only one, which was not able to survive the experimental conditions and all plants died at the beginning of the study. This species seemed to be the most sensitive to salinity and/or waterlogging. Several studies discussed the sensitivity of *Pinus* species to abiotic stress (Calamassi et al. 2001; Calamassi and Paoletti 2004; Espinoza et al. 2014). Therefore, *Pinus halepensis* should not be considered anymore in soil reclamation plantation on saline or waterlogged soils in Tunisia.

Differences in nutrient uptake were observed between the studied species. According to Grattana and Grieveb (1999), crops differ not only in the rate at which they absorb available nutrients but also in the way by which they distribute the element inside the plant. Our results showed that N, P, and K were accumulated in leaves of all studied plants, especially *Acacia cyanopyllia*.

On the other hand, the concentrations of Na and Cl were higher in the roots of all species than in leaves or stems indicating to the ability of these species to prevent uptake of Na and Cl into vegetative plant parts. The highest value was found in roots of *Atriplex nummularia*. This corroborates with other authors, who found that *Atriplex nummuularia* has a great affinity for Na and Cl ions during nutrient uptake (de Sandro et al. 2006; Flowers and Colmer 2008; Nasir 2009; Belkheiri and Mulas 2013; Melo et al. 2016).

Plant growth in heavy metal-contaminated soils shows a variety of adaptations similar to those observed under salinity (Sebastiani et al. 2004). The selected plants accumulated higher levels of heavy metal (Co, Cu, Fe, Zn, Ni, Cd, and Pb) in the roots than in leaves or stems as well. This suggests that these forest species adopts a root accumulation strategy that avoids harming the leaves and damaging plant growth (Sebastiani et al. 2004). Many studies have reported that forest plants have the ability to respond with root exudation of organic acids, which hinder metal uptake (Heim et al. 1999; Ahonen-Jonnarth et al. 2000; Qin et al. 2007). In fact, the plant roots have a crucial role because they can fix and take up heavy metals. Our results showed that *Atriplex nummularia* accumulated high levels of Cu, Zn, and Cd in their roots and transferred only low concentrations to the shoots. Kachout et al. (2011) obtained similar results. The authors suggested an exclusion strategy for metal tolerance. In general, halophytes are considered good candidates for the reclamation of saline soils (Ruan et al. 2010) or heavy metal contaminated sites (Lutts and Lefèvre 2015). *Atriplex nummularia* may be adapted to high levels of heavy metals, which can be of special importance because of their deep rooting system that let them survive in poor and contaminated soils. Also, *Casuarina glauca* showed higher concentrations of Co and Pb in its root tissues and has been recognized as a plant species with a high capability of absorbing and accumulating heavy metals (Jin et al. 2014).

Conclusion

The results of the field experiment revealed the possibility to reuse TWW for the irrigation of forest species and show a recultivation strategy of degraded soils. Among the selected species, *Atriplex nummularia* showed the best performance under the constraints of the salinity affected soils and was able to accumulate a high concentration of mineral elements despite salinity and waterlogging. Likewise, the other plant species, except *Pinus halepensis*, were suitable to establish a vegetation cover on such critical sites in order to prevent further soil degradation. A vegetation cover will in the long-term, have a positive effect on soil salinity and waterlogging as the plants take up water and salts, which will diminish the effects of high winter precipitation and salinity. Especially with the additional TWW irrigation during summer, plants will be able to produce higher biomass raising the positive effect.

The application of TWW had some additional positive effects on soil properties. TWW decreased the pH, EC, and ion contents over time, and heavy metals tend to increase with soil depth but were lower in the topsoil.

Further studies should be conducted in this respect to test for long-term effects and the optimum application of TWW to such saline and waterlogged soil. It is important to mention, that the experimental site was high in heavy metal concentrations and results on additional contamination would be different on sites less affected by pollution.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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