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Irrigation with Treated Wastewater: Quantification of Changes in Soil Physical and Chemical Properties

Pradip Adhikari[1], Manoj K. Shukla[2]*, John G. Mexal[2] and David Daniel[3]

[1]Postdoctoral Fellow, Dept. of Soil Environment and Atmospheric Sciences, Univ. of Missouri, Columbia, Missouri, USA
[2]Dept. of Plant and Environmental Sciences, New Mexico State University, New Mexico 88003-8003, USA
[3]Dept. of Economics and International Business, New Mexico State University, Las Cruces, New Mexico 88003-8003, USA

Abstract

Land application of treated wastewater is increasing particularly in areas where water stress is a major concern. The primary objective of this study was to quantify the effect of irrigation with aerated lagoon treated wastewater on soil properties. Core and bulk soil samples were collected from areas under the canopies of mesquite and creosote and intercanopy areas from each of the three plots. Irrigation water quality from 2006 to 2008 showed that average sodium adsorption ratio (SAR), electrical conductivity (EC) and pH of irrigation water were 37.16, 5.32 dS m^{-1} and 9.7, respectively. The sprinkler uniformity coefficients of irrigated plot-I was 49.34 ± 2.23 % and irrigated plot-II was 61.57 ± 2.11 %. Within irrigated and between irrigated and un-irrigated plots, most soil physical properties remained similar except saturated hydraulic conductivity (K_s) which was significantly higher under mesquite canopies than in the intercanopy areas. Chloride (Cl^-) concentrations below 60 cm depth were higher under creosote than mesquite canopies in irrigated plots indicating deeper leaching of Cl^-. Nitrate (NO_3^-) concentrations below 20 cm depth under canopy and intercanopy areas were low indicating no leaching of NO_3^-.The average SAR to 100 cm depth under shrub canopies was 18.46 ± 2.56 in irrigated plots compared to 2.94 ± 0.79 in the un-irrigated plot. The Na^+ content of creosote was eleven times higher un-irrigated than un-irrigated plot and Na^+ content of herbaceous vegetation was three times higher in the irrigated than unirrigated. Thus irrigation with high sodium wastewater has exacerbated the soil sodicity and plant Na^+ content. Since the majority of mesquite roots are found within 100 cm, and creosote and herbaceous vegetation roots are found within 25 cm from soil surface, a further increase in sodicity may threaten the survival of woody and perennial herbaceous vegetation of the study site.

Keywords: Wastewater; Chemical properties; Herbaceous vegetation; Irrigation

Introduction

Southern New Mexico is characterized as semi-arid region where wastewater reclamation and reuse for irrigation has become important part of water resources planning. This has occurred as a result of the increasing fresh water scarcity, high nutrients in wastewater, and the high cost of advanced treatment required for other wastewater uses. United Nations Millennium Development Goal also targets the use of wastewater as irrigation to reduce the water deficit [1]. Certain quality criteria should be met prior to using wastewater for irrigation. Some of the parameters requiring close attention are electrical conductivity (EC), total dissolved solids (TDS), sodium adsorption ratio (SAR), suspended heavy metals and organic matter (OM). Without proper management, wastewater application can pose serious risks to human health and the environment [1]. Treatment of urban and industrial wastewater is complex, expensive, and requires energy and technology. The safe disposal of the treated wastewater is also a challenge because the effect of wastewater on the soil and plant environment is complex and depends upon the amount of various elements present in the wastewater. Reuse of effluent could be beneficial especially in areas where water stress is a major concern primarily due to limited water resources, higher water demands and limited economic resources. Wastewater can add nutrients to the soil system stimulating plant growth, increasing plant NO_3^- uptake, and the turnover of soil NO_3^- and denitrification. A major objective of land application systems is to allow the physical, chemical, and biological properties of the soil-plant environment to assimilate wastewater constituents without adversely affecting beneficial soil properties [2]. However, when wastewater is irrigated beyond the assimilation capacity of the soil-plant system, it can provide a source of readily leachable nutrient or contaminant [3]. Waste water can also affect soil physical properties, including bulk density (BD), drainable porosity *(d)*, soil moisture retention and hydraulic conductivity (K_s). Recent study on the same location reported lower *Ks* and macroporosity in the wastewater irrigated areas than in the unirrigated areas [4]. The levels of dissolved OM and suspended solids in effluent depend on the quality of the raw sewage water and the degree of treatment [5,6] Suspended solids present in effluents accumulate in soil voids and physically block water-conducting pores leading to a sharp decline in soil hydraulic properties [4,5]. The reduction in K_s could be due to the retention of OM during infiltration and the change of pore size distribution as a result of expansion or dispersion of soil particles. Application of wastewater with sodium (Na^+) content to soil increases sodicity, causes clay dispersion, changes pore geometry, and reduces K_s [7,8]. In contrast, [9] found no adverse impact on the hydraulic parameters while applying standard domestic effluents to soil in Israel. Soils in the arid region are generally calcareous with high pH in the upper soil horizons favoring the precipitation of most heavy metals and reduce the risk of groundwater pollution [10]. The primary goal of land application of wastewater is to maximize vegetative cover to increase the capacity of the soil to serve as a sink for wastewater contaminants, minimize salt accumulation in the root zone, and avoid NO_3^- leaching to the groundwater [11,12]. In this context application of treated wastewater on common arid and semiarid shrubs could be more

***Corresponding author:** Manoj K. Shukla, Dept. of Plant and Environmental Sciences, New Mexico State University, New Mexico 88003-8003, USA, Tel: 575-646-2324; Fax: 575-646-6041; E-mail: shuklamk@nmsu.edu

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economical and environmentally beneficial. Soil chemical properties are one of the most researched aspects of wastewater irrigation. Changes due to irrigation vary greatly and are largely dependent on the quality of the irrigation water. However, little work has been conducted on the impact of wastewater irrigation in Chihuahuan desert ecosystem on the native vegetation. An earlier study conducted on part of the West Mesa irrigated site reported that the sprinkler distribution uniformity was low (53.7%) and could have caused the variability in soil chemical and physical properties between canopies and intercanopy areas [11]. In spite of the variability of application, the previous study did not report statistical differences in chemical and physical properties between vegetation canopies and intercanopy areas likely due to low sample size. Similarly, NO_3^- and OM content of wastewater listed by the Environmental Protection Agency (EPA) as a method of recycling nutrients and OM were not addressed in that study. The present study overcomes these limitations of the earlier study and provides a detailed account of the impact of wastewater on physical and chemical properties under different vegetation canopies and intercanopy areas within the entire irrigated site. The objectives of this study were to: (1) determine the influence of lagoon treated wastewater interception by shrub canopies on physical and chemical properties of canopy soil, and (2) compare physical and chemical properties among the canopy and intercanopy areas.

Materials and Methods

Experimental site

The West Mesa industrial and municipal wastewater land application facility (West Mesa) is located near Las Cruces, NM(longitude W 106° 54.408' latitude N 32° 15.99', altitude 1298 m). This includes a wastewater treatment plant and a land application system. The untreated industrial and municipal wastewater generated from dairy processing and metal wire fabrication industries is treated in a 1,500 m^3d^{-1} capacity treatment plant, which can discharge 200 m^3d^{-1} of wastewater to the 36-ha study site. Additional details about the study locations could also found in [13,14]. Aerated lagoon effluent application on this site began on February 5, 2002 to the Chihuahuan Desert upland adjacent to the wastewater treatment plant by 1,243 fixed-head sprinklers operated by automated pumps [15]. The treated plots received variable amounts of effluent due to the temporal fluctuations in tenant-generated wastewater and the high evaporation losses from the wastewater lagoons through the peak summer months. During the late summer the application onto the treated site increased usually due to the decreased evaporation and increased tenant's wastewater discharge. From 2006 to 2008, the entire 36-ha received an average of 57.66 cm of water of which 34.68 cm came from the effluent application (Table 1). Total average non stressed ET for mesquite and creosote shrubs was 154.06 cm during 2006-08 and the ratio of total water applied to ET was about 0.37 ± 0.03. Overall, vegetation in the experimental site was water stressed because little or no wastewater was available for application during the summer months when ET demands were high. This area is dominated by woody perennials such as creosote (*Larreatridentata,* (DC) Cov.) and honey mesquite *(Prosopisglandulosa Torr. varglandulosa*) whose percent groundcover in 2002 were approximately 8.7 and 14.4%, respectively (Babcock et al. [11]). The visual observation during the spring and early summer months of 2008 revealed that approximately 80% of the irrigated area was covered with perennial vegetation including, desert daisy (*Bebbiajuncea*Benth.),snakeweed (*Gutierreiza*Lag.), pigweed (*Amaranthus*L.), spiderling (*Boerhavia*L.), sagebrush (*Artemisia* L.), and chinchweed (*Pectis*L.). Coppice dunes occur under mesquite canopies and occasionally under creosote canopies over most of the experimental site. Before the development of coppice dunes the area was level and surface horizons consisted of coarse textured materials [16] that provides better condition for infiltration and leaching of Na^+ and other soluble salts. Soil texture of the coppice dunes and the intercanopy areas varies from sand to light sandy loam with little or no gravel. Soil series identified in and around the West Mesastudy site are Onite (coarse-loamy, mixed, superactive, thermic TypicCalciargids), Pintura (Mixed, thermic Typic Torripsamments), Bucklebar (TypicHaplargid), Pajarito (Coarse-loamy, mixed, superactive, thermic TypicHaplocambids), and Bluepoint (Mixed, thermic TypicTorripsamments) [16].

Soil sampling and analysis

Three plots were identified for soil sampling: an unirrigated plot, irrigated plot-I, and irrigated plot- II. The soils in unirrigated and irrigated plot-I were classified as Blue point loamy sand whereas in irrigated-II, it was Onite-Pajarito association. Amount of wastewater received was approximately 10 % higher in the Irrigated plot-I than the Irrigated plot-II due to the head differences from the wastewater holding point. Three mesquite and three creosote shrubs were selected randomly in each plot. Shrubs within the irrigated plot-I and II were located on the periphery of the sprinkler uniformity test site. Four sampling points were selected in the center of each canopy (four cardinal directions within the canopy) and three on each intercanopy area. Intact soil cores were taken by a core sampler (19 cm length and 5.5 cm diameter) from each sampling point at 0-20 cm and 20-40 cm depths. Similarly, bulk soil samples were taken by a metal auger (3 cm diameter) from each sampling point at 0-20, 20-40, 40-60, 60-80, 80-100 and 100-150 cm depths. Thus, a total of 162 core and 486 bulk soil samples were collected from all three plots. Visual observations were made to detect the signs of stress and leaf burn caused by wastewater application. Particle size analysis (PSA) was performed by hydrometer method using air-dried sample < 2 mm [17]. Soil cores were trimmed and the BD was determined by soil core method [18]. Cores were saturated with tap water by slowly raising water level in the trough and K_s was determined by the constant head method [19]. Volumetric moisture content (θ) of each core was determined at 0, 0.003, 0.006 MPa suctions using tension table and 0.03, 0.1, 0.3, 1, 1.5 MPa using pressure plate apparatus [20].The difference in θ at 0 MPa and 0.006 MPa was calculated to estimate drainable porosity (θ_d) or soil macroporosity, the difference in θ at 0.03MPa (field capacity; FC) and 1.5 MPa (wilting point; WP) was used to estimate plant available water content (AWC). The van Genuchten (1980) model was fitted to the measured soil moisture retention [$h(\theta)$] curves to obtain the air entry value (1/α),the pore size distribution parameter(λ), and empirical

Year	Wastewater	Precipitation	Total water applied	Creosote ET	Mesquite ET	Average crop ET	Deficit
	--cm---						
2006	17.62	33.93	51.55	170.30	179.83	175.18	123.63
2007	36.79	20.45	57.24	177.66	143.63	158.53	101.29
2008	49.65	14.55	64.20	135.73	121.23	128.48	64.27
Ave.	34.68	22.97	57.66	161.23	148.23	154.06	96.39

Table 1: Amounts of wastewater, precipitation, and evapotranspiration (ET) during 2006-2008 at West Mesa land application site.

	----------TDS (mg L^{-1})-----------		---------Chloride (mg L^{-1})---------	
Year	Influent	Effluent	Influent	Effluent
2006	1866.66 ± 450.41	3160.00 ± 900.68	320.66 ± 43.07	528.00 ± 169.00
2007	810.00 ± 28.86	3455.00 ± 293.72	247.00 ± 28.61	633.25 ± 67.71
2008	982.50 ± 221.74	3607.50 ± 455.60	252.50 ± 73.86	855.00 ± 127.19
Average	1219.72 ± 223.67	34075.50 ± 550.00	273.39 ± 145.54	672.08 ± 121.30
	--------------Nitrate (mg L^{-1})----------		------------Sodium (mg L^{-1})---------	
2006	1.47 ± 0.47	13.49 ± 13.04	332.00 ± 83.57	1175.33 ± 149.69
2007	1.61 ± 0.97	1.19 ± 0.32	215.00 ± 47.61	1094.00 ± 17.87
2008	0.66 ±0.22	0.36 ± 0.10	184.75 ± 48.58	1097.75±94.63
Average	1.24 ± 0.55	5.01 ± 4.48	389.40 ± 64.76	1122.36 ± 87.39
	-----------EC (dS m^{-1})---------------		-------------------SAR------------------	
2006	2.91 ± 1.21	4.93 ± 1.40	7.55 ± 1.91	41.47 ± 4.33
2007	1.26 ± 0.04	5.39 ± 0.45	5.46 ± 1.08	36.89 ± 1.60
2008	1.54 ± 0.34	5.64 ± 0.72	4.13 ± 0.89	33.14 ± 1.52
Average	1.90 ± 0.53	5.32 ± 2.57	5.71 ± 1.29	37.16 ± 2.48

Source-City of Las Cruces, Water Quality Lab

Table 2: Influent and effluent chemical values means and standard errors from 2006-2008.

parameters (n and m) using the retention curve (RETC) program of van Genuchten et al., (1991).

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + (\alpha h)^n\right]^{-m} \ldots h < 0 \qquad (1)$$
$$= \theta_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots h \geq 0$$

Where S_e is the degree of saturation $0 \leq S_e \leq 1$, θ_s and θ_r are saturated and residual water contents. The RETC uses a non-linear least-square optimization approach to estimate the unknown model parameters and empirical constants affecting the shape of the retention curve. Chemical properties, like EC and pH were determined on 1:2 ratio of soil: water. NO_3^-concentration was measured using auto analyzer [21]. For NO_3^- concentration, 2.5 g of sieved soil sample was mixed with 25 ml of 2N sodium chloride (KCL) solution in 125 ml Erlenmeyer flask and shaken for one hour using mechanical shaker. The solution was filtered through Whatman no. 2 filter paper before analysis. The extract was used to analyze the amount of nitrate-nitrogen (NO_3^--N) through the Technicon auto analyzer [22]. The amount of NO_3^- was calculated from NO_3^--N. For Cl^- analysis, about 5 g of soil and 25 ml of DI water was mixed in a centrifuge tube, shaken for an hour in a mechanical shaker, and centrifuged for15 minutes at 2000 rpm speed. A mixture consisting of 5-ml of final soil solution, 35 ml of DI water and 2 ml of nitric acid was titrated with the 0.1 N silver nitrate by 798 MPT Titrinotitrator. Only one sample was analyzed for OM, SAR, ESP and Na^+ from unirrigated plot because no wastewater was applied to this plot and an earlier study showed no significant differences in soil chemical properties between 2002 and 2006 for the unirrigated plot. In addition, 126 composite soil samples were analyzed for pH, EC, Cl^-, NO_3^-, OM, ESP and SAR (Harris Lab, Columbus, Nebraska). Plant samples of mesquite, creosote and perennial weeds from intercanopy areas were collected from both irrigated and unirrigated plots. Each sample was washed, oven dried at 60°C, ground and analyzed for Na^+ and NO_3 (Harris Lab, Columbus, Nebraska). Chemical properties including heavy metal concentrations of wastewater influent and effluent from 2006-2008 were provided by the City of Las Cruces, Water Quality Lab. All the wastewater analysis was conducted in the Continental Analytical Service Inc., Salina Kansas, following the United States Environmental Protection Agency (USEPA) guidelines. Sprinkler uniformity tests were conducted to determine the effectiveness of sprinklers to discharge the wastewater uniformly. The sprinklers in irrigated I were installed on a trapezoidal grid rather than on a square grid. The spacing of sprinklers was 11 m by 12.7 m and 11.5 m by 14.2 m in irrigated I and 11.9 m by 12.6 m and 12.0 m by 11.4 m in the irrigated II. Uniformity of wastewater application with sprinkler irrigation system was calculated by Christiansen's coefficient (Cu) (Christiansen, 1942) using the American Society of Agricultural Engineers standard #3301 (ASAE Standards, 1993)

$$Cu = 100\left(1.00 - \sum |dv| / nX\right) \qquad (2)$$

Where *Dv* = deviations of volume of water collected in the catch funnel from the mean catch volume; *n*= number of catch funnels; *X* =mean volume collected in catch funnel.

Statistical analysis

To assess differences in soil chemical and physical properties among plots, one-way analysis of variance (ANOVA) with contrasts was performed. Similarly, ANOVA was also performed to assess differences in soil chemical and physical properties between the canopies within the plots. The SAS General Linear Model Procedure (Proc GLM) was used to assess plot, vegetation and plot x vegetation interaction due to the application of wastewater for soil physical and chemical properties at 0-20 and 20-40 cm depths. All statistical analyses were performed using SAS® software version 9.1.3 (SAS Institute Inc., 2002-2003). All statistical analyses were performed for a significance level of $P \leq 0.05$.

Results and Discussion

Wastewater quality and application

Evaporation losses at the experimental site ranged from 50 to 90% similar to the typical values reported for arid regions, which can result in 2 to 20 fold increases in soluble salt concentrations [23]. Water quality for the irrigation water was based on the SAR, total salinity, EC, and specific ion concentrations. Analysis of the wastewater showed higher amounts of TDS, Cl^-, Na^+, EC, and SAR in the effluent than influent primarily due to high rate of evaporation in the holding ponds (Table 2). Wastewater generated from meat and dairy processing industry is reported to contain elevated concentrations of Na^+, with SAR ranging between 4 and 50 [24]. The average SAR and Na^+ concentration of applied wastewater was 37.16 ± 2.48 and 1122.36 ± 87.39 mg L^{-1}, respectively. Irrigation with water having high Na^+concentrations is reported to cause an accumulation of exchangeable Na^+ on soil

Properties	-----Unirrigated----		------Irrigated-I--------		--------Irrigated-II----------	
	0-20	20-40	0-20	20-40	0-20	20-40
	--P-values--					
Sand	(>.08)[1,2,3]	(>.08)[1,2,3]	(<.05)[1*](>.08)[2,3]	(>.12)[1,2,3]	(>.07)[1,2,3]	(<.01)[1*](>.06)[2,3]
Silt	(>.55)[1,2,3]	(>.18)[1,2,3]	(>.09)[1,2,3]	(>.07)[1,2,3]	(<.05)[1,3*] (>.48)[2]	(>.10)[1,2,3]
Clay	(>.17)[1,2,3]	(>.05)[1,2,3]	(>.69)[1,2,3]	(>.41)[1,2,3]	(>.18)[1,2,3]	(>.05)[1,2,3]
BD	(<.005)[2,3*] (>.08)[1]	(>.66)[1,2,3]	(>.05)[1,2,3]	(>.06)[1,2,3]	(>.14)[1,2,3]	(>.07)[1,2,3]
Ks	(<.001)[2,3*] (<.08)[1]	(0.09)[1,2,3]	(<.001)[2*](>.09)[1,3]	(>.08)[1,2,3]	(<.005)[1,2,3*]	(>.48)[1,2,3]
AWC	(>.07)[1,2,3]	(<.005)[1*] (>.38)[2,3]	(>.61)[1,2,3]	(>.44)[1,2,3]	(>.52)[1,2,3]	(>.38)[1,2,3]
FC	(>.17)[1,2,3]	(<.05)[1*] (>.07)[2,3]	(>.21)[1,2,3]	(>.21)[1,2,3]	(>.05)[1,2,3]	(>.07)[1,2,3]
θd	(>.33)[1,2,3]	(>.27)[1,2,3]	(>.37)[1,2,3]	(>.39)[1,2,3]	(>.42)[1,2,3]	(>.25)[1,2,3]

[1]= one-way ANOVA contrast between mesquite vs. creosote, [2]= mesquite vs. intercanopy, [3]= creosote vs. intercanopy. Numbers inside the parenthesis indicate the *P*-values
* Indicates significant differences at $P < 0.05$

Table 3: One-way ANOVA contrasts between vegetation canopies and intercanopy areas for particle size, bulk density (BD), hydraulic conductivity (K_s) available water content (AWC), field capacity (FC) and drainable porosity (θd) at 0-20 and 20-40 cm depth during 2007.

Source	DF	F value	Pr>F	F Value	Pr>F
		0-20 cm		20-40 cm	
		----------------------------Sand---------------------------			
Plot	2	1.07	0.365	2.20	0.227
Vegetation	2	2.45	0.114	2.14	0.233
Plot x vegetation	4	0.16	0.956	1.35	0.288
		-------------------------------Silt----------------------------			
Plot	2	1.49	0.328	2.06	0.156
Vegetation	2	0.56	0.611	4.62	0.024
Plot x vegetation	4	0.99	0.438	0.23	0.911
		-------------------------------Clay-------------------------			
Plot	2	3.73	0.121	2.53	0.194
Vegetation	2	4.62	0.091	2.40	0.206
Plot x vegetation	4	0.86	0.503	0.63	0.647
		----------------------------------K_s--------------------------			
Plot	2	5.28	<.05*	129.43	<.0005*
Vegetation	2	29.04	<0.0001*	22.83	<.005*
Plot x vegetation	4	2.64	<.05*	0.05	0.994
		---------------------------------BD--------------------------			
Plot	2	1.97	0.253	1.47	0.331
Vegetation	2	4.65	0.090	2.07	0.155
Plot x vegetation	4	1.89	0.156	1.00	0.434
		--------------------------------AWC------------------------			
Plot	2	4.95	0.082	0.29	0.760
Vegetation	2	3.35	0.139	0.60	0.593
Plot x vegetation	4	0.76	0.564	5.34	0.005*
		--------------------------------FC--------------------------			
Plot	2	20.19	<.005*	57.03	<.001*
Vegetation	2	6.66	0.053	2.66	0.069
Plot x vegetation	4	0.78	0.555	0.27	0.894
		--------------------------------*θd* ---------------------------			
Plot	2	3.34	0.140	8.87	<.05*
Vegetation	2	1.21	0.065	7.28	0.05
Plot x vegetation	4	0.36	0.832	1.03	0.418

* Indicates significant differences at $P < 0.05$

Table 4: Values of F statistic and the probability (Pr) from analysis of variance (n=27) for sand, silt, clay, K_s, BD, available water content (AWC), field capacity (FC), and drainable porosity(θd) at 0-20 and 20-40 cm depth during 2007

colloids and affect the survival of vegetation in the long run [25]. Visual observations during field visits also indicated sign of stress e.g., leaf burn in creosote and wilting in the mesquite possibly due to the application of sodic wastewater. The EC tolerance limit for mesquite is 9.36 dS m^{-1} [26] and for creosote is 7.51 dS m^{-1} [27]. The highest measured wastewater EC form 2006 -2008 was 5.64 dS m^{-1}. Thus, with regard to EC of wastewater, there is no immediate danger for the sustainability of native shrubs in the area. However, shallow rooted annual and perennial weed mustard may be threatened due to higher SAR irrigation water (37.16 ± 2.48).

Water transport and retention parameters

There are several attributes of wastewater, such as SAR, EC and OM content that can affect the soil hydraulic properties. Soil porosity can change due to the blockage of the inter-soil spaces by suspended materials [6] and can also impact soil hydraulic conductivity [28,29]. A one -way ANOVA contrast detected significant difference for K_s and *d* between irrigated -I and unirrigated plots at 0-20 cm depth (Table 3).The plot and vegetation interactions were significant for *Ks* at both depths and plot x vegetation interaction at 0-20 cm depth (Table 4). The average K_s of canopies and intercanopy areas at 0-20 cm depth in the unirrgated plot was 15.18 ± 1.50 cm h^{-1}, irrigated plot -I was 11.16 ± 1.42cm h^{-1} and in irrigated plot-II was 12.33 ± 0.80cm h^{-1} (Table 4). The K_s was higher under mesquite canopies (18.20 ± 1.29 cm h^{-1}) followed by creosote (14.20 ± 0.78 cm h^{-1}) and intercanopy areas (4.80 ± 0.34 cm h^{-1}) in all three plots (Table 3). Higher K_s under mesquite canopies than intercanopy areas and creosote canopies were likely due to higher sand content and higher amounts of macrospores associated with coppice dunes. In addition, differences in K_s between vegetation canopies might be due to the differences in morphological structure of the vegetation and differences in the interception of wastewater by vegetation canopies. A white coating on the soil surface was observed only in the intercanopy areas, which was due to the reprecipitation of salt due to evaporation and could have caused reductions in the K_s at the intercanopy areas. The water content at FC and AWC are reported to increase due to the application of wastewater [30]. In this study, significant differences for water content at FC were detected between irrigated and unirrigated plots at both depths; some differences were observed among vegetations but were not significant (Table 4). No significant plot, vegetation or plot x vegetation interactions were detected for AWC and θd at 0-20 cm depth (Table 5) but θd was significantly different among plots and vegetation at 20-40 cm depth (Table 5). The θd was higher under the mesquite than creosote canopy and was in accord with high macroporosity of coppice dunes.

Soil moisture content variations under vegetation and intercanopy areas in different plots expressed as standard errors were generally lower at most suctions for vegetation canopies as well as for intercanopy areas in unirrigated than in irrigated-I and irrigated-II plots at 0-20 cm depth (Figure 1). The coefficient of determination (R^2) between measured and [31] model fitted $h(\theta)$ ranged from 0.96 to 0.99 (Table 6). The bubbling pressure, which is the inverse of α, was higher under vegetation canopies and intercanopy areas of unirrigated plot than both the irrigated plots. The irrigated plots have higher SAR and EC and lower bubbling pressure, which could be due to the higher osmotic potential than the unirrigated plot.

Soil nitrate and chloride concentration

Significant plot, vegetation and plot x vegetation interaction effects were obtained for NO_3^- at 0-20 and 20-40 cm depths (Table 7). One-way ANOVA contrasts also detected differences for NO_3^- between creosote canopies and intercanopy areas at 0-20 cm depth, between mesquite and creosote canopie at 60-80 and 100-150 cm in the irrigated plot-I (Table 8). NO_3^- concentration was higher under mesquite canopies in both irrigated and unirrigated plots than under creosote canopies and intercanopy areas at 0-20 cm depth (Figure 2A). Mesquite is N fixing tree and that may be the reason for higher NO_3^- under mesquite canopies because nitrate concentration of effluent water was low. It is reported that mesquite can store soil nitrogen 3 to 7 times greater beneath its canopies than in the interspaces between species [32]. Higher NO_3^- at upper depths than deeper depths indicated no leaching of NO_3^-. Significant plot, vegetation and plot x vegetation interaction effects were observed for Cl^- at 0-20 cm and only plot interaction was significant at 20-40 cm depth (Tables 7). Chloride concentration was higher under creosote canopies than mesquite and intercanopy areas in irrigated plot-I at all depths (Figure 2B; Table 8). The Cl^- concentration almost linearly increased with depth under creosote and intercanopy areas. Higher Cl^- concentration under creosote canopies than intercanopy areas and mesquite canopies could be due to the higher wastewater interception by creosote canopies. Soil Cl^- accumulation was observed between 60 and 150 cm depth under creosote and intercanopy areas (Figure 3). However, a lower level of Cl^- under mesquite might be the effect of higher K_s that resulted in the deeper leaching of Cl^- below the sampling depths. This is also supported by larger errors in the Cl^- balance (total applied-available at 0-150 cm depth) under mesquite

Vegetation	Sand (%)	Silt (%)	Clay (%)	BD (Mg m^{-3})	K_s (cm h^{-1})	AWC (cm^3 cm^{-3})	FC (cm^3 cm^{-3})	*d* (cm^3 cm^{-3})
	Unirrigated							
Mesquite	89.77 ± 0.31	3.61 ± 0.24	6.62 ± 0.37	1.52 ± 0.00	22.20 ± 2.82	1.85 ± 0.13	0.11 ± 0.00	0.14 ± 0.01
Creosote	89.69 ± 0.41	3.83 ± 0.41	6.48 ± 0.72	1.57 ± 0.01	12.35 ± 0.30	2.02 ± 0.15	0.13 ± 0.00	0.11 ± 0.14
Intercanopy	88.64 ± 1.15	4 .00 ± 0.57	7.36 ± 0.57	1.59 ± 0.03	11.00 ± 1.40	1.27 ± 0.19	0.11 ± 0.00	0.12 ± 0.00
Average	89.37 ± 0.62	3.81 ± 0.40	6.82 ± 0.55	1.56 ± 0.01	15.18 ± 1.50	1.71 ± 0.15	0.12 ± 0.00	0.12 ± 0.05
	Irrigated-I							
Mesquite	89.19 ± 0.06	4.67 ± 0.05	7.14 ± 0.13	1.54 ± 0.01	13.54 ± 1.58	2.06 ± 0.25	0.16 ± 0.01	0.12 ± 0.03
Creosote	88.94 ± 0.16	3.41± 0.22	7.62 ± 0.08	1.49± 0.00	11.65± 1.97	2.90 ± 0.19	0.21 ± 0.01	0.11 ± 0.01
Intercanopy	87.98 ± 0.57	4.2 ± 0.33	7.84 ± 0.09	1.57± 0.01	8.20 ± 0.72	2.21 ± 0.29	0.17 ± 0.01	0.10 ± 0.01
Average	88.70 ± 0.26	3.76 ± 0.20	7.53 ± 0.10	1.53 ± 0.01	11.16 ± 1.42	2.39 ± 0.24	0.18 ± 0.01	0.11 ± 0.01
	Irrigated-II							
Mesquite	89.35 ±0.66	3.67 ± 0.72	6.98 ± 0.21	1.51 ± 0.01	18.20 ± 1.29	2.08 ± 0.21	0.17 ± 0.01	0.13 ± 0.00
Creosote	88.98 ± 0.43	3.90 ± 0.36	7.12 ± 0.16	1.50 ± 0.03	14.00 ± 0.78	2.37 ± 0.14	0.20 ± 0.01	0.10 ± 0.00
Intercanopy	89.12 ± 1.33	2.83 ± 1.20	8.05 ± 0.33	1.55 ± 0.01	4.80 ± 0.34	2.07 ± 0.53	0.16 ± 0.00	0.10 ± 0.02
Average	89.15 ± 0.80	3.47 ± 0.76	7.38 ± 0.23	1.52 ± 0.01	12.33 ± 0.80	2.17 ± 0.29	0.17 ± 0.00	0.11 ± 0.02
One way ANOVA Contrast								
Irri-I vs. Uni	0.055	0.315	0.201	0.074	<0.001*	0.823	0.047*	0.029*
Irri-II vs. Uni	0.093	0.106	0.319	0.285	0.496	0.446	0.005*	0.094
Irri-I vs. Irri-II	0.085	0.523	0.057	0.603	0.459	0.62	0.39	0.29

*Indicates significant differences at $P< 0.05$

Table 5: Mean, standard errors and one-way ANOVA contrasts between plots for particle size, bulk density (BD) and hydraulic conductivity (K_s) available water content (AWC), field capacity (FC), and drainable porosity (θd) at 0-20 cm depth during 2007.

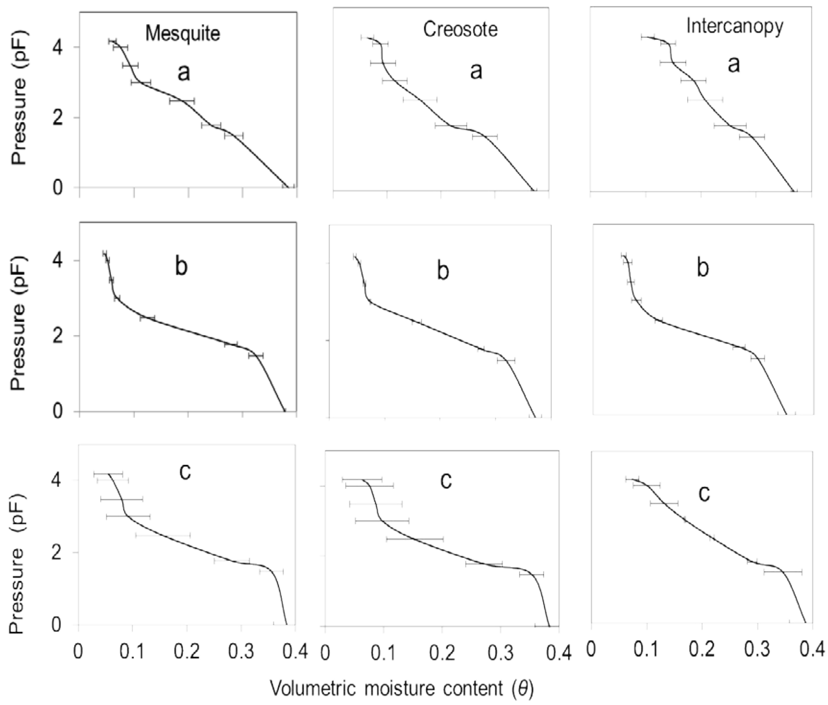

Figure 1: Soil moisture release curves of mesquite, creosote, and intercanopy areas at 0-20 cm depth by plot where pF is log of pressure in centimeters (a) irrigated plot-I (b) unirrigated (c) irrigated plot-II during 2007 [1-5].

Plots	Vegetation	θ_r	θ_s	α	η	R^2	α^{-1}cm
Irrigated-I	Mesquite	0.03 ± 0.02	0.38 ± 0.00	0.65 ± 0.15	1.35 ± 0.03	0.98	1.54
	Creosote	<0.001	0.36 ± 0.01	0.94 ± 0.47	2.10 ± 0.89	0.98	1.06
	Intercanopy	<0.001	0.35 ± 0.05	0.83 ± 0.47	1.13 ± 0.00	0.99	1.22
Unirrigated	Mesquite	0.04 ± 0.00	0.37 ± 0.00	0.17± 0.05	1.93 ± 0.13	0.99	5.88
	Creosote	0.03 ± 0.01	0.36 ± 0.00	0.17 ± 0.05	1.77 ± 0.19	0.98	5.56
	Intercanopy	0.04 ± 0.00	0.36 ± 0.00	0.18 ± 0.00	1.79 ± 0.05	0.99	5.56
Irrigated-II	Mesquite	0.05 ± 0.01	0.37 ± 0.00	0.38 ± 0.04	1.35 ± 0.04	0.98	2.63
	Creosote	0.09 ± 0.02	0.39 ± 0.00	0.44 ± 0.04	1.39 ± 0.08	0.96	2.27
	Intercanopy	0.01± 0.01	0.37 ± 0.02	0.50 ± 0.04	1.21 + 0.02	0.99	2.00

Where θ_r is residual soil moisture, θ_ss is saturation soil moisture, α and η are equation parameters, R^2 is coefficient of determination

Table 6: Mean and standard errors for the van Genuchten (1980) parameters at 0-20 cm depth in both irrigated and unirrigated plots during 2007.

canopy than creosote or intercanopy area. An earlier study conducted on the same site reported high Cl^- concentration in the upper profile (0-15cm) of intercanopy areas due to wastewater ponding that could not be supported by this study and the white precipitate observed in the intercanopy areas were primarily due to Na^+. The $NO_3^-$and Cl^- are weakly held anions and can leach to greater depths with percolating water; however, most of the applied NO_3^- was accounted for within 0-150 cm depth. This study demonstrated that Cl^- but not the NO_3^- was leached below the sampling depths of 150 cm.

Soil electrical conductivity and pH

Significant interactions in EC were obtained only among plots (Table 7). The EC was higher under creosote than mesquite canopies at 0-20 cm depth of the irrigated plot-I (Figure 2C). Higher EC under creosote canopies was also in accord with the higher wastewater interception by the canopies. The EC was similar under vegetation canopies at all sampled depths in the unirrigated plot. Similar to Cl^-, EC in irrigated-I increased by depth under both vegetation canopies and intercanopy areas.

Increased irrigation with salty water generally tended to increase soil EC with soil depth except at shallow (2.5-5 cm) depths because of the evaporation at the soil surface [33]. Similar patterns of increases in EC were observed except under mesquite canopies in irrigated plot-II. These values were lower in 2007 than those reported in 2005 [11]. This might be due to the time of the sampling, amount of wastewater application and precipitation. Samples were collected during July 2007 after some rainfall events and no application of wastewater was made during March 2007 to July 2007. Whereas in 2005 samples were collected during December and wastewater was continuously applied from September onwards with no precipitation recorded during the past three months.

Soil pH was similar (9.20 ± 0.01 to 9.80 ± 0.09) under vegetation canopies and intercanopy areas in both irrigated plots until 60 cm depth. Although plot interaction for pH was significant at 0-20 and 20-40 cm depths (Table 7), one-way ANOVA contrasts for pH did not detect differences between vegetation canopies and intercanopy areas in the irrigated plots (Table 8). Irrigation with wastewater with a pH of 9.70 ± 0.10 on soils in irrigated plots raised the soil pH to >9. Although

Source	DF	F value	Pr>F	F Value	Pr>F
		0-20 cm		20-40 cm	
		----------------------------NO_3^-----------------------------			
Plot	2	16.33	<.0001*	16.24	<0.0001*
Vegetation	2	8.12	<.005*	8.5	<.005*
Plot x vegetation	4	4.7	<.005*	4.3	<.05*
		---------------------------------Cl^-----------------------------			
Plot	2	24.45	<0.0001*	9.3	<.05*
Vegetation	2	10.67	<.0005*	2.84	0.177
Plot x vegetation	4	4.84	<.005*	2.09	0.124
		-------------------------------EC-----------------------------			
Plot	2	11.92	<.05*	13.96	<.05*
Vegetation	2	2.08	0.240	3.07	0.155
Plot x vegetation	4	2.14	0.117	1.62	0.213
		-------------------------------pH-----------------------------			
Plot	2	45.69	<0.0001*	66.82	<.005*
Vegetation	2	9.57	<.05*	1.87	0.267
Plot x vegetation	4	0.25	0.908	1.31	0.303
		-------------------------------SAR-----------------------------			
Plot	2	7.14	<.001*	3.47	0.133
Vegetation	2	1.66	0.298	0.06	0.946
Plot x vegetation	4	0.68	0.61	2.11	0.141
		--------------------------------Na^+--------------------------			
Plot	2	19.53	<.005*	18.52	<.005
Vegetation	2	1.5	0.327	1.08	0.421
Plot x vegetation	4	0.51	0.731	0.58	0.684
		--------------------------------ESP---------------------------			
Plot	2	9.48	<.005*	5.21	0.076
Vegetation	2	0.93	0.420	0.06	0.946
Plot x vegetation	4	0.64	0.645	2.01	0.157
		-------------------------------OM-----------------------------			
Plot	2	0.1	0.905	0.31	0.738
Vegetation	2	0.96	0.456	2.91	0.083
Plot x vegetation	4	3.04	0.05*	3.04	0.05

* Indicates significant differences at $P < 0.05$

Table 7: Values of F statistic and the probability (Pr) from analysis of variance (n=27) for nitrate (NO_3^-), chloride (Cl^-), electrical conductivity (EC), pH, sodium adsorption ratio (SAR), sodium (Na^+), exchangeable sodium percentage (ESP), and organic matter (OM) at 0-20 and 20-40 cm depth during 2007

Chemical properties	0-20	20-40	40-60	60-80	80-100	100-150
	----------------------Irrigated-I----------------------					
pH	(>.28)^{1,2,3}	(>.72)^{1,2,3}	(>.321)^{1,2,3}	(>.15)^{1,2,3}	(>.11)^{1,2,3}	(>.25)
EC	(<.05)^{1*} (>.08)^{2,3}	(>.72)^{1,2,3}	(>.32)^{1,2,3}	(>.15)^{1,2,3}	(>.12)^{1,2,3}	(>.12)^{1,2,3}
NO_3^-	(<.009)^{3*} (>.13)^{1,2}	(>.23)^{1,2,3}	(>.32)^{1,2,3}	(<.01)^{1*} (>.29)^{2,3}	(>.15)^{1,2,3}	(<.01)^{1*} (>.07)^{2,3}
Cl^-	(<.05)^{1,3*} (>.45)^{2}	(<.05)^{2*} (>.10)^{1,3}	(>.08)^{1,2,3}	(>.07)^{1,2,3}	(>.18)^{1,2,3}	(>.25)^{1,2,3}
SAR	(>.24)^{1,2,3}	(>.35)	(>.31)^{1,2,3}	(>.64)	(>.18)^{1,2,3}	(>.25)^{1,2,3}
Na^+	(>.37)^{1,2,3}	(>.35)^{1,2,3}	(>.40)^{1,2,3}	(>.30)^{1,2,3}	(>.12)^{1,2,3}	(>.15)^{1,2,3}
ESP	(>.26)^{1,2,3}	(>.35)^{1,2,3}	(>.37)^{1,2,3}	(>.11)^{1,2,3}	(>.25)^{1,2,3}	(>.11)^{1,2,3}
OM	(>.12)^{1,2,3}	(<.05)^{2,3*} (>.97)^{1}	(<.05)1^{2,3*} (>.45)^{1}	(<.05)^{1,2*} (>.59)^{3}	(<.04)^{1*} (>.27)^{2,3}	(>.15)^{1,2,3}
	----------------------Irrigated-II----------------------					
pH	(>.28)^{1,2,3}	(>.51)^{1,2,3}	(>.54)^{1,2,3}	(>.58)^{1,2,3}	(>.36)^{1,2,3}	(>.56)^{1,2,3}
EC	(<.05)^{1*} (>.08)^{2,3}	(>.06)^{1,2,3}	(>.08)^{1,2,3}	(>.13)^{1,2,3}	(>.15)^{1,2,3}	(>.27)^{1,2,3}
NO_3^-	(>.13)^{1,2,3}	(>.34)^{1,2,3}	(>.05)^{1,2,3}	(>.09)^{1,2,3}	(>.37)^{1,2,3}	(>.12)^{1,2,3}
Cl^-	(<.05)^{1,3*} (>.45)^{2}	(>.10)^{1,2,3}	(>.21)^{1,2,3}	(>.26)^{1,2,3}	(>.55)^{1,2,3}	(>.26)^{1,2,3}
SAR	(>.29)^{1,2,3}	(>.33)^{1,2,3}	(>.51)^{1,2,3}	(>.38)^{1,2,3}	(<.05)^{3*} (>.54)^{1,2}	(>.54)^{1,2,3}
Na^+	(<.05)^{2*} (>.09)^{1,3}	(>.05)^{1,2,3}	(>.36)^{1,2,3}	(>.31)^{1,2,3}	(>.25)^{1,2,3}	(>.42)^{1,2,3}
ESP	(>.05)^{1,2,3}	(>.33)^{1,2,3}	(>.53)^{1,2,3}	(>.38)^{1,2,3}	(<.05)^{3*} (>.26)^{1,2}	(>.55)^{1,2,3}
OM	(>.09)^{1,2,3}	(<.05)^{2,3*} (>.59)^{1}	(<.05)^{2,3*} (>.14)^{1}	(>.12)^{1,2,3}	(<.05)^{2,3*} (>.09)	(<.05)^{2} (>.06)^{1,3}

^{1}= mesquite vs. creosote, ^{2}= mesquite vs. intercanopy, ^{3}= creosote vs. intercanopy. Numbers inside the parenthesis indicated the contrast *P*-values
*Indicates significant differences at $P < 0.05$

Table 8: One way ANOVA contrast for chemical properties at different depths between vegetation canopies and intercanopy areas in irrigated-I and irrigated-II plots during 2007.

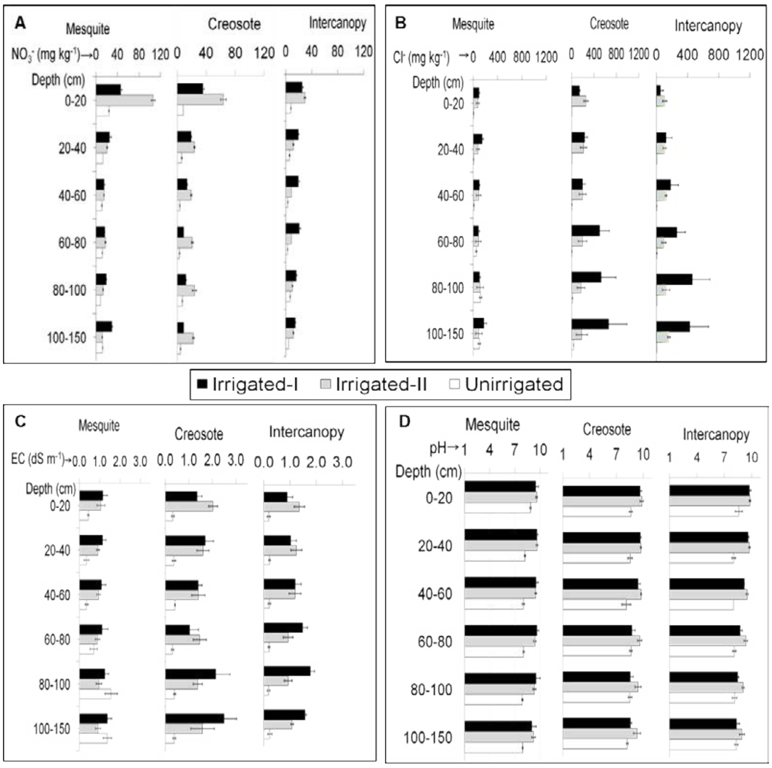

Figure 2: Concentration of (A) nitrate, NO3;(B) chloride, Cl-; (C) electrical conductivity, EC and (D) pH in three plots under the canopies of mesquite, creosote and intercanopy area during 2007 [1-5].

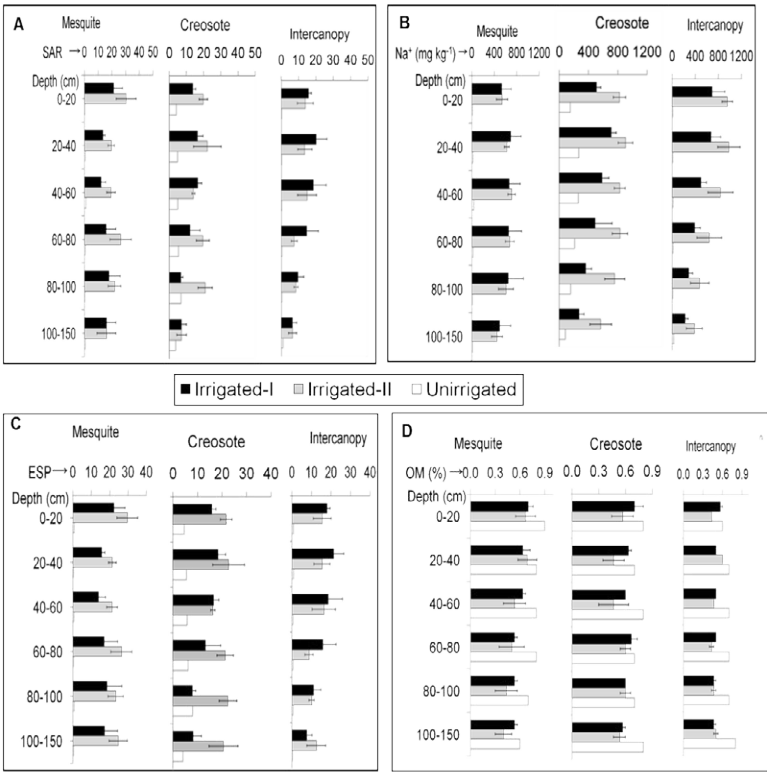

Figure 3: Concentration of (A) sodium adsorption ratio, SAR; (B) sodium, Na^+; (C) exchangeable sodium percentage, ESP; and (D) organic matter, OM, in three plots under the canopies of mesquite, creosote and intercanopy area during 2007 [1-5].

mesquite and creosote are deep rooted bushes, it is difficult to assess the exact influence of high surface pH on their survival. However, high pH can certainly have an effect on survival and growth of native perennial and herbal vegetation by reducing the availability of certain micronutrients, particularly iron (Fe) and manganese (Mn).

Sodium adsorption ratio and exchangeable sodium percentage

Application of high SAR wastewater raised soil SAR in both irrigated plots and the SAR was higher in irrigated than unirrigated plots at most depths (Figure 4A). Significant plot interactions for SAR were observed at 0-20 cm depth alone (Table 7). One way ANOVA contrasts for SAR did not detect differences between vegetation canopies and intercanopy areas among the plots (Table 8). The SAR under vegetation canopies and intercanopy areas was >15 and pH> 8.5 within 0-100 cm depth which is characterized by reduced nutrient and micronutrient availability (Brady and Weil, 2000). Mesquites are deep-rooted plants which can survive with less moisture [32]. The rooting depth is about 12 m for mesquite and 3 m for creosote. However, majority of mesquite roots are distributed within 0-100 cm depth [34] and creosote within 0-25 cm depth [35]. Therefore high SAR and Na^+ concentration would affect the survival of mesquite and creosote bushes along with other perennial vegetation. Significant plot interactions were observed for Na^+ concentration at 0-20 and 20-40 cm depths (Table 7). The Na^+ concentration was higher in the intercanopy areas at 0-20 cm depth than under vegetation canopies in both irrigated plots (Figure 3B). Higher Na^+ in upper depths in the intercanopy areas were likely due to lower K_s and θd at the intercanopy areas than under the vegetation canopies which accumulated Na^+ in the upper depths. The ESP showed a similar trend as SAR and only plot interaction was significant (Figure 3C, Table 7). Differences in ESP were also detected between creosote canopies and the intercanopy areas at 0-20 and 80-100 cm depth in the irrigated plot-II (Table 8). However, no significant plots, vegetations and plot x vegetation interactions were observed for ESP at 0-20 and 20-40 cm depth (Table 7).

Soil organic matter

Few differences were detected for OM between mesquite canopies and intercanopy areas, between creosote canopies and intercanopy areas at 20-40, 40-60, 80-100 and100-150 cm depth of the irrigated plots (Table 7). The EPA has recommended wastewater application as a method of recycling nutrients and organic matter. However, organic matter content was lower in both irrigated plots than in the unirrigated plot. Soil microorganisms and plants prefer a near neutral pH range of 6 to 7 for better performance [36]. Since the pH of irrigated plot is >9 at upper depths, it may have decreased the performance of microorganisms and the decomposition of OM in the irrigated plots. This study did not support that land application of solid organic residuals increases the OM content and soil moisture retention [3].

Vegetation analysis

The analysis of plant samples showed higher amount of Na^+ in the vegetation of irrigated than the unirrigated plots. The Na^+ content of creosote was eleven times higher in irrigated plots (880 mg.kg^{-1})than the unirrigated plot (80 mg kg^{-1}), mesquite Na^+ content was two times higher in irrigated (1600 mg kg^{-1}) than unirrigated (800 mg.kg^{-1}) and perennial vegetation Na^+ content was three times higher in irrigated (240 mg.kg^{-1}) than unirrigated (80 mg kg^{-1}). Total percentage N in irrigated mesquite was 3.5 %, unirrigated mesquite was 2.9%, irrigated creosote 2.5% and unirrigated creosote 1.9%. The N percentage in the irrigated perennial vegetation was three times higher (4.952) then in the unirrigated weeds. Thus native vegetations were taking up chemical constituents from the soil added through wastewater. The SAR under vegetation canopies and intercanopy areas was >15 and pH > 8.5 within 0-100 cm depth which is characterized by reduced nutrient and micronutrient availability (Brady and Weil, 2000). As the primary vegetation in the study areas are mesquite and creosote with rooting depths of about 12 m and 3 m, respectively. Majority of mesquite roots are distributed within 0-100 cm depth [34] and creosote within 0-25 cm depth [35]. Therefore high SAR and Na^+ concentration would affect the survival of mesquite and creosote bushes along with other perennial vegetation.

Conclusions

Chemical parameters were higher in the effluent than in the influent primarily due to evaporation in the holding pond. Low sprinkler uniformity in both irrigated plots was observed primarily due to the non uniform sprinkler distances, wind velocities and wastewater interception by vegetation canopies. Application of wastewater containing high EC, SAR, and Na^+ concentration decreased the K_s of the irrigated west mesa soil. NO_3^- did not leach to the deeper depths but Cl^- did leach below the sampling depths. High Na^+ concentration (>693 mg kg^{-1}), SAR (>15) and pH (>8.5) at 0-100 cm depth of the irrigated plots threaten the survival of woody as well as annual and perennial forbs and grass in the study areas as can be seen from high Na^+ content of vegetation of the irrigated area. Necessary steps should be taken to schedule uniform application of wastewater all around the year and measures should be taken to reduce the evaporation in the holding pond. Wastewater application in the site should also take into account the relative differences and importance of intercanopy and under the canopy soils.

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