Soil Salinity of an Urban Park after Long-Term Irrigation with Saline Ground Water

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ABSTRACT

Chamizal National Park, located in El Paso, TX, extends over 140,000 m^2 and has been irrigated with saline water for 46 yr. In recent years, turf areas in the park have severely degraded and bare spots have developed. Root zone salinity and sodicity were suspected to be the main reasons for the turf conditions. Developing salinity management and remediation strategies to improve turf quality requires information on the distribution of salinity (EC_e) within the turf root zone. Electromagnetic induction (EMI) uses apparent electrical conductivity (EC_a) to delineate salinity distribution, and is reportedly superior to traditional wet chemistry analyses. This study was conducted to investigate the spatial distribution of soil salinity and sodicity using the EMI technique. In addition, we assessed irrigation distribution uniformity and compared findings with root zone salinity and sodicity. The EMI data correlated well with saturated paste results and indicated that root zone salinity ranged from <1 to 43 dS m^{-1}. In several parts of the park, EC_e exceeded the threshold values for bermudagrass of 15 dS m^{-1}. Root zone sodium adsorption ratio values ranged from <1 to 21 $mmol^{1/2}$ $L^{-1/2}$ and in areas where increased runoff and surface ponding were observed, values exceeded the threshold level of 12 $mmol^{1/2}$ $L^{-1/2}$. Correlation analysis between irrigation uniformity parameters and standard deviation of EC_e and SAR values revealed that more than 90% of the variability of EC and SAR in the top 30 cm of the root zone could be explained by irrigation uniformity.

Core Ideas

- Changes in soil salinity after 46 yr of irrigation.
- Using electromagnetic induction to map soil salinity and sodicity.
- Correlate soil salinity with irrigation system distribution uniformity.

Chamizal National Memorial, a major urban recreational area in El Paso, TX, was built in 1969 to commemorate the Chamizal Convention (treaty) of 1963 that ended a long-standing border dispute between the United States and Mexico. The park consists of 120,000 m^2 of grassed area and approximately 24,000 m^2 of paved area with buildings. Chamizal Memorial serves as a cultural exchange center for visitors from both countries. The park was originally established with an unknown variety of tall fescue (*Festuca arundinacea* L.) and has been irrigated with on-site ground water. The irrigation water is classified as C3-S1, namely high in salinity and low for sodium hazard (Richards, 1954), (Table 1). In the early 1980s, bare spots developed and soil testing indicated that the shrinking tall fescue stand could be attributed to increasing soil salinity. At the same time, a common type bermudagrass (*Cynodon dactylon* L.) had invaded the park and was rapidly outcompeting tall fescue (Alex Tapia, Chief of Maintenance, personal communication, 2016). At present, even the stand of bermudagrass is sparse and the park shows areas of bare soil. Consequently, El Paso's City administration has made the restoration of the vegetation in Chamizal Park as one of its top priorities.

Impaired water such as recycled wastewater or saline ground water unfit for human consumption has been used for decades to irrigate turf and landscapes to reduce the use of potable water (Leinauer and Devitt, 2013; Qian and Mecham, 2005). Several studies have investigated spatial and temporal changes in soil salinity, particularly during the first 3 to 5 yr after irrigation with saline or reused water has been initiated (Ganjegunte et al., 2013; Schiavon et al., 2014; Sevostianova et al., 2011a, 2011b; Thomas et al., 2006). Thomas et al. (2006) and Schiavon et al. (2014) reported an increase in soil salinity but only to the levels that were not detrimental to the turf stand. Sevostianova et al. (2011a, 2011b) described changes in soil salinity that followed a cyclical pattern between summer and winter but reported no overall increase in salinity after 3 yr due to the sandy nature of the soil.

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Abbreviations: CU, coefficient of uniformity; DU, distribution uniformity; EC_a, apparent electrical conductivity; EC_e, saturated paste electrical conductivity ; EMI, electromagnetic induction; ESAP, EC_e sampling assessment and prediction; SAR, sodium adsorption ratio.

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Table 1. Chemical parameters of the ground water used to irrigate Chamizal Park.

Chemical parameters†	Value
EC_{iw}, dS m^{-1}	1.07
pH	6.42
K, mmol L^{-1}	0.66
Ca, mmol L^{-1}	0.86
Mg, mmol L^{-1}	0.68
Na, mmol L^{-1}	6.46
SAR, $mmol^{1/2}$ $L^{-1/2}$	5.2
Cl, mmol L^{-1}	10.61
SO_4, mmol L^{-1}	0.50

† EC_{iw}, electrical conductivity of irrigation water; SAR, sodium adsorption ratio.

A sinusoidal type pattern for the temporal response of soil salinity over a 4 yr investigative period was also reported by Devitt et al. (2007). The authors measured peak salinity levels as high as 40 dS m^{-1} on golf course fairways irrigated for several years with reused water of approximately 2.0 dS m^{-1}. In a survey of 10 golf courses irrigated with recycled wastewater averaging 0.84 dS m^{-1} for periods ranging from 4 to 33 yr, Qian and Mecham (2005) reported average salinity levels of 4.3 dS m^{-1} on fairways with soil textures ranging from loam to clay loam. Detailed information on soil properties, irrigation water salinity and sodicity, irrigation system uniformity and irrigation amounts for these research reports are listed in Table 2. The range of values reported in these studies underscores how numerous factors, such as climate and irrigation (precipitation, leaching fraction), soil type and original soil salinity, salinity of irrigation water, and system distribution uniformity, all influence and contribute to changes in soil salinity following irrigation with saline water (Devitt et al., 2007; Ganjegunte et al., 2013; Qian and Mecham, 2005; Schiavon et al., 2014; Sevostianova et al., 2011a, 2011b; Thomas et al., 2006).

Developing appropriate salinity management and remediation strategies requires detailed information on the distribution of salinity (EC_e) within the turf root zone. Electromagnetic induction uses EC_a to delineate salinity distribution within an affected area and has advantages over traditional methods that can be labor intensive, time consuming, and expensive (Corwin et al., 2010). Accuracy of EMI is influenced by soil properties such as moisture content, clay type and content, salinity, and organic matter content (Friedman, 2005; Sudduth et al., 2005; Ganjegunte and Braun, 2011). To use the EMI technique to assess salinity, a conversion of the EMI signals (EC_a) to soil saturated paste electrical conductivity (EC_e) is required. Different approaches have been used to convert EC_a to EC_e (Rhoades et al., 1990; Lesch et al., 1995; Herrero et al., 2003; Corwin and Lesch, 2005). In recent years, the EC_e Sampling Assessment and Prediction (ESAP) model, developed by the U.S. Department of Agriculture's Salinity Laboratory, is gaining popularity and has been successfully used for delineating the spatial distributions of soil properties from EC_a survey data (Lesch, 2006; Ganjegunte and Braun, 2011; Ganjegunte et al., 2013). A strong correlation (e.g., 0.89 in Ganjegunte et al. (2013) between EC_e and sodium adsorption ratio (SAR) observed in many arid regions indicate that EMI data can also be used to determine spatial distribution of sodicity (Amezketa, 2007).

A study was conducted to determine salinity and sodicity distribution within the turfgrass root zone of Chamizal National Memorial Park after 46 yr of irrigation with saline ground water using the EMI technique. To the best of our knowledge, this is the only report available that offers information on changes in soil salinity of a turfgrass root zone after almost half a century of irrigation with saline ground water. Moreover, we investigated whether there is a correlation between the variability of soil salinity levels in the root zone and the uniformity of irrigation distribution.

MATERIALS AND METHODS

Study Site

The Chamizal National Memorial is located in El Paso, TX, along the United States–Mexico international border (31°46′3″N, 106°27′17″ W). The climate at the location is considered arid with a 30-yr average precipitation of 247 mm, almost half of which (114 mm) is received during the summer months (Arguez et al., 2010). Turney silty clay loam (fine-loamy, mixed, superactive, thermic Typic Haplocalcid) was reportedly imported from nearby locations at the time of park construction in 1969 to create artificial mounds and undulating topography (Miyamoto, 2000). This topsoil was placed on top of a well-drained naturally occurring Gila soil (coarse-loamy, mixed, superactive, calcareous, thermic Typic Torrifluvent) (USDA-NRCS, 2015). Initial soil salinity was measured at 0.8 dS m^{-1} and tall fescue was originally planted when the park was established (Miyamoto, 2000). Bermudagrass has become the dominant turfgrass in the park, having outcompeted and replaced tall fescue. Arizona ash (*Fraxinus velutina* Torr.) trees line the edges of the park and access roads inside the

Table 2. Soil properties, irrigation water salinity and sodicity, sprinkler irrigation system uniformity, and irrigation amounts from previous research.

		Irrigation water			
Reference	Soil type	Electrical conductivity	Sodium adsorption ratio	Sprinkler system uniformity	Irrigation amount (% evapotranspiration)
		dS m^{-1}	$mmol^{1/2}$ $L^{-1/2}$		
Devitt et al., 2007	USGA greens mix, sandy loam, loam	0.8– 2.2	na	0.77–0.92†	55–133
Ganjegunte et al., 2013	sandy loam	2.98	2.25	>0.8‡§	120
Qian and Mecham, 2005	sandy loam, clay loam, loam	0.84	3.1	na	na
Schiavon et al., 2014	sandy loam	2.25	5.25	>0.7‡§	50
Sevostianova et al., 2011a, 2011b	sandy loam	2.0, 3.5	6.4, 8.9	>0.7‡§	110 (a) 120 (b)
Thomas et al., 2006	silty clay	1.1	na	0.82‡	110

† Christiansen's uniformity coefficient.

‡ Low quarter distribution uniformity.

§ The study includes both subsurface drip and sprinkler system. Value applies to sprinkler system only.

park. The park is nearly level, with a 0.3% slope and elevation decreasing from 1132 m in the northeastern corner to 1129 m in the southwestern corner. However, within the turf area, there are man-made mounds composed of clay top soil. Drains are located in the southwestern part of the park. The depth to the ground water is approximately 18 m, well below the root zone.

The park is divided into 64 irrigation zones and had been irrigated since 1970 with ground water drawn from a low-lying saline aquifer at a rate of 1300 mm yr^{-1} (Alejandro Tapia, park superintendent, personal communication, 2016). Grab samples of irrigation water were collected at the time of this study and analyzed for pH, salinity, major anions, and cations using the methods described by American Public Health Association (APHA, 2005). The SAR values of water samples were determined using the empirical equation described in Essington (2003). The irrigation water was applied with 962 pop-up sprinklers from several different companies. Detailed chemical constituents of the irrigation water are listed in Table 1.

Salinity Measurements and Data Modeling

Electromagentic Induction Survey

The Geospatial EC_a survey was conducted using a model EM38 EMI meter (Geonics Limited, Mississauga, ON, Canada). The EC_a survey was conducted following the detailed protocols outlined by Corwin and Lesch (2005). Geospatial measurements were collected with the coil configuration of the EMI meter oriented in the horizontal position thereby providing an effective measurement depth of about 0.75 m. About 12,800 EC_a measurements covering the entire 12 ha of turfed area of the park along with their respective coordinates (latitude and longitude) were collected. A high precision (within 2 m) global positioning system (GPS) device (Etrex Legend, Garmin, Olathe, KS) was used to obtain coordinates for all the measurement locations. Both EC_a and GPS data were logged at a frequency of two readings per second. To achieve uniform soil moisture conditions across all irrigation sections, which are necessary to measure EC_a correctly, the park was irrigated daily with 12 mm of water for 14 d. This amount was approximately 50% higher than an average daily irrigation amount during the summer. The EMI survey was subsequently performed from East to West for 5 d after 2 wk of daily irrigation and covered the entire turf area of the park. Calibration soil samples were collected within 3 d after the EMI survey.

Calibration and Validation of Soil Samples

After the EMI survey, 20 sampling locations that encompassed the full range of EC_a values obtained in the field were selected for calibration. Sampling locations were selected using the ESAP-Response Surface Sampling Design (RSSD) to identify locations that best represented the frequency statistics of the soil sensor data while spacing out the soil sampling locations as much as possible to minimize/reduce the risk of violating the independent error assumptions of ordinary linear regression modeling (Lesch, 2006). Soil samples from five depths (0–15, 15–30, 30–45, 45–60, and 60–75 cm) were collected. However, a visual examination of the turfgrass rooting depth revealed an effective root zone of 30 cm. Therefore, soil samples collected from depths 0 to 15 and 15 to 30 cm at each of the 20 sampling sites were used for calibration. Samples were analyzed for field moisture content immediately after collection using the gravimetric method described by Topp and Ferre (2002). Soil samples were air-dried, ground, and passed through a 2-mm sieve. Soil texture of subsamples was determined using the hydrometer method (Gee and Or, 2002). Processed soil samples were analyzed for salinity (EC_e) (Rhoades, 1996); and concentrations of Na, Ca, and Mg using ion chromatography (Helmke and Sparks, 1996; Suarez, 1996). Sodium adsorption ratios of the samples were estimated from Ca, Mg, and Na concentrations (Essington, 2003). Summary statistics of EC_e and SAR data were obtained using GENSTAT (version 4.1). Multiple linear regression (MLR) calibration equations included in the ESAP-CALIBRATE module for the 0- to 15-cm, 15- to 30-cm, and 0- to 30-cm depths were used to estimate EC_e and SAR values from EMI survey EC_a data. When placed in a horizontal position on the ground, the EMI meter provides EC_a to a depth of 0.75 m. The instrument's effective depth can be altered by lifting it off the ground. Consequently, a custom developed equation needs to be applied to record EC_a based on a depth-specific conductivity because the EMI signal does not integrate soil EC_a linearly with depth. To convert the EMI readings to depth-specific soil conductivity data we used a published equation (Rhoades, 1992) that is available within the ESAP-Calibrate submodule. Our readings indicated that EC_a measurements at a depth of 0 to 0.3 m corresponded to approximately 45% of the EC_a values measured for 0.75 m. These findings supported Rhoades (1992), who reported that the top 30 cm soil depth represented 43% of the conductivity measured for 0.75 m.

Parameter values of 0- to 30-cm depth were obtained by taking average values for 0- to 15- and 15- to 30-cm depths. De-correlated EMI data (z1) and scaled location coordinates (x, y) were used as predictor variables in the regression equation. The general form of MLR model for estimating salinity or sodicity is represented by Eq. [1].

$$EC_e = b0 + b1(\mathrm{z1}) + b2(\mathrm{z1}^2) \qquad [1]$$

where $b0$ = intercept, z1 = a1[ln EC_a–mean(ln EC_a)], a1 = 1/[standard deviation (EC_a)] (Lesch, 2006).

The model for which all parameters differed significantly from zero (at $P < 0.05$) with the lowest predicted residual sum of squares (PRESS score) was selected as the best equation to calibrate EM38 signals. The residual spatial independence was examined using the Moran residual autocorrelation test (Lesch et al., 1995). Linear regression was used to model the relationship between the estimated and wet chemistry measured values for EC_e and SAR at 20 locations within the study site and to validate the model results. Model-generated EC_e and SAR values were imported into the mapping software (Surfer, ver. 13). Omni-directional variograms were computed for EC_e and SAR values corresponding to depths of 0 to 15 cm, 15 to 30 cm and 0 to 30 cm. Both EC_e and SAR experimental variograms were best fitted with a linear model with nugget effect. Thus, a linear model with nugget effect of point kriging method was used for the interpolation of EC_e and SAR data. Validity of the gridding method was determined by examining the three statistics provided in the cross-validation report generated by the surfer software: residual median absolute deviation, residual standard deviation, and Pearson and Lee's correlation between the measured and the estimated Z (Kitanidis, 1997).

Irrigation Audits

Irrigation audits to determine the irrigation system's distribution uniformity were performed following guidelines established by the Irrigation Association (Irrigation Association, 2010). Thirteen irrigated areas, each operated by a separate valve, were randomly selected. Areas ranged in dimensions from 80 by 60 m to 120 by 80 m. Catch cans were placed on center in a grid of 5 to 7 m to each side and the irrigation system was operated for 15 min. The volume of the water collected in the catch cans was subsequently used to calculate standard deviation, Lower Quarter Distribution Uniformity (DU), and Coefficient of Uniformity (CU) (Irrigation Association, 2010). Distribution Uniformity is a measure that compares the driest 25% of the area to the overall average, whereas CU is calculated using the deviation of each individual container from the average. Irrigation uniformity values were subsequently compared with the standard deviation of soil salinity values at depths of 0 to 15, 15 to 30, and 0 to 30 cm at the same area. Correlation analyses were performed using SAS (version 9.3; SAS Institute, Cary, NC). As an assessment of simple association, the corresponding coefficient of determination values (r^2) are reported.

RESULTS AND DISCUSSION

Irrigation Water Quality, Apparent Electrical Conductivity Data, and Soil Samples Analysis

Water sample analyses indicated that irrigation water although saline (C3-S1 as per Richards, 1954) was of relatively better quality (lower salinity and sodicity) than the salinity values reported for other ground waters in the area used for irrigation (Schiavon et al., 2014; Sevostianova et al., 2011a, 2011b). The Chamizal Memorial is located on the Rio Grande river flood plain and ground water is derived from freshwater zone of the Rio Grande Aquifer. The shallow depth aquifer near the Rio Grande can have better water quality than other aquifers due to recharge from surface river water (Hibbs and Boghici, 1999). However, even when water with a relatively low level of salinity is used for irrigation, soil salinity can increase under arid conditions. This is because salts accumulated during the weathering process were not leached from the root zone due to low precipitation. When irrigation is introduced, the salts present in arid soils become soluble and are redistributed within the root zone (Ganjegunte et al., 2017). Moreover, the amount of irrigation is not sufficient to overcome the high potential evapotranspiration demands resulting in accumulation of salts close to surface due to evapo-concentration (Tedeschi and Menenti, 2002; Ganjegunte and Clark, 2017). The park has been irrigated annually with 1300 mm of water and annual precipitation averages 243 mm. A combined total of 1470 mm is lower than the evaporative demand for El Paso, TX, of 1600 mm (Beard, 2002). Thus, salinity present in the root zone of the park is primarily the result of evaporative concentration of salts present in the soil. In addition, based on the application rate of 1300 mm yr^{-1}, 140,000 m^2 area of turf area, and salinity of irrigation water (1.07 dS m^{-1} or TDS of 685 mg L^{-1}) on average irrigation water has contributed about 9 Mg of salts per ha per year for 46 yr.

Mean values and range statistics for EC_a determined by the EMI, soil moisture at the time of the EMI survey, clay content, EC_e, and SAR of the calibration soil samples are presented in Table 3. Average EC_e and SAR values were 8.7 dS m^{-1} and 4.1 mmol$^{1/2}$ L$^{-1/2}$, respectively and varied widely for both parameters. Soil EC_e ranged from <1 to 45 dS m^{-1} and SAR varied from <1 to 21 mmol$^{1/2}$ L$^{-1/2}$. These values closely matched with the EC_e and SAR values modeled from the EMI signals (see discussion under Geospatial Distribution Section).

Results of simple correlation analyses for EMI and soil parameters for the upper 30-cm depth are presented in Table 4. Strong correlations between EC_a and soil parameters such as clay content, saturated paste EC_e, and SAR of the calibration samples were observed. Soil clay serves as a reservoir of cations (such as Na, Mg, and Ca) and soil moisture content positively influences the conductivity (Friedman, 2005; Jung et al., 2005). Higher clay content tends to have greater soil moisture and salt holding capacity, consequently the clay content is also positively correlated with the bulk electrical conductivity (EC_a) of the soil. Only a moderate correlation between soil moisture and EC_a was observed. While a stronger association between the two parameters was expected, the relatively weak correlation may have been due to the variability introduced by the undulating topography. Although the overall slope of the turf areas in the park is small (0.3%), manmade mounds and valleys control irrigation water infiltration into the root zone. Soil texture analyses from calibration samples indicated a slightly higher clay content in the northeastern section compared to the other parts of the park. The higher clay content of the soil may have reduced irrigation water infiltration and thereby increased runoff. A second factor that has certainly contributed to the high variability of soil moisture distribution and hence

Table 4. Correlation coefficients r ($p < 0.05$, $n = 20$) for relationships between apparent electrical conductivity (EC_a), soil salinity (saturated paste electrical conductivity, EC_e), clay content (%), moisture content (%), and soil sodicity (sodium adsorption ratio, SAR). EC_a was measured by the electromagnetic induction (EMI) technique in irrigated turf in El Paso, TX.

Parameter	EC_a	EC_e	Clay	Field moisture
EC_e	0.839			
Clay content	0.868	0.841		
Field moisture	0.567	0.692	0.562	
SAR	0.814	0.972	0.784	0.765

Table 3. Mean and range statistics of electromagnetic induction meter signal and select soil properties in irrigated turf in El Paso, TX.

Parameter†	*n*	Minimum	Maximum	Mean	SD	Coefficient of variation
						%
EC_a, mS m^{-1}	12,808	0.13	386.13	95.79	95.09	99
EC_e, dS m^{-1}	20	0.78	45.18	8.70	11.06	127
SAR, mmol$^{1/2}$ L$^{-1/2}$	20	0.35	20.81	4.11	4.61	112
Clay, %	20	5.00	40.00	15.50	8.09	52
Field moisture, %	20	2.20	20.53	7.36	4.22	57

† EC_a, apparent electrical conductivity; EC_e, saturated paste electrical conductivity; SAR, sodium adsorption ratio.

moderate correlation with EC_a is the poor distribution of the irrigation water. The poor performance of the irrigation system is most likely due to a lack of maintenance of the system. The system is as old as the park itself and has not received any major renovation since its installation nearly 50 yr ago (Alex Tapia, Chief of Maintenance, personal communication, 2016). Nonetheless, the significant positive correlation between EC_a and soil properties indicated that an electromagnetic induction survey is an effective technique to capture the geospatial variability in the soil properties.

Our findings of a strong correlation between EC_e and SAR in soils of arid regions have also been reported by several other authors (Corwin et al., 2003; Amezketa, 2007; Ganjegunte et al., 2014). In areas where salts in the soil are accumulated due to evapo-concentration, EC_e and SAR were strongly correlated because of the selective precipitation of Ca minerals in the concentrated soil solution, especially if there are considerable amounts of carbonates. The study site soil contained up to 10% $CaCO_3$ by weight. The strong positive correlation observed between saturated paste EC_e and SAR further suggests that the EMI method can be used to accurately estimate both salinity and sodicity.

Model Calibration and Geospatial Distribution of Saturated Paste Electrical Conductivity and Sodium Adsorption Ratio in the Root Zone

To choose the best equation for calibrating the EM38, the model with all parameters significantly differed from zero (at $P < 0.05$) and with the smallest sum of squares of prediction errors (PRESS score, i.e., predicted residual sum of squares) were selected. Calibration Eq. [2] and [3] that met the above criteria were developed and used to estimate EC_e and SAR from EC_a at 0 to 30 cm.

$$EC_e = 0.482 + 2.294\, b1 + 4.816\, b2 \qquad [2]$$

where $R^2 = 0.919$, root mean square error (RMSE) = 3.299, and PRESS Score = 428.136.

$$SAR = 0.482 + 2.294\, b1 + 4.816\, b2 \qquad [3]$$

where $R^2 = 0.881$, RMSE = 1.670, and Press Score = 89.445.

The ESAP model, developed by the U.S. Department of Agriculture's Salinity Laboratory, provides separate MLR for each of the five depths (0–15 cm, 15–30, 30–45, 45–60 and 60–75 cm). However, the effective root zone was only 30 cm therefore the MLR model for 0 to 30 cm was used to evaluate salinity and sodicity distribution. The model R^2 for both EC_e and SAR was statistically significant. Moran spatial auto correlations were nonsignificant, indicating that the residuals of the regression models were normally distributed with a homogenous variance. Regression between MLR estimated EC_e and SAR values and those determined by wet chemistry methods for samples at 20 calibration locations was significant. Point kriging (an advanced geostatistical interpolation procedure that generates an estimated surface from a scattered set of points with z values such as EC_e or SAR) using a linear model with nugget effect (refers to the nonzero intercept of the variogram and is an overall estimate of error caused by measurement inaccuracy and environmental variability) fitted the experimental variograms well for both EC_e and SAR at the 0- to 30-cm depth. Thus, point kriging using a linear model with nugget effects was applied to prepare maps of the spatial distribution of soil salinity (EC_e) and sodicity (SAR). Since a depth of 0 to 30 cm encompasses the effective root zone of turfgrass, only the EC_e and SAR maps for depths of 0 to 30 cm are presented (Fig. 1 and 2) (Ganjegunte et al., 2013).

The EC_e distribution map (Fig. 1) showed salinity levels ranging from <1 to 43 dS m^{-1}, with levels of 10 dS m^{-1} or greater for the majority of the park (>80% of the area), which exceeded the tolerance limits for cool-season tall fescue. Although Friell et al. (2013) showed that tall fescue can tolerate salinity levels of up to 24 dS m^{-1} for 2 wk in solution culture, Marcum (1999) reported a general threshold of 7 dS m^{-1} for tall fescue at which a 50% decrease of growth can be observed. Soil salinity at the Chamizal Park is no longer conducive to a high quality stand of tall fescue. Warm-season bermudagrass is generally considered more salt tolerant and has a reported short-term salinity tolerance of up to 40 dS m^{-1} (Marcum and Pessarakli, 2006) when tested hydroponically.

Within the park, soil salinity increased from Southwest to the Northeast (Fig. 1). Estimation of visual coverage indicated that sparsely covered or bare soil areas in the northern and western parts of the park matched the areas with the highest salinity levels of 15 dS m^{-1} or higher. These observations support findings of Shaba (2010) and Marcum and Pessarakli (2006), who reported a threshold level of 15 dS m^{-1} at which bermudagrass drops below a rating of 6 for visual quality (Shahba, 2010) or reduces growth by 50% (Marcum and Pessarakli, 2006). Our observations also support findings of Xiang et al. (2017) who documented a drop in live green cover for several bermudagrasses from greater than 80% at $EC \le 15$ dS m^{-1} to less than 50% at $EC \ge 15$ dS m^{-1}.

Sodicity levels ranged from 2 to 21 $mmol^{1/2}\,L^{-1/2}$, with many parts of the park recording SAR values that exceeded the threshold level of 12 $mmol^{1/2}\,L^{-1/2}$ (Carrow and Duncan, 2012) to cause impaired permeability. We hypothesize that in the northeastern area increased runoff as a result of higher clay content and lower permeability due to higher SAR prevented the leaching of salts. Since salinity in the soil solution was due predominantly to Na salts (owing to selective precipitation of Ca minerals) the northeastern areas exhibited the highest SAR values (Fig. 2).

Large coefficients of variation for the EMI signals and hence the great variability for soil salinity and sodicity are consistent with results of other studies (Kaffka et al., 2005; He et al., 2015). The spatial distribution of soil salinity is influenced by many factors such as underlying soil heterogeneity, micro-topography, vegetation, directional effect of an environmental gradient, and irrigation system uniformity (Gallardo, 2003; Devitt et al., 2007). Irrigation audits conducted separately on 13 zones immediately after the EMI measurements, revealed DU ranging from 0.35 to 0.66, CU from 0.37 to 0.77, and standard deviations ranging from 4.2 to 20.6. These uniformity values are significantly correlated with salinity and sodicity levels from 0- to 30-cm depths (Table 5). Using CU to model salinity and sodicity distribution in the upper 30 cm of the root zone, more than 90% of the variability of EC and SAR can be explained by irrigation uniformity (Table 5). Uneven turfgrass cover within the park is highly influenced by soil edaphic factors (mainly clay content, which influences soil salinity, permeability and moisture content) and can be explained by the spatial distribution of soil salinity and sodicity.

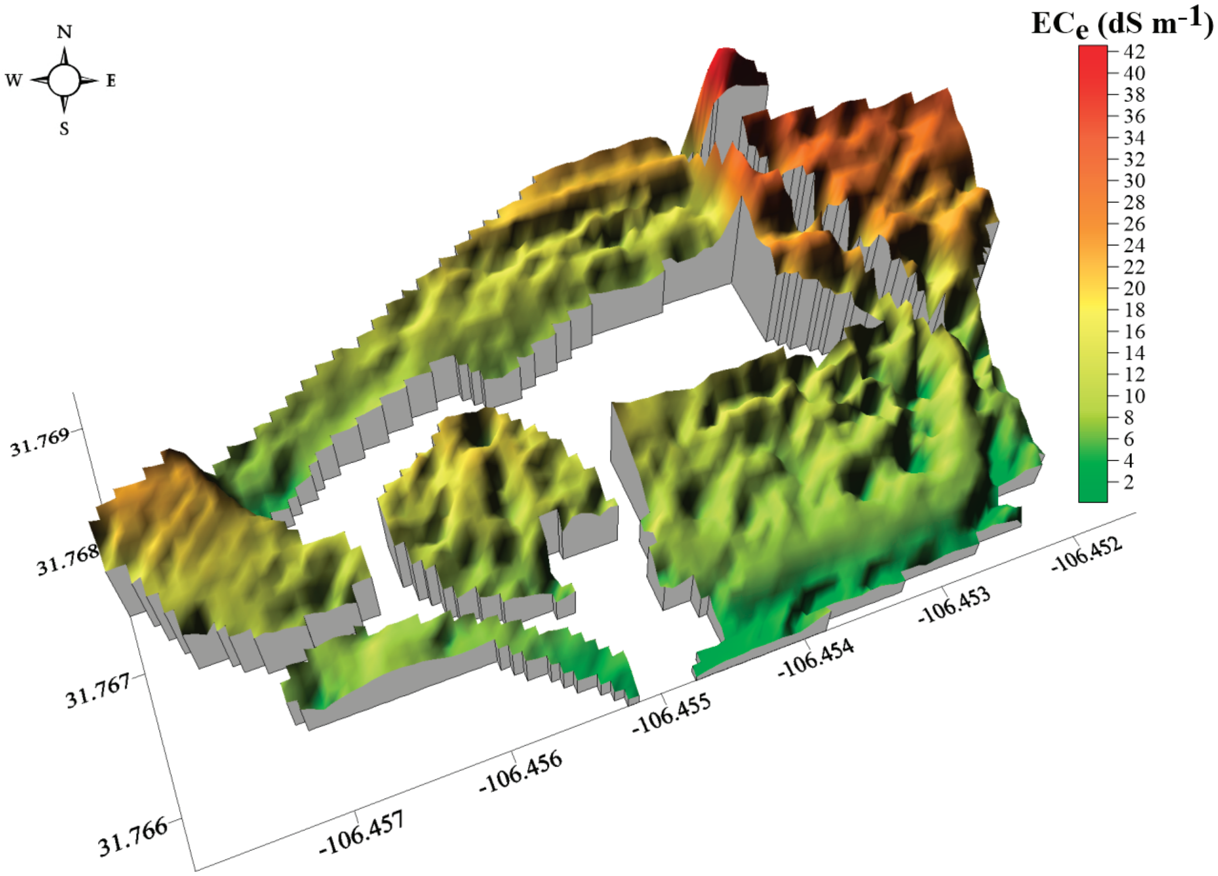

Fig. 1. Spatial distribution soil salinity (saturated paste electrical conductivity, EC_e) in the 0- to 30-cm depth estimated based on apparent electrical conductivity (EC_a) measured by the electromagnetic induction technique in irrigated turf in El Paso, TX.

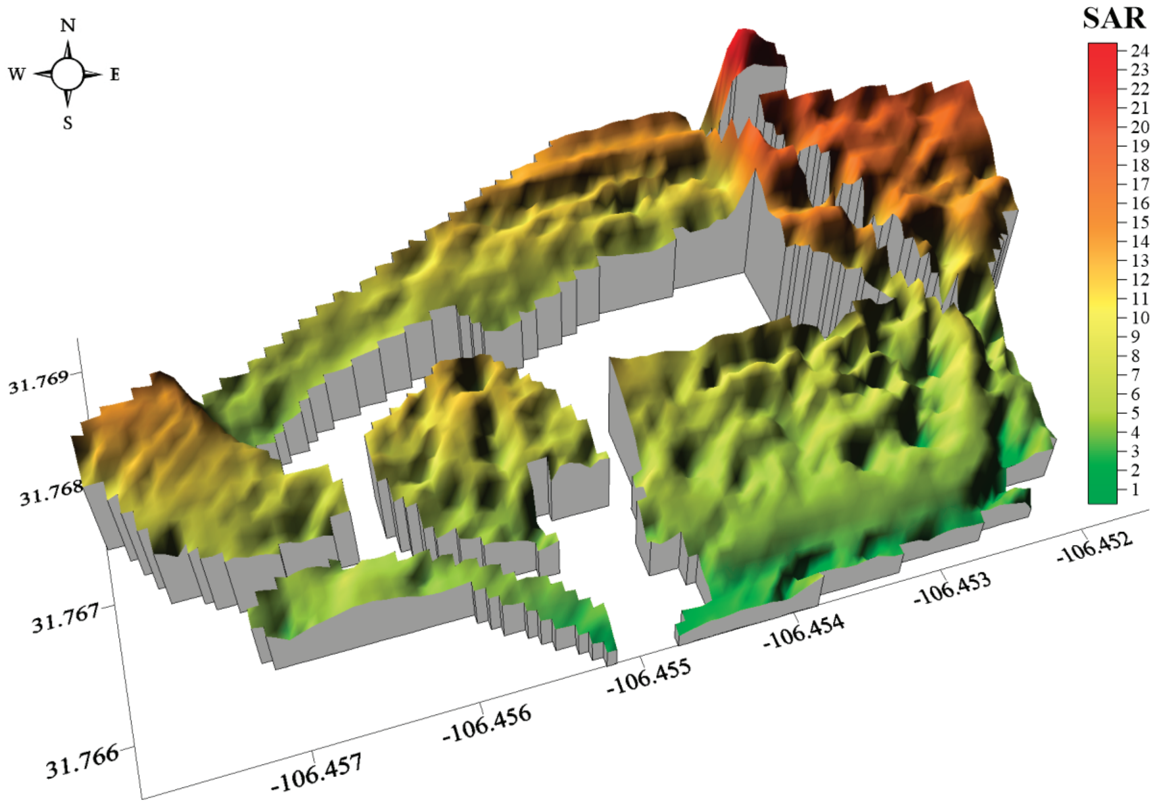

Fig. 2. Spatial distribution soil sodicity (SAR) in the 0- to 30-cm depth estimated based on apparent electrical conductivity (EC_a) measured by the electromagnetic induction (EMI) technique in irrigated turf in El Paso, TX.

Table 5. Correlation coefficients r ($p < 0.05$, $n = 13$) for relationships between irrigation system uniformity parameters (low quarter distribution uniformity [DU], coefficient of uniformity [CU], standard deviation of measured volumes in catch cans [SD]) and soil salinity in depths of 0 to 15 cm (EC 15), 15 to 30 cm (EC 30) and averaged over 0 to 30 cm (EC_e), and soil sodicity in depths of 0 to 15 cm (SAR 15), 15 to 30 cm (SAR 30) and averaged over 0 to 30 cm (SAR). Parameters were determined on irrigated turf in El Paso, TX.

Uniformity parameters	EC 15	EC 30	ECe	SAR 15	SAR 30	SAR
DU	–0.62	–0.61	–0.87	–0.88	–0.89	–0.86
CU	–0.84	–0.84	–0.96	–0.98	–0.98	–0.96
SD	0.68	0.68	0.84	0.91	0.90	0.84

CONCLUSIONS

A majority of the turf areas in the Chamizal National Park had root zone salinity levels that exceed the tolerance of the original established tall fescue. Some areas have even exceeded tolerance levels of the now dominant bermudagrass. Sodicity and salinity in the root zone are strongly correlated and indicated a strong influence of evaporation on salt build-up in the root zone. Thus salinity and sodicity hazards in the Chamizal National Park could primarily be attributed to evapo-concentration of salts in the effective root zone (30 cm) and to a lack of drainage. Uneven distribution of irrigation water combined with undulating topography, and a variability in clay content may have caused the uneven distribution of salinity and related sodicity. Sodicity levels in the turf area far exceeded a documented threshold level of 12 $\text{mmol}^{1/2}\ \text{L}^{-1/2}$ and potentially created impaired soil permeability that resulted in increased run-off and surface ponding of irrigation water. Results of this study indicated that the EMI technique provides rapid and accurate information on geospatial distribution of salinity and sodicity within the affected areas of the park. Our results further highlight the importance of a uniform irrigation system to prevent salinity and sodicity build-up in the root zone and to maintain high quality turf even when saline water is used for irrigation.

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