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

Girisha K. Ganjegunte, John A. Clark, Rossana Sallenave, Elena Sevostianova, Matteo Serena, Guillermo Alvarez, and Bernhard Leinauer*

ABSTRACT
Chamizal National Park, located in El Paso, TX, extends over 140,000 m² 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 (ECₑ) within the turf root zone. Electromagnetic induction (EMI) uses apparent electrical conductivity (ECₐ) 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, ECₑ exceeded the threshold values for bermudagrass of 15 dS m⁻¹. Root zone sodium adsorption ratio values ranged from <1 to 21 mmol1/2 L⁻1/2 and in areas where increased runoff and surface ponding were observed, values exceeded the threshold level of 12 mmol1/2 L⁻1/2. Correlation analysis between irrigation uniformity parameters and standard deviation of ECₑ and SAR values revealed that more than 90% of the variability of ECₑ 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.

Abbreviations:
CU, coefficient of uniformity; DU, distribution uniformity; ECₑ, apparent electrical conductivity; ECₛ, saturated paste electrical conductivity; EMI, electromagnetic induction; ESAF, ECₑ 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.

<table>
<thead>
<tr>
<th>Chemical parameters†</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECi, dS m⁻¹</td>
<td>1.07</td>
</tr>
<tr>
<td>pH</td>
<td>6.42</td>
</tr>
<tr>
<td>K, mmol L⁻¹</td>
<td>0.66</td>
</tr>
<tr>
<td>Ca, mmol L⁻¹</td>
<td>0.86</td>
</tr>
<tr>
<td>Mg, mmol L⁻¹</td>
<td>0.68</td>
</tr>
<tr>
<td>Na, mmol L⁻¹</td>
<td>6.46</td>
</tr>
<tr>
<td>SAR, mmol1/2 L⁻1/2</td>
<td>5.2</td>
</tr>
<tr>
<td>Cl, mmol L⁻¹</td>
<td>10.61</td>
</tr>
<tr>
<td>SO₄, mmol L⁻¹</td>
<td>0.50</td>
</tr>
</tbody>
</table>

† ECi, 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 (ECe) within the turf root zone. Electromagnetic induction uses ECe 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; Sudduh et al., 2005; Ganjegunte and Braun, 2011). To use the EMI technique to assess salinity, a conversion of the EMI signals (ECa) to soil saturated paste electrical conductivity (ECe) is required. Different approaches have been used to convert ECa to ECe (Rhoades et al., 1990; Lesch et al., 1995; Herrero et al., 2003; Corwin and Lesch, 2005). In recent years, the ECe 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 ECe 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 ECe and sodium adsorption ratio (SAR) observed in many arid regions indicates 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°46’59”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 silky clay loam (fine-loamy, mixed, superactive, thermic Typic Hapludalf) 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.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Soil type</th>
<th>Electrical conductivity</th>
<th>Sodium adsorption ratio</th>
<th>Sprinkler system uniformity</th>
<th>Irrigation amount (% evapotranspiration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Devitt et al., 2007</td>
<td>USGA greens mix, sandy loam, loam</td>
<td>0.8–2.2</td>
<td>na</td>
<td>0.77–0.92†</td>
<td>55–133</td>
</tr>
<tr>
<td>Ganjegunte et al., 2013</td>
<td>sandy loam</td>
<td>2.98</td>
<td>2.25</td>
<td>&gt;0.81‡§</td>
<td>120</td>
</tr>
<tr>
<td>Qian and Mecham, 2005</td>
<td>sandy loam, clay loam, loam</td>
<td>0.84</td>
<td>3.1</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Schiavon et al., 2014</td>
<td>sandy loam</td>
<td>2.25</td>
<td>5.25</td>
<td>&gt;0.74‡§</td>
<td>50</td>
</tr>
<tr>
<td>Sevostianova et al., 2011a, 2011b</td>
<td>sandy loam</td>
<td>2.0, 3.5</td>
<td>6.4, 8.9</td>
<td>&gt;0.74‡§</td>
<td>110 (a) 120 (b)</td>
</tr>
<tr>
<td>Thomas et al., 2006</td>
<td>silty clay</td>
<td>1.1</td>
<td>na</td>
<td>0.82‡§</td>
<td>110</td>
</tr>
</tbody>
</table>

† Christensen’s uniformity coefficient.
‡ Low quarter distribution uniformity.
§ The study includes both subsurface drip and sprinkler system. Value applies to sprinkler system only.
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 has been irrigated since 1970 with ground water drawn from a low-lying saline aquifer at a rate of 1300 mm yr

Electromagnetic Induction Survey

The Geospatial ECₐ survey was conducted using a model EM38 EMI meter (Geonics Limited, Mississauga, ON, Canada). The ECₐ 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 measure of the top 30 cm soil depth. About 12,800 ECₐ measurements were collected with the coil configuration of the EMI meter oriented 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 measure of the top 30 cm soil depth. Approximate 75% of the ECₐ values measured for the top 30 cm soil depth represented 43% of the conductivity 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.

Salinity Measurements and Data Modeling

Calibration and Validation of Soil Samples

After the EMI survey, 20 sampling locations that encompassed the full range of ECₐ values obtained in the field were selected for calibration. Sampling locations were selected using the ESAP-CALIBRATE module for the 0- to 15-cm, 15- to 30-cm, and 0- to 30-cm depths were used to estimate ECₑ and SAR values from EMI survey ECₐ data. When placed in a horizontal position on the ground, the EMI meter provides ECₑ 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 ECₑ based on a depth-specific conductivity because the EMI signal does not integrate soil ECₑ 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 ECₑ measurements at a depth of 0 to 0.3 m corresponded to approximately 45% of the ECₑ 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 for 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].

\[
EC_e = b_0 + b_1(z_1) + b_2(z_1^2)
\]

where \(b_0\) = intercept, \(z_1 = \frac{1}{a_1}[\ln EC_e - \text{mean}(\ln EC_e)], a_1 = 1/\text{standard deviation } [EC_e]\) (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 ECₑ and SAR at 20 locations within the study site and to validate the model results. Model-generated ECₑ and SAR values were imported into the mapping software (Surfer, ver. 13). Omni-directional variograms were computed for ECₑ and SAR values corresponding to depths of 0 to 15 cm, 15 to 30 cm and 0 to 30 cm. Both ECₑ 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 ECₑ 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., 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 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 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$_{sp}$ and SAR of the calibration soil samples are presented in Table 3. Average EC$_a$ and SAR values were 8.7 dS m$^{-1}$ and 4.1 mmol/L$^{1/2}$, respectively and varied widely for both parameters. Soil EC$_a$ ranged from <1 to 45 dS m$^{-1}$ and SAR varied from <1 to 21 mmol/L$^{1/2}$. These values closely matched with the EC$_a$ 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$_{sp}$, 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$_b$) 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 a higher salt adsorption capacity.

<table>
<thead>
<tr>
<th>Parameter†</th>
<th>EC$_a$</th>
<th>EC$_{sp}$</th>
<th>Clay</th>
<th>Field moisture</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC$_a$, mS m$^{-1}$</td>
<td>12,808</td>
<td>0.13</td>
<td>386.13</td>
<td>95.79</td>
<td>95.09</td>
</tr>
<tr>
<td>EC$_{sp}$, dS m$^{-1}$</td>
<td>20</td>
<td>0.78</td>
<td>45.18</td>
<td>8.70</td>
<td>11.06</td>
</tr>
<tr>
<td>SAR, mmol/L$^{1/2}$</td>
<td>20</td>
<td>0.35</td>
<td>20.81</td>
<td>4.11</td>
<td>4.61</td>
</tr>
<tr>
<td>Clay, %</td>
<td>20</td>
<td>0.00</td>
<td>40.00</td>
<td>15.50</td>
<td>8.09</td>
</tr>
<tr>
<td>Field moisture, %</td>
<td>20</td>
<td>2.20</td>
<td>20.53</td>
<td>7.36</td>
<td>4.22</td>
</tr>
</tbody>
</table>

† EC$_a$, apparent electrical conductivity; EC$_{sp}$, saturated paste electrical conductivity; SAR, sodium adsorption ratio.

Table 3. Mean and range statistics of electromagnetic induction meter signal and select soil properties in irrigated turf in El Paso, TX.
moderate correlation with ECa 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 ECa 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 ECe 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, ECe 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% CaCO3 by weight. The strong positive correlation observed between saturated paste ECe 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 Sodicity 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 ECe and SAR from ECa from 0 to 30 cm.

\[
EC_e = 0.482 + 2.294b_1 + 4.816b_2
\]

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

\[
SAR = 0.482 + 2.294b_1 + 4.816b_2
\]

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 ECe 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 ECe 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 a non-zero 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 ECe 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 (ECe) and sodicity (SAR). Since a depth of 0 to 30 cm encompasses the effective root zone of turfgrass, only the ECe and SAR maps for depths of 0 to 30 cm are presented (Fig. 1 and 2) (Ganjegunte et al., 2013).

The ECe 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 (Shaba, 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 ≤ 15 dS m⁻¹ to less than 50% at EC ≥ 15 dS m⁻¹.

Sodicity levels ranged from 2 to 21 mmol L⁻¹/₂, with many parts of the park recording SAR values that exceeded the threshold level of 12 mmol 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, ECₜ) in the 0- to 30-cm depth estimated based on apparent electrical conductivity (ECₐ) 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 (ECₐ) 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 (EC15), 15 to 30 cm (EC30) and averaged over 0 to 30 cm (ECe), and soil sodicity in depths of 0 to 15 cm (SAR15), 15 to 30 cm (SAR30) and averaged over 0 to 30 cm (SAR). Parameters were determined on irrigated turf in El Paso, TX.

<table>
<thead>
<tr>
<th>Uniformity parameters</th>
<th>EC15</th>
<th>EC30</th>
<th>ECe</th>
<th>SAR15</th>
<th>SAR30</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>DU</td>
<td>-0.62</td>
<td>-0.61</td>
<td>-0.87</td>
<td>-0.88</td>
<td>-0.89</td>
<td>-0.86</td>
</tr>
<tr>
<td>CU</td>
<td>-0.84</td>
<td>-0.84</td>
<td>-0.96</td>
<td>-0.98</td>
<td>-0.98</td>
<td>-0.96</td>
</tr>
<tr>
<td>SD</td>
<td>0.68</td>
<td>0.68</td>
<td>0.84</td>
<td>0.91</td>
<td>0.90</td>
<td>0.84</td>
</tr>
</tbody>
</table>

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 mmol/L 1/2 to 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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