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Comparison of Soil Chemical Properties Prior to and Five to Eleven Years after Recycled Water Irrigation

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Abstract

Increasing demand on freshwater supplies in the arid and semiarid western United States and more stringent wastewater discharge standards have made recycled water a common water source for irrigating urban green spaces. This has created the need to study the effects of recycled water irrigation on soil chemical properties. We collected and analyzed soil samples at the commencement (in 2004) and 5 and 11 yr after recycled water irrigation on two golf courses, five metropolitan parks, and one school ground. Samples were taken at depths of 0 to 20, 20 to 40, 40 to 60, 60 to 80, and 80 to 100 cm on golf courses and at depths of 0 to 20 and 20 to 40 cm at other locations. Soil samples were tested for soil pH, soil organic matter, soil salinity (soil electrical conductivity [EC]), and exchangeable sodium percentage (ESP). Average soil EC was 0.82, 0.90, and 1.04 dS m^{-1} in 2004, 2009, and 2015, respectively. Soil pH was 0.25 to 0.3 units higher in 2009 and 2015 than in 2004. The degree of soil pH increase was greater at deeper than at shallower soil depths. Compared with 2004, samples collected in 2009 and 2015 had 137 and 100% increases in ESP, respectively, suggesting that sodicity was of greater concern than salinity when recycled water was used for irrigation. On Golf Course I, gypsum application after aerification displaced sodium (Na) and reduced ESP at the surface depth (0–20 cm), but soil ESP increased significantly at deeper soil depths. More research is needed to develop techniques to address the risks of soil pH and ESP increases, especially in deep rootzones.

Core Ideas

- Recycled water has become a common water source for irrigating urban green spaces.
- Eleven years of recycled water irrigation increased soil salinity by 27% and pH by 0.32 units.
- Eleven years of recycled water irrigation increased soil sodium exchangeable percentage (ESP) by 101%.
- The degree of soil pH increase was greater at deeper than at shallower soil depths.
- Gypsum application after aerification reduced ESP at the surface depth (0–20 cm) only.

The World Resources Institute (2015) predicted that due to uneven distribution of rainfall, increasing population growth, and urbanization, at least 3.5 billion people on earth will face water insecurity by 2025. To manage finite water sources, western United States have long implemented reuse programs for municipal wastewater. California began water recycling in 1910, with annual reuse of 826 million m^3 of recycled water (California Department of Water Resources, 2013). Sixty percent of the recycled water used was for urban and agricultural irrigation (Ambroselli, 2010). In Arizona, 320 million m^3 of recycled water was reused in 2014 (Arizona Department of Water Resources 2014). Thirty-three million cubic meters of recycled water was used in southern Nevada for golf courses and green belt irrigation (Southern Nevada Water Authority, 2009).

Water reuse for irrigation in urban green spaces and landscapes is a powerful means of water conservation, water reclamation, and nutrient recycling. Due to their dense plant canopy and active root systems, turfgrass landscapes are increasingly viewed as environmentally desirable disposal sites for recycled water. Although the conservation benefits of wastewater reuse in landscape and turfgrass irrigation are clear, concerns associated with wastewater reuse may include potential salt accumulation in the soil profile and potential contamination of ground water caused by leaching of excess nutrients.

Landscape and golf course soils receiving recycled water irrigation in Tucson, AZ, were found to have higher electrical conductivity (EC) (Schuch et al., 2008). Seven urban landscape sites irrigated with recycled water over $\geq$5 yr had average soil salinity of 3.2 dS m^{-1} at the 0- to 40-cm soil depth. The EC value was 70% higher than in nearby soils irrigated with potable water (Schuch et al., 2008). After transitioning to recycled water irrigation for 1.5 to 3.7 yr, 3.97 dS m^{-1} mean EC was recorded in golf course fairways in Las Vegas, NV. Soil salinity was 27 to 32% higher than in soils irrigated with freshwater (Lockett et al., 2008). Chen et al. (2013) observed a 19.2% increase in soil salinity in urban green land irrigated with recycled water for 10 yr in Beijing, China. Turfgrass salinity stress has been reported with long-term irrigation with recycled water or other saline water (Ganjegunte et al., 2017; Lin and Qian, 2019).

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Abbreviations: AB-DTPA, ammonium bicarbonate-diethylenetriaminepentaacetic acid; EC, electrical conductivity; ESP, exchangeable sodium percentage; ICP, inductively coupled plasma; OES, optical emission spectroscopy; SAR, sodium adsorption ratio.

These published papers have documented the degree to which soil salinity increases after the use of recycled water for irrigation. However, much less data is available regarding the changes of soil sodicity as gauged by soil ESP and soil alkalinity as gauged by soil pH. Qian and Mecham (2005) reported golf courses irrigated with recycled water for 4 to 33 yr exhibited several-fold higher sodium absorption ratio (SAR) than sites irrigated with surface water. Mounzer et al. (2013) found that deficit irrigation intensified the development of salinity gradient away from drip emitters and strengthened the presence of high transient salinity and sodicity risk. The authors suggested that the combination of deficit irrigation with saline recycled could threaten the sustainability of agricultural soils.

More information is needed concerning effects of irrigation with recycled water on soil salinity, soil exchangeable sodium percentage (ESP), and soil pH. Since the magnitude of soil salinity, pH, and sodicity changes in a single year is often small and may not be readily detectable, long-term research is needed in cool, arid or semiarid regions. In this study, we (i) assess changes in soil chemical properties after 5 and 11 yr of recycled water irrigation on eight landscape facilities by collecting and analyzing soils at the start of using recycled water for irrigation, and after 5 and 11 yr of recycled water irrigation, and (ii) evaluate soil pH, EC, and ESP changes along the soil profiles at 0- to 100-cm depth on two golf courses and at 0- to 40-cm depth on five metropolitan parks and one school ground.

Materials and Methods

Site Description

Our research sites have used the same recycled water source for irrigation since 2004. Facilities included in this study were two golf courses, five metropolitan parks, and one school ground (Table 1). All study facilities are situated within 11 km of premises in metropolitan Denver, a semiarid temperate climate with average annual precipitation of 391 mm (Western Regional Climate Center, 2016). Rainfall throughout the year is concentrated in March to October. The mean 15-yr air temperature is 10.2°C. This region's population has increased by 65% during the past 25 yr (US Census Bureau, 2015). Anticipating population growth over the next 50 yr, recycled water utilization is deemed to be an effective solution to mitigate limited water resources.

All eight facilities (two golf courses, five metropolitan parks, and one school ground) were transitioned to recycled water irrigation in 2004. Prior to 2004, two parks and one golf course were irrigated by raw ditch water, and the other landscape sites were irrigated with potable water. Compared with the freshwater and potable water used prior to 2004, recycled water contained higher levels of sodium (Na), total dissolved solids, nitrate (NO_3–N), phosphorus (P), and bicarbonate, which may pose agronomic and environmental concerns (Table 2) (Qian and Harivandi, 2007). The average water quality values of recycled water, potable water, and ditch water are presented in Table 2.

In 2004, baseline soil samples were collected. All sampling sites were managed as urban turfgrass during the past 25+ yr. In 2009 and 2015, 5 and 11 yr after the initiation of recycled water for irrigation, we collected and tested soils again from these original sites.

Sampling Procedures

From July to September in 2004 (at the commencement of recycled water irrigation), 2009 (5 yr after recycled water irrigation), and 2015 (11 yr after recycled water irrigation), soil from aforementioned landscape locations were sampled. At each location, three to six sites were randomly selected for sampling (Table 1). The three to six sampling sites were considered as replications at each urban landscape facility (location). At each sample site, three cores were collected using a handheld boring tool. At parks and the school ground, samples were taken at depths of 0 to 20 and 20 to 40 cm; at golf course fairways, samples were taken at depths of 0 to 20, 20 to 40, 40 to 60, 60 to 80, and 80 to 100 cm. Three cores at each site and depth were combined. Metal rods were buried at each sampling site in 2004 as a location reference. In 2009 and 2015, soil samples were collected 30 cm away from the 2004 original sampling points.

Established turfgrass was grown where soil sampling was conducted. Kentucky bluegrass (*Poa pratensis* L.) was grown on all park and school ground sites, and perennial ryegrass (*Lolium perenne* L.) and Kentucky bluegrass mixture were grown on golf course fairways. All sites received approximately 60 to 75 cm of recycled water and were fertilized at 75 kg ha^{-1} nitrogen (N) annually. Irrigation uniformity was assessed for each soil sampling area before 2009 soil sampling using a five-by-five grid of cups (1-m spacing). All sites had a >70% irrigation distribution uniformity. The total annual precipitation (snow and rainfall) received was 37.2, 46.0, and 46.3 cm for the years of 2004, 2009, and 2015, respectively. The annual potential turfgrass evapotranspiration was about 102 to 108 cm.

At Golf Course I, gypsum at 1.5 to 2.0 Mg ha^{-1} yr^{-1} was applied to fairways after aerification events. At Golf Course II, aerification without gypsum application was practiced annually. In the parks and school playgrounds, little or no aerification was done (Table 1). Despite the nonuniformity, no clear

Table 1. Soil texture and management, number, and depth of sampling sites of landscape facilities included in the project to evaluate long-term recycled water irrigation on soil properties.

Landscape facilities included in this project	Frequency of aerification	Gypsum additions	Soil texture classification	No. of sampling sites and sampling depths
Golf Course I	1–2 times yr^{-1}	1.5–2.0 Mg ha^{-1} yr^{-1}	Loamy sand, sandy loam	4 sampling sites at 5 depths
Golf Course II	1–2 times yr^{-1}	None	Clay loam, clay loam, clay	4 sampling sites at 5 depths
School ground	None	None	Sandy loam	3 sampling sites at 2 depths
Park I	None	None	Clay loam	6 sampling sites at 2 depths
Park II	Once every 2 yr	None	Sandy clay loam, loam	3 sampling sites at 2 depths
Park III	Once every 2 yr	None	Sandy loam	3 sampling sites at 2 depths
Park IV	Once every 2–4 yr	None	Sandy loam	3 sampling sites at 2 depths
Park V	None	None	Loam	6 sampling sites at 1 depths

and significant changes in turf quality was observed among the three sampling years.

Soil Analysis

All soil samples were air dried, ground, and screened to pass through a 10-mesh (2 mm) sieve. Soil samples were tested at the Soil, Water, and Plant Testing Laboratory at Colorado State University. Each soil sample was tested for soil organic matter, EC, pH, ESP, SAR, and soil NO_3–N, P, Na, Ca, Mg, K, Zn, Fe, and Mn concentrations.

Soil pH and EC were analyzed using a saturated paste extract. Deionized water was added to ground and sieved soil and mixed uniformly until a saturated paste was obtained. The EC value was measured using an EC meter (Model 3100, YSI conductivity meter). Soil pH was measured using a pH meter (Model 2700, Oakton Benchtop pH Meter). The saturated paste extracts were transferred to autosampler tubes and analyzed for Ca, Mg, and Na concentrations by using an inductively coupled plasma optical emission spectrophotometer (ICP–OES) (Model 7300DV, PerkinElmer Optima ICP–OES system). Soil Na, Ca, and Mg concentrations in saturated paste extracts were used to determine SAR by the following equation: $SAR = Na/[(Ca + Mg)/2]^{1/2}$.

Ammonium bicarbonate-diethylenetriaminepentaacetic acid (AB-DTPA) solution was added to soil samples to analyze exchangeable Ca, Mg, K, Na, Fe, Mn, and Zn from ICP–AES (Self and Rodriguez, 1997). Phosphorus concentration was measured by colorimeter after adding AB-DTPA extract and ascorbic acid into the soil samples. The Walkley–Black test for organic matter uses potassium dichromate ($K_2Cr_2O_7$) as the oxidizer and ferrous sulfate ($FeSO_4.7H_2O$) to titrate dichromate solution. The organic matter is calculated as the difference between the total volume of dichromate injected and the titration volume after reaction. Cation exchange capacity was measured using the ammonium acetate method at a buffered pH of 7 (Self and Rodriguez, 1997). Exchangeable Na concentration was measured by ICP in soil ammonium acetate extracts. Exchangeable Na percentage was calculated as soil exchangeable Na divided by cation exchange capacity (CEC): $ESP = (Na/CEC) \times 100\%$.

Table 2. Average water quality values of recycled water, potable water, and ditch water.

Water parameter	Recycled water	Potable water	Ditch water
pH	7.2	7.5	7.9
NH_4–N (mg L^{-1})	0.25	–	–
NO_3–N (mg L^{-1})	11.8	0.1	0.4
Total P	0.15	–	0.1
Total dissolved solids (mg L^{-1})	550	187	130
Electrical conductivity (dS m^{-1})	0.86	0.23	0.20
Ca (mg L^{-1})	50	11	16
Mg (mg L^{-1})	12	1.1	5
Na (mg L^{-1})	121	21	15
Cl (mg L^{-1})	106	29	10
Bicarbonate (mg L^{-1})	92	36	57
Sulfate (mg L^{-1})	142	36	25
Boron (mg L^{-1})	0.27	0.03	0.04
K (mg L^{-1})	13	1.0	0.9
Fe (mg L^{-1})	0.22	–	–

Statistical Analysis

All data from eight facilities were pooled and were subjected to ANOVA, and significant differences in soil pH, EC, ESP, soil organic matter, and other mineral concentrations prior to, 5 and 11 yr after recycled water irrigation began were determined by using the general linear model (GLM) procedure using SAS 9.4 (SAS Institute, 2017). The LSD was set at $P \leq 0.05$ (Table 3).

Data from eight landscape facilities at each depth were also analyzed separately. At each facility, three to six sites were treated as replications. Comparisons were made for the three sampling years at each landscape facility at each depth for individual parameters, including pH, EC, ESP, concentrations using ANOVA (SAS Institute, 2017). The results are presented in Tables 4 to 6 for sites sampled to 40-cm depth, and in figures for golf course study sites where soil was sampled to 100-cm depth (Fig. 1–3).

Results and Discussion

Soil pH

Even though the average pH of recycled water leaving the recycling plant was lower than potable water and ditch water (Table 2), results from all facilities indicated that soil pH increased from 2004 to 2015 for all sites by 0.32 units (Tables 3 and 4). The observed pH increase was consistent across all study sites. Previously, Qian and Mecham (2005) and Mancino and Pepper (1992) also found that irrigation with recycled water increased soil pH compared with freshwater or potable water irrigation.

Soil pH increase under recycled water irrigation was greater at 20- to 40-cm depths than at 0- to 20-cm depth at three out of five parks (Table 4). Moreover, the degree of soil pH increase under recycled water irrigation was greater at deeper depths than at shallow soil depths at two golf courses where soils were sampled to 100 cm deep (Fig. 1). At Golf Course 1, pH did not show increase trend after the use of recycled water at the 0- to 20-cm depth. From the 20- to 100-cm soil profile, soil pH significantly

Table 3. Mean soil chemical properties from the eight landscape facilities at the initial (baseline) and 5 and 11 yr after recycled water irrigation (soils were sampled to 1 m at golf courses and 0.4 m at parks).

Soil parameter	Baseline	5 yr after	11 yr after
Cation exchange capacity ($cmol_c$ kg^{-1})	20.77	18.51	19.16
pH	7.11b†	7.43a	7.43a
Soil organic matter (%)	2.2	2.1	2.3
Electrical conductivity (dS m^{-1})	0.82b	0.90ab	1.04a
Ca ($cmol_c$ kg^{-1})	3	3.1	3.4
Mg ($cmol_c$ kg^{-1})	1.34b	0.94c	1.78a
Na ($cmol_c$ kg^{-1})	3.4b	6.66b	5.76a
K ($cmol_c$ kg^{-1})	0.58c	0.86b	1.11a
Mn (mg kg^{-1})	2.3a	1.4b	1.8b
Cu (mg kg^{-1})	4.9 a	4.4ab	3.8b
Zn (mg kg^{-1})	16.1	15.1	15.3
Fe (mg kg^{-1})	25.3	27.5	30.1
Boron (mg kg^{-1})	0.67b	0.51b	1.4a
Cl (mg kg^{-1})	27.68a	24.6a	17.6b
Exchangeable sodium percentage	2.25c	5.35a	4.51b
Sodium adsorption ratio	2.38c	5.39a	3.74b

† The mean followed by letter "a" is significantly higher than the mean followed by a letter "b" for individual parameters at $P \leq 0.05$.

increased at each depth after 5 and 11 yr of recycled water irrigation. At the deepest depth tested (80–100 cm), recycled water irrigation increased soil pH by 0.8 units. At Golf Course II, from the 0- to 60-cm soil profile, soil pH in 2009 and 2015 was greater than soil pH in 2004. At the 60- to 100-cm depth, soil pH in 2015 was greater than that in 2009, and soil pH in 2009 was greater than that in 2004, with the degree of soil pH increase over time being greater at deeper depths than at shallow soil depths. The soil pH increase may be partially due to the bicarbonate concentration (92 mg L^{-1}) in recycled water. At many of the sites, recycled water was stored in irrigation ponds. During the storage, algae activity likely had increased water pH due the absorption of CO_2.

A main implication of increasing soil pH is plant nutrient availability. The increase of soil pH can have effects on plant growth as the availability of certain nutrients in soil solution begins to decrease above pH ~6.5 (Fe, Mn, and Zn), above ~7.0 (P and B), and above 8.5 (Ca^{2+} and Mg^{2+}) (Sims and Patrick, 1978; Jensen, 2010). Results of ANOVA on soil Fe, Mn, and Zn concentrations indicated that the soil extractable Fe concentration did not change significantly after 11 yr of using recycled water (Table 3), although the recycled water contained small quantities of Fe and Zn (Table 2). Recycled water could supply the soil with Fe if soil pH was in a proper pH range. Soil extractable Mn level decreased after 5 and 11 yr of recycled water irrigation (Table 3). This finding

Table 4. Results of soil pH at depths of 0 to 20 cm (Depth 1) and 20 to 40 cm (Depth 2) for assessment over three different years (2004, 2009, and 2015) at six landscape locations in Denver.

Depth	Year	School ground	Park I	Park II	Park III	Park IV	Park V
cm							
0–20	2004	7.57b†	6.88b	6.47b	6.83c	6.66b	6.80b
	2009	7.83a	7.20a	7.00a	7.30a	7.00a	7.00a
	2015	7.93a	7.30a	6.80a	6.90b	6.80a	6.90a
20–40	2004	7.60b	7.07b	6.67b	7.10c	6.63b	N.A.‡
	2009	8.00a	7.50a	7.10a	7.60a	7.20a	N.A.
	2015	7.91a	7.50a	7.40a	7.30b	7.30a	N.A.
					P value		
Depth 1 vs. 2		0.66ns¶	0.07ns	0.002	0.0009	0.018	N.A.

† Within an individual location, each depth with different letters (a, b, or c) are significantly different at $P \leq 0.05$.

‡ N.A., not available.

¶ ns, nonsignificant.

Table 5. Results of soil electrical conductivity (EC) at depths of 0 to 20 cm (Depth 1) and 20 to 40 cm (Depth 2) for assessment over three different years (2004, 2009, and 2015) at six landscape locations in Denver.

Depth	Year	School ground	Park I	Park II	Park III	Park IV	Park V
cm				dS m^{-1}			
0–20	2004	1.20b†	0.67b	0.60b	0.83b	0.83a	0.72c
	2009	0.80b	0.90a	1.00a	1.00a	1.00a	1.00a
	2015	1.90a	1.20a	0.80ab	0.90a	0.90a	0.80b
20–40	2004	1.20b	0.60b	0.50c	0.93b	0.77a	N.A.‡
	2009	0.50b	1.00a	0.90a	1.10a	0.80a	N.A.
	2015	2.40a	1.18a	0.60b	0.60c	0.60b	N.A.
					P value		
Depth 1 vs. 2		0.83ns§	0.51ns	0.44ns	0.89ns	0.81ns	N.A.

† Within an individual location, each depth with different letters (a, b, or c) are significantly different at $P \leq 0.05$.

‡ N.A., not available.

§ ns, nonsignificant.

Table 6. Results of soil exchangeable sodium percentage (ESP) at depths of 0 to 20 cm (Depth 1) and 20 to 40 cm (Depth 2) for assessment over three different years (2004, 2009, and 2015) at six landscape locations in Denver.

Depth	Year	School ground	Park I	Park II	Park III	Park IV	Park V
cm				%			
0–20	2004	2.93c†	2.60b	3.53b	2.57b	3.13b	2.16c
	2009	3.97b	4.55a	6.40a	6.07a	6.20a	3.87b
	2015	5.73a	2.92b	2.30b	2.67b	2.60b	5.85a
20–40	2004	1.8c	2.03b	2.60b	1.73b	2.63b	N.A.‡
	2009	4.83b	5.08a	9.40a	6.83a	9.53a	N.A.
	2015	6.73a	4.18a	4.37b	4.70b	4.60b	N.A.
					P value		
Depth 1 vs. 2		0.63ns§	0.23ns	0.007	0.20ns	0.001	N.A

† Within an individual location, each depth with different letters (a, b, or c) are significantly different at $P \leq 0.05$.

‡ N.A., not available.

§ ns, nonsignificant.

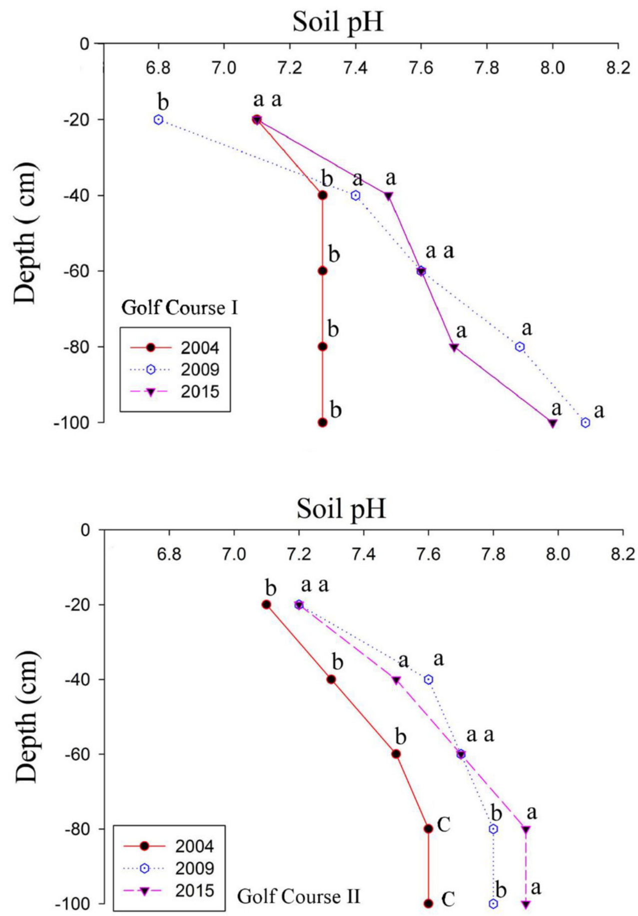

Fig. 1. Soil pH of 2004, 2009, and 2015 at Golf Courses I and II. Letters indicate significant difference ($P \leq 0.05$) among years at each depth. Each data point is the mean of four replications.

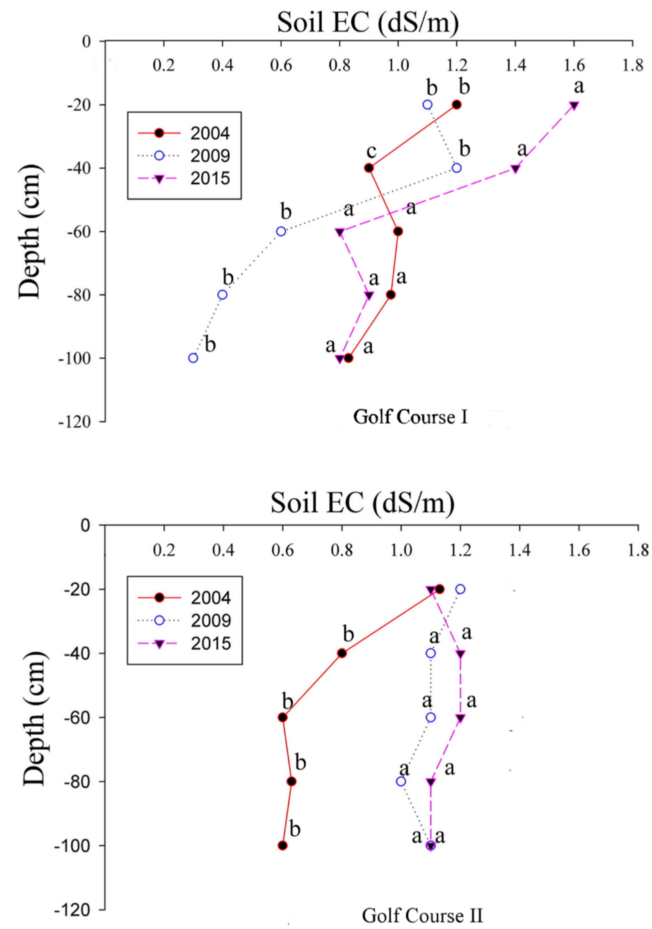

Fig. 2. Soil electrical conductivity (EC) of 2004, 2009, and 2015 at Golf Courses I and II. Letters indicate significant difference ($P \leq 0.05$) among years at each depth. Each data point is the mean of four replications.

agrees with Naidu and Rengasamy (1993), who report that soil micronutrient (Fe and Mn) availability declined in an Australian sodic soil simultaneously with increasing soil pH.

Different plants respond differently to high soil pH. Consistently high soil pH often causes Fe and/or Mn deficiencies in sensitive landscape plants, resulting in interveinal chlorosis, although the critical pH levels that result in leaf chlorosis are variable among plants.

The using of acidifying fertilizers including ammonium sulfate and other sulfur-containing products at Golf Course I successfully prevented soil pH increase under recycled water irrigation at the surface depth. However, it is often necessary to reapply these substances to sustain the effect. In addition, it is difficult to prevent soil pH from increasing deep in the soil profile. The greater increase in soil pH deep in the soil would likely have a greater impact on deep-rooted landscape plants such as shrubs and trees than on shallow-rooted plants such as grasses.

Electrical Conductivity

When data from all facilities and all depths were pooled, the average soil salinity was 0.82, 0.90, and 1.04 dS m^{-1} in 2004, 2009, and 2015, respectively (Table 3). Eleven years of recycled water irrigation increased the overall soil EC by 27%. Soil EC in 2009 was not significantly different from that in 2004 or in 2015.

All samples collected in 2009 and 2015 had soil salinity of <4 dS m^{-1}; in general, soils with EC <4.0 dS m^{-1} are considered nonsaline soils (Richards, 1954). However, soil samples (0–20 cm) from five facilities, including the school playground and Parks I, II, III, and V, showed an increased soil salinity 5 or 11 yr after recycled water irrigation (Table 5). No clear trend of increasing soil salinity under recycled water irrigation was observed from 2004 to 2015 at Park III (at the 20- to 40-cm soil depth) and Park IV (Table 5).

At Golf Course I, where soils were sampled to 100 cm deep, soil EC increased from 2004 to 2015 at the surface 0- to 20-cm and 20- to 40-cm depths. At the 60- to 100-cm depths, soil salinity level was <1.0 dS m^{-1}, with EC in 2009 being significantly lower than that in 2004 and 2015. At Golf Course II, soil salinity was not significantly different among years at the 0- to 20-cm surface depth; however, at the 20- to 100-cm depths, soil EC increased by 48 and 94% after 5 and 11 yr of recycled water irrigation (Fig. 2), indicating that the degree of soil EC increase after the use of recycled water was greater at deeper depths than at shallow soil depths at Golf Course II.

The rate at which salts accumulate in a soil profile partially depends on the amount of water applied, and the particular soil's physical and chemical characteristics. Since Golf Course I had predominantly sandy soil (Table 1), soil salinity could change greatly with irrigation management. Good permeability and drainage allow leaching of excessive salt beyond the rootzone by periodic heavy irrigations.

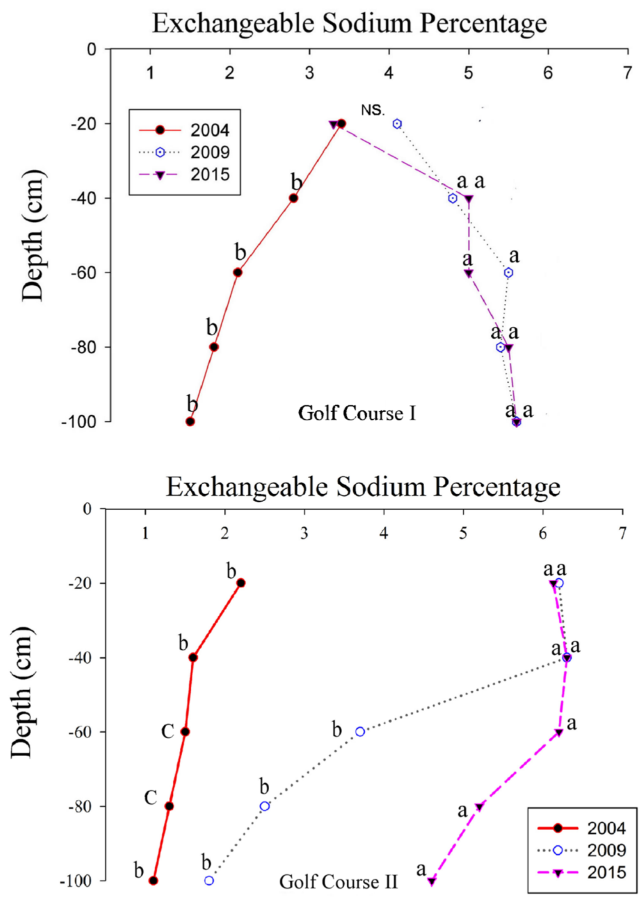

Fig. 3. Soil exchangeable sodium percentage (ESP) of 2004, 2009, and 2015 at Golf Courses I and II. Letters indicate significant difference ($P \leq 0.05$) among years at each depth; NS indicates no statistically significant difference. Each data point is the mean of four replications.

Increased soil EC with recycled water irrigation has been reported for golf course fairways (Qian and Mecham, 2005; Lockett et al., 2008; Skiles and Qian, 2013) and urban parks (Schuch et al., 2008; Chen et al., 2013). Soil EC changes along the soil profile to 40 and 100 cm below the soil surface in this study further help to elucidate the salinity dynamics and to develop salinity management strategies.

Exchangeable Sodium Percentage

Several publications have also stated that soil SAR is correlated with ESP (USDA, 1954; Qadir and Schubert, 2002; Chi et al., 2011). In our study, the SAR values in every location, year (2004, 2009, and 2015), and depth corresponded with ESP measurements, with a linear regression coefficient of 0.95 (data not shown); therefore, only soil ESP data are presented.

All samples collected in 2004, 2009, and 2015 had average ESPs of 2.25, 5.35, and 4.51%, respectively (Table 3). All facilities showed significant increases in ESP after 5 yr of irrigation with recycled water (Table 6). The school ground, Park V, and Golf Course II exhibited linear increases in ESP over time ($P < 0.05$; $R^2 = 0.90$, 0.78, and 0.90, respectively) (Table 6, Fig. 3). At Park II and IV, soil at 20 to 40 cm had higher ESP value than soil at 0 to 20 cm after 5 and 11 yr of recycled water irrigation (Table 6). The increased ESP was mainly attributed to the increased soil Na content. When all data were pooled, soils in 2009 and 2015 exhibited 96% and 69% higher AB-DTPA-extractable Na than soil sampled in 2004, respectively. The AB-DTPA-extractable Na in soils sampled in 2015 was elevated from the 2004 baseline but has decreased from the 2009 soil samples (Table 3). The high Na content reflected Na addition via irrigation with recycled water; the average Na concentration over 11 yr in the recycled water was 120 mg L^{-1} compared with 15 and 21 mg L^{-1} in ditch water and potable water, respectively (Table 2).

At Golf Course I, no increase in ESP from 2004 to 2009 and 2015 at the surface 0- to 20-cm depth was observed (Fig. 3). However, the increase in ESP became significant from 20 to 100 cm along the soil profile; at 20 to 40, 40 to 60, 60 to 80, and 80 to 100 cm below soil surface, soil ESP increased 76, 150, 160, and 205%, respectively, after 5 and 11 yr of recycled water irrigation. The degree of soil ESP increase was greater at deeper soil profile. However, soil ESP measured in 2009 and 2015 was not different. The changes along the soil profile reflect soil types, environmental conditions, and management that are conducive to Na leaching from the surface layer at this golf course. The course was built on alluvial sand deposits. Soils at this golf course are mostly sandy and drain well, and turf managers have used aggressive aeration and gypsum addition programs. They generally aerate one to two times a year for fairways and apply about 1.5 to 2.0 Mg ha^{-1} yr^{-1} gypsum after aerification. Apparently, the aggressive soil aerification and gypsum addition plus the dominant presence of sandy soil effectively prevented a significant increase in soil ESP at the shallow soil depths (0–20 cm) 11 yr since the start of recycled water irrigation; however, ESP in the 40- to 60-cm, 60- to 80-cm, and 80- to 100-cm soil profile was more than double or triple the 2004 baseline.

At Golf Course II, the soil ESP value at the surface 0- to 20-cm and 20- to 40-cm depths increased from 2.35 and 1.88 in 2004 to 6.0 and 6.1 in 2009 and 2015, representing 150 and 220% increases when recycled water was used for irrigation for 5 and 11 yr (Fig. 3). At the 40- to 100-cm depths, soil ESP exhibited a linear increase over time ($R^2 = 0.90$) (Fig. 3), with soil ESP measured in 2009 being 122% greater than that in 2004. From 2009 to 2015, soil ESP was increased further by 87%. This golf course has fine-textured soil (clay loam to clay). Although landscape managers aerated one to two times per year for fairways, no gypsum treatment to soil was done over the experiment period. The relatively high levels of Na concentration relative to Ca and Mg in recycled water along with the fine-textured soil and the lack of Ca addition resulted in increased soil ESP, especially at the shallow soil depths (Fig. 3). The ability of the soil to retain cations is much higher for fine-textured soils than for sandy soils. As a result, soil ESP at Golf Course II increased slowly at deeper depths; it took longer than 5 yr to exhibit significant ESP increase at the deepest sampling depth (80–100 cm).

Our results indicated that with no or minimal management (aggressive aerification and Ca additions) such as at the school ground, Park V, and Golf Course II, ESP increased linearly over time. With aggressive aerification and Ca addition, the ESP increase became apparent at deeper soil depths, although ESP in surface soil could be managed, such as at Golf Course I. These results suggest that sodicity (as gauged by soil ESP) is a concern on the reuse sites, since ESP was a parameter that exhibited the most significant changes from 2004 to 2009 on most study sites (Table 6, Fig. 3). However, the average soil ESP did not show further increase from 5 to 11 yr of recycled water for irrigation. Further increases of ESP could potentially cause long-term reductions in soil hydraulic conductivity, especially in soil with a higher percentage clay content.

Gypsum application helped to displace Na and reduce ESP, especially at the surface depth on Golf Course I. Gypsum application is also commonly recommended not only for landscapes irrigated with recycled water, but also for agricultural soils in Australia and the Middle East with sodic soils (Naidu and Rengasamy, 1993; Ilyas et al., 1997; Qadir et al., 2005). The treatment may be more effective in sandy soil than in clay soil. More research is needed to develop low-cost, pre-irrigation water treatment strategies and specific landscape management techniques to decrease soil ESP.

Conclusions

This study of 11 yr of recycled water irrigation on landscapes found that compared with baseline data, soil salinity (EC) increased 27%, pH increased 0.2 to 0.3 units, and ESP increased the most significantly by 101%. A relatively modest recycled water total dissolved solids ($\sim$550 mg L^{-1}) contributed to the slight but significant increase in soil EC.

The degree of soil pH change was greater at deeper soil depths. On many sites, the degree of soil ESP change was greater at deep soil depth, which provided reason for concern about possible long-term reductions in soil hydraulic conductivity in soil with high clay content, although measured ESPs were not high enough to result in short-term soil deterioration. These chemical changes along the soil profile may in part contribute to the stress symptoms and die off observed in some deep-rooted ornamental trees and, to a lesser degree, in shallow-rooted Kentucky bluegrass–perennial ryegrass turf (Qian et al., 2005; Nackley et al., 2015). Although the ESP values are not high enough to be classified as a sodic soil, urban landscapes may be more susceptible to the relatively high ESP due to the fact that urban landscapes are not subject to annual soil plowing and urban soil has a great compaction pressure from traffic. Salt leaching would become less effective when soil hydraulic conductivity was reduced at deep soil depths. Cultural practices including aerification and gypsum application can reduce soil ESP in surface soil (0–20 cm). On the other hand, the average soil ESP did not show further increase from 5 to 11 yr of recycled water for irrigation, suggesting that Na interactions in irrigated soil–plant systems are complex, with many factors influencing the ESP changes.

This study demonstrated that despite the clear benefits of recycled water irrigation in urban landscapes (such as water conservation, nutrient recycling, and pollution reduction), there are concerns relating to soil ESP increase, soil pH increase, and salinity buildup. As more landscape facilities switch to recycled water irrigation, landscape managers need to apply proactive management practices, such as applications of soil amendments that provide Ca to replace Na, periodic leaching to reduce salt accumulation, improvement of drainage, adjustment of fertilization program, and selection and use salt-tolerant turfgrass and landscape plants to mitigate the negative impact and ensure continued success in recycled water reuse for landscape irrigation.

Conflict of Interest

The authors declare no conflict of interest.

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