soil systems

MDPI

Article

Soil Salinity Variations in an Irrigation Scheme during a Period of Extreme Dry and Wet Cycles

Sheyda Chamaki [1,*], Saleh Taghvaeian [1], Hailin Zhang [2] and Jason G. Warren [2]

1 Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, OK 74078, USA; saleh.taghvaeian@okstate.edu
2 Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078, USA; hailin.zhang@okstate.edu (H.Z.); jason.warren@okstate.edu (J.G.W.)
* Correspondence: sheyda@okstate.edu

Received: 23 April 2019; Accepted: 10 May 2019; Published: 14 May 2019

check for updates

Abstract: Salinization of irrigated lands is a major challenge towards supplying required food and feed to meet the needs of an increasing global population. In this study, the changes in soil salinity and several other chemical properties were investigated in an irrigation scheme during a period that experienced severe drought followed by above-normal precipitation. Soil salinity, represented by the electrical conductivity (EC) of the saturated paste extract, decreased for the top layers and increased for the bottom layers during the study period, suggesting some level of leaching had occurred. However, the change in the average EC of top 1.5 m of the soil was not statistically significant. The change in exchangeable sodium percentage (ESP) was not significant over the study period either. In contrast, average pH and calcium concentrations increased and decreased significantly during the study period, respectively. EC and ESP data were used in soil classification. The percentage of all sampled sites classified as saline was 60 at the beginning of the dry–wet period, but dropped to 50% at the end of this period. All tested parameters were temporally stable, preserving their spatial rank during the study period.

Keywords: electrical conductivity; sodicity; cotton; drought; Oklahoma

1. Introduction

Ever increasing world population in recent decades has led to intensification of competition over water resources between agriculture, industries, and municipalities. In addition, crop production must increase to provide food for the growing population, mainly through increasing crop intensity. Irrigation has enabled increased yields and multiple cropping in traditionally single-cropped regions [1]. This in return has provided a sense of stability and security for utilization of fertilizers and pesticides, ensuring a viable crop yield even in areas with unstable and non-uniform precipitation patterns [2]. Despite the above-mentioned benefits, irrigation can have negative effects. One potential adverse impact is related to salt concentrations. Salts and nutrients in the water are added to the soil during each irrigation event. In addition, the salts already present in the soil are mobilized in the irrigation process. Irrigation can also raise the water table and bring the salts in the groundwater to within the root zone, affecting crop growth [2–4].

In the early 1990s, around 45 million ha of irrigated land was salt spoiled [5]. This area has increased to more than 62 million ha, or about 20% of the world's total irrigated area [1,6]. According to Qadir et al. [6], more than 2000 ha of irrigated land has been lost to salinization every day during the last 20 years. The estimated economic loss was more than $441 per hectare in 2013, which adds to around $27.3 billion in annual global loss. These loss estimates would have been even higher if the extensive costs associated with losses in property and business values, infrastructure deterioration, and the negative impacts on social structure and stability of the communities were taken into consideration. Furthermore, there is an environmental cost associated with the increased water and wind erosion from salt induced farms.

Soil remediation for removal of salts from the root zone is both costly and time consuming and, in many cases, the damage is irreversible. Therefore, the economic and sustainable solution to the salinity issue is to prevent rather than cure [1]. Effective prevention (or minimization) requires a comprehensive understanding of salt dynamics and responses to spatially variable agricultural, climatological, and hydrological characteristics. Wallender et al. [7] categorized the scale of spatial and temporal variations in water dependent properties of soil in four groups of micro (laboratory), macro (greenhouse), mega (field), and system (watershed/district). Previous studies have investigated the complex solute dynamics in the soil profile, with a major focus on short term responses and micro to macro scales of controlled environments [8–10]. Such studies have provided in-depth information about salt movement in the soil. However, this knowledge may have limited practical applications due to ignoring some of the major factors that complicate salt dynamics under natural conditions of large-scale ecosystems [11].

Some researchers have conducted long-term salinity studies at larger geographical scales, such as irrigation districts. Ballantyne [12] analyzed electrical conductivity (EC) of soil profiles at 64 sites for a period of 11 years and found that salt movements occurred well below the apparent root zone. They concluded that the annual net salinity change was site-specific and further studies were required to understand the trend of salt change and reasons behind it. They also pointed out that monitoring salinity at specific sites over the long-term could help better understand salt movement patterns in soil profile. Herrero and Pérez-Coveta [13] assessed variations in soil salinity and sodicity of an irrigation district in northeast Spain during a 24-year period. Considering the sampling period and large number of soil samples, they were able to determine a general desalinization trend which increased by soil sampling depth. However, the lack of data on crop management practices confined them from determining what triggered the observed pattern. In Hetato Irrigation District in China, Wu et al. [14] studied long-term changes in salinity and reported that installation and improvement of drainage systems at district and field scales along with maintaining a large portion of fallow fields led to successful salinity control in the cropped areas.

Although these few studies have provided valuable information about long-term soil salinity dynamics at large scales, none of them (to the best of our knowledge) has included periods of extreme weather events such as droughts and floods. As a changing climate is expected to bring a higher frequency and severity of extreme events, it is of great importance to study the effects of intense dry and wet cycles on salinity variations in the crop root zone. The present study explored the dynamics of soil salinity and associated chemical properties across an irrigation district in southwest Oklahoma over eight growing seasons. About half of this period was characterized by an extreme drought, in which irrigation application was halted due to unavailability of water supply. This dry period was succeeded by extreme precipitation events that replenished local water resources in a short period. The research hypothesis was that this no-irrigation period followed by intensive precipitation should have a significant influence on leaching salts and creating a more favorable condition for crop production.

2. Materials and Methods

2.1. Study Area

The area studied was the Lugert-Altus Irrigation District (LAID), which occupies over 190 km^2 in southwestern Oklahoma [15]. An irrigation water right was obtained by the LAID from the State of Oklahoma in 1939, allowing the district to use up to 105 million cubic meter per year from the North Fork Red River for irrigation purposes [15]. This makes LAID the largest surface water irrigation scheme in Oklahoma. The water is stored in the Lugert-Altus Reservoir (Lake Altus) and released during the growing season for agricultural irrigation through a network of main canals (83 km) and laterals (351 km), while open drains (42 km) provide the required water removal from the fields [16]. Figure 1 demonstrates the location of LAID and its water reservoir in southwest Oklahoma, along with the irrigation canal network and the sampling locations used in the present study. The average size of fields within LAID is 53 hectare (ha) and most of them are flood irrigated using a furrow system. The average seasonal irrigation allocation is about 500 mm. Upland cotton is the most dominant crop in the study area, with a growing season that spans from May to September and an irrigation season from early July to late September in most years [17].

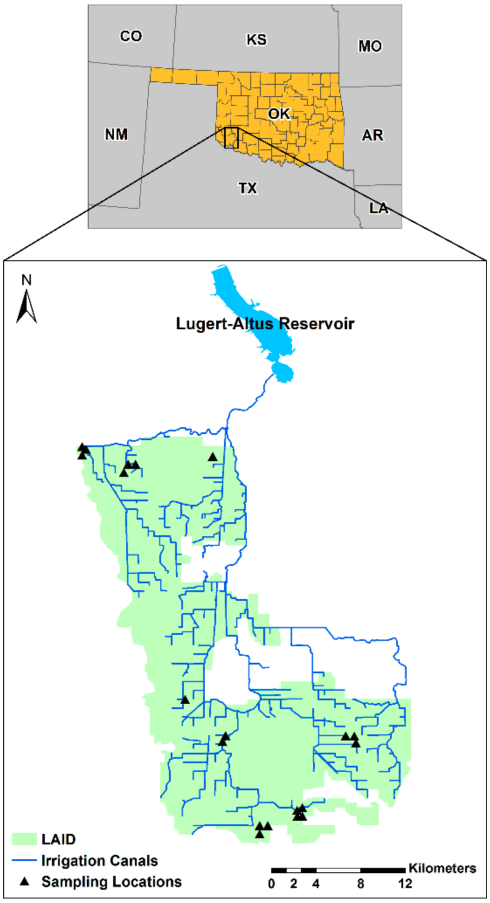


Figure 1. The Lugert-Altus Irrigation District (LAID) in southwest Oklahoma. Sampling locations are also identified within LAID.

The two major soils of the study area are Hollister silty clay loam (Fine, smectitic, thermic Typic Haplusterts) and Roark loam (Fine, mixed, superactive, thermic Pachic Argiustolls), which account for 41% and 15% of the total LAID area, respectively. Hollister soils have the parent material of Calcareous clayey alluvium. Typical profile for this soil is silty clay loam for the top 0.2 m of the soil, followed by silty clay to 0.4 m depth and then clay for deeper layers. At an elevation varying from 350 to 500 m [18], LAID has sub-humid climate with hot and dry summers [17]. Table 1 summarizes average growing season (May to September) and annual weather parameters for a 20-year period.

Table 1. Average growing season (May to September) and annual meteorological parameters for the period of 1997–2016.

Parameter	Growing Season	Year
Total Prec. [1] (mm)	322	610
Mean R_s [2] (MJ m^{-2})	21.8	17.0
Min T_{air} [3] (°C)	18.6	9.4
Max T_{air} (°C)	32.2	23.3
Mean T_{air} (°C)	25.2	16.1
Min RH [4] (%)	34.4	37.2
Mean VPD [5] (kpa)	1.6	1.0
Mean U_2 [6] (m s^{-1})	3.0	3.2

[1] Precipitation; [2] Total daily accumulation of solar radiation; [3] Air temperature; [4] Relative humidity; [5] Vapor pressure deficit; [6] Wind speed at 2.0 m above the ground.

In 2011, southwest Oklahoma experienced record low precipitation (262 mm) and entered a period of severe drought. This drought led to drastic reductions in Lake Altus water levels, which serves as the sole source of water for LAID. As a result, the release of water to LAID irrigators was terminated for the first time in its history. This in return led to the decline of the irrigated area to near zero [19] and had a devastating impact on the regional cotton industry. Heavy spring rains in 2015 ended the drought and refilled the reservoirs [20]. In May 2015 alone, 281 mm of rainfall was recorded at an Oklahoma Mesonet weather station (Altus) located within LAID. This was 3.5 times greater than the 20-year average participation of 80 mm for the same month and weather station.

2.2. Soil Sampling Procedure

Soil sampling was conducted at two times, covering a period of over eight years. The first sampling took place in October 2007, when soil cores were extracted at twenty locations across the LAID using a deep soil core sampler (Giddings Machine Company, Inc., Windsor, CO, USA). Each core was 1.5 m deep and was divided into five sub-cores of equal lengths upon extraction of the core. The sub-cores represented soil layers 0.0–0.3, 0.3–0.6, 0.6–0.9, 0.9–1.2, and 1.2–1.5 m. The sampling depth of 1.5 m was selected because it represents the active crop root zone, where soil salinity has the largest impact on crop yield. In addition, pushing the sampler to deeper layers could have caused soil compaction and consequently errors in salinity estimate of each sub-core.

The coordinates of all sampling locations were recorded from a Global Positioning System (GPS) and used in February 2016, when the same locations were visited and the same procedure was followed to take soil cores. The spatial distribution of sampling points covered the entire irrigation scheme, with seven, six, and seven samples taken from the north, central, and south regions, respectively (Figure 1). Within each region, the number of samples was divided equally between samples taken from near the upstream and near the downstream ends of the furrows. The north and south regions had one extra sample each from an upstream location. Out of the 20 sampling locations, 12 were classified as Hollister soil and four as Roark soil.

2.3. Soil Testing Methods

Soil samples were oven dried at 65 °C and grounded to pass through 2-mm sieve. Soil pH and salinity parameters were determined using the 1:1 water to soil extraction and converted to the saturated paste extract equivalent based on the conversion factors described in [21]. Briefly, 100 g of oven-dried soil was mixed with 100 mL of deionized water. After reaching equilibrium (about 4 h), the suspension was extracted using the low-pressure filter press apparatus. The electrical conductivity (EC) and pH were measured by a conductance cell and pH electrode. An inductively coupled plasma (ICP) spectrometer (SPECTRO Analytical Instruments GmbH, Germany) was used to quantify the amounts of boron (B), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) in the extract [22]. Exchangeable sodium percentage (ESP) was calculated using the equations provided in [21]. The conversion factors used were 3.0 for EC, 2.78 for K and Na, and 1.67 for Ca and Mg [21]. All values reported in this article represent the saturated paste extract equivalent.

2.4. Statistical Analysis

All statistical analysis for significant differences were conducted using the general linear model procedure in Minitab V.13 (Minitab Inc., State College, Pen., USA). Analysis were based on one-way ANOVA along with Tukey's pairwise comparison test at family error of 0.05 (95% confidence interval). The general linear model is a flexible and useful statistical model as it assumes an exponential family model for the response. Once a significant difference between groups was found, the Tukey's test was used to determine where the significant difference lied.

In addition, two approaches were implemented to assess the temporal stability of measured soil parameters during the course of this study. The first approach was the nonparametric Spearman's rank correlation outlined in [23]. In this test the degree of change in the ranking of each sampling site compared to a previous sampling date is determined by estimating the Spearman's rank correlation coefficient (r_s) as

$$r_s = 1 - \frac{6\sum\left(R_{i,j} - R_{i,j'}\right)^2}{n(n^2-1)} \tag{1}$$

where $R_{i,j}$ is the rank of the measured parameter at the site i and time j (2007 in the case of this study), $R_{i,j'}$ is the rank of the same site at sampling time j' (2016), and n is the number of samples (20). An r_s value of unity indicates no change in the ranking, or otherwise a perfect temporal stability of the parameter of interest. The estimated r_s values are compared against the critical r_s to identify their statistical significance. In this study, the critical r_s was determined as 0.447 and 0.570 at the significance levels of 0.05 and 0.01, respectively [24].

The second approach was based on the linear regression between measured soil properties at two sampling periods as explained in [25,26]

$$Z_{i,j'} = I_{i,j} + S_{i,j}\, Z_{i,j} \tag{2}$$

where I is the intercept, S is the slope, and Z is the soil property of interest measured at location i and two times of j and j'. Douaik et al. [26] defined four different scenarios based on the possible values of I and S:

1. I = 0 and S = 1: There is no change in the measured soil property by time (perfect stability),
2. I ≠ 0 and S = 1: The mean soil property changed by time, and the change was spatially uniform (static),
3. I = 0 and S ≠ 1: The mean soil property did not change by time, and changes at different locations were non-uniform (dynamic),
4. I ≠ 0 and S ≠ 1: The mean soil property changed by time and the change was non-uniform (dynamic).

3. Results

3.1. Variations in Soil Chemical Properties

Variations in the concentration of pH, several major ions, exchangeable sodium percentage, and electrical conductivity of the soil extracts were investigated at different soil layers during the study period to identify potential impacts of wet and dry cycles on profiles of these parameters in irrigated soils of the study area.

3.1.1. pH

Soil pH is an important parameter as it impacts the availability of nutrients [27]. High pH levels can lead to decreased availability of positively charged ions, while negatively charged ions become more soluble [28–30]. In this study, pH values had a range of 6.7–9.3 in 2007 and 7.3–9.4 in 2016. The average pH increased from 7.7 to 8.1 during the study period and this difference was statistically significant ($p = 0.01$). For cotton production, the desired range of root zone pH is between 5.6 and 8.0, with an optimum range of 6.0 to 6.5. The pH had small variations among the soil layers and these variations were not statistically significant on either sampling dates (Figure 2). The change in pH over time was depth dependent, ranging from 0.5 unit increase for the shallowest layer to 0.2 unit increase at the 0.9–1.2 m layer. This change was statistically significant for the top three layers (0.0–0.9 m).

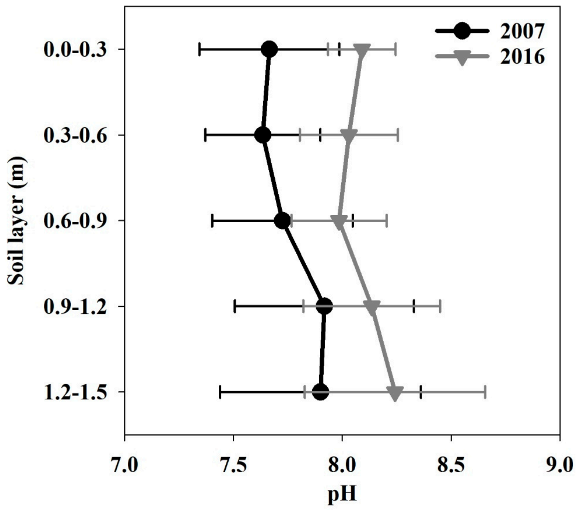


Figure 2. Mean pH for each soil layer at the two sampling dates in 2007 and 2016. Error bars represent one standard deviation from the mean.

3.1.2. Boron

Boron (B) is an essential micronutrient for crop production. However, it has a narrow range of optimum concentration in soil solution before it becomes deficient at lower levels or toxic at higher levels than the desired range [30]. In the case of cotton, B deficiency is a major limiting factor in the US [31], especially since cotton is very tolerant to B toxicity [32]. In this study, B concentrations had a similar range ($0.0–1.9 \times 10^{-4}$ mol L^{-1}) and average (3.6×10^{-5} mol L^{-1}) in both 2007 and 2016. The profiles of B at each sampling date are presented in Figure 3. When considering B profiles, concentrations were smallest for the top two layers and then increased with depth on both sampling dates. Boron exists in the neutral boric acid form so it is not adsorbed by charged soil colloids. In 2007, the minimum B was observed at the top two layers of 0.0–0.3 and 0.3–0.6 m with average values of 1.8×10^{-5} and 1.6×10^{-5} mol L^{-1}, respectively. The concentrations increased by depth to the maximum average of 5.6×10^{-5} mol L^{-1} at the deepest layer (Figure 3). In 2016, the average B was 1.6×10^{-5} and 2.1×10^{-5} mol L^{-1} for the top two layers, respectively. These values increased with depth to the maximum average of 6.1×10^{-5} mol L^{-1} at the deepest soil layer.

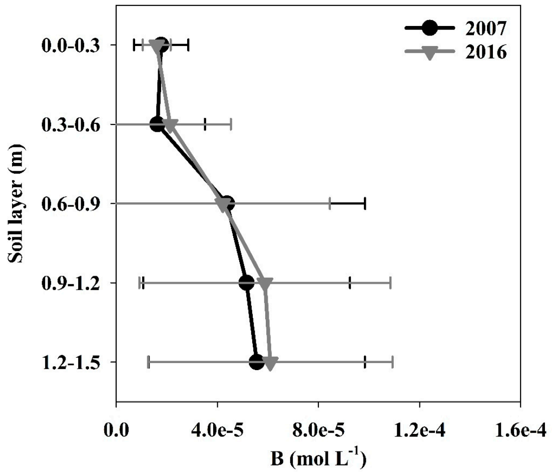


Figure 3. Mean B for each soil layer at the two sampling dates in 2007 and 2016. Error bars represent one standard deviation from the mean.

The amount of B in the soil was adequate for most plants and was not toxic even with the highest amount in the lower part of the soil profile. The ANOVA revealed that some of the layers had statistically significant differences. Based on the Tukey's pairwise comparison, the two layers of 0.0–0.3 m and 0.3–0.6 m were significantly different from the two layers 0.9–1.2 and 1.2–1.5 m at 0.05 level on both sampling dates. The change in B over time was not significant at any depth, suggesting that the wet and dry cycles during the study period did not have any considerable impact on B concentrations.

3.1.3. Sodium

In 2007, average sodium (Na) concentration increased with depth to a maximum of 0.049 mol L^{-1} at the 0.6–0.9 m soil layer, and then declined to the minimum of 0.031 mol L^{-1} at the deepest soil layer (Figure 4). However, Tukey's pairwise comparison showed that the differences in Na among soil layers were not statistically significant. The profile of Na had a similar pattern in 2016, but the minimum average was observed at the topmost layer with the value of 0.018 mol L^{-1}. It then increased gradually by depth until the maximum of 0.055 mol L^{-1} at the 0.6–0.9 m depth and decreased slightly for the two deeper layers. Based on the Tukey's pairwise comparison for data obtained in 2016, the first layer was significantly different from the third and fourth layers at 0.05 level, but the remaining layers were not significantly different.

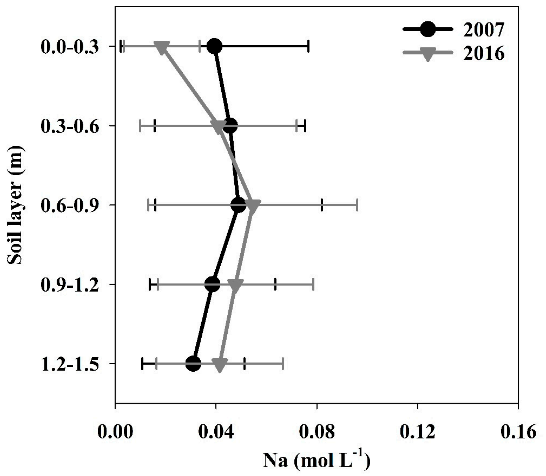


Figure 4. Mean Na for each soil layer at the two sampling dates in 2007 and 2016. Error bars represent one standard deviation from the mean.

When considering all locations/depths, the average Na was 0.042 and 0.040 mol L^{-1} in 2007 and 2016, respectively, demonstrating no significant difference. The change in Na during the study period was strongly depth dependent. The top two soil layers experienced a decrease while the bottom three layers showed an increase in Na concentrations. The maximum reduction was at the top layer at 0.021 mol L^{-1}, which is about 53% reduction based on the 2007 level. This difference was statistically significant (p = 0.02). The maximum increase in Na was at the bottom layer at 0.010 mol L^{-1}, or about 34% of the 2007 levels. However, this difference was not statistically significant. The magnitudes of total decreases and increases in Na concentration were similar, resulting in a value of zero when differences were summed for all soil layers. These findings suggest that the top 0.6 m of the soil experienced leaching of Na during the study period, but the net change for the top 1.5 m of the soil was negligible as transported Na was deposited in the layers below.

3.1.4. Calcium

The average Calcium (Ca) reduced from 1.3×10^{-2} mol L^{-1} in 2007 to 8.9×10^{-3} mol L^{-1} in 2016 and this decrease was statistically significant (p = 0.008). It is worth mentioning that higher levels of Ca concentration in soil have been found to help minimize adverse impacts of salinity on cotton growth [28] since Ca flocculates clay particles and builds better soil structure. Similar to Na findings, the reduction in Ca with time was strongly depth dependent, being largest at the top layer (0.0–0.3 m) with a decline of 6.2×10^{-3} mol L^{-1} on average and smallest at 0.9–1.2 m layer with a decline of 6.0×10^{-4} mol L^{-1}. The change in Ca over the study period was statistically significant only for the top layer (p = 0.002). Little or no salt input during the drought and salt movement downward during the wet period might have contributed to the decrease in Ca in the surface soil. The increase in pH may have also resulted in downward movement of soluble Ca. When considering each sampling date separately, Ca concentrations first increased and then decreased with depth, but these changes were not statistically significant (Figure 5).

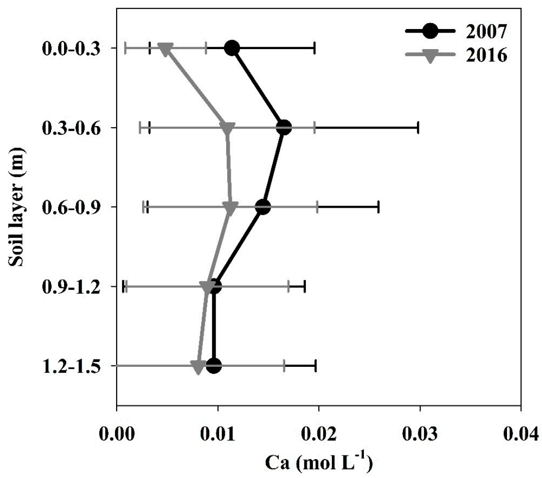


Figure 5. Mean Ca for each soil layer at the two sampling dates in 2007 and 2016. Error bars represent one standard deviation from the mean.

3.1.5. Magnesium

The average magnesium (Mg) concentration reduced from 7.3×10^{-3} mol L^{-1} in 2007 to 6.3×10^{-3} mol L^{-1} in 2016, but this decrease was not statistically significant. The reduction in Mg with time was depth dependent, with the largest decrease observed at the top layer (2.1×10^{-3} mol L^{-1}) and the smallest decrease of near zero at the bottom two layers. These changes, however, were not statistically significant at any layer. The change in Mg over time was expected to be significant at least for the top layer (similar to Na and Ca). A possible reason for not observing a significant change may be the impact of increase in pH on decreasing Mg solubility due to precipitation with carbonate.

Variations in Mg with depth were similar to those observed in Ca, with concentrations increasing gradually from the top layer to maximum levels at 0.6–0.9 m and then decreasing at deeper layers (Figure 6). The differences in Mg among soil layers were not statistically significant in 2007, and in 2016 only the two layers of 0.0–0.3 and 0.6–0.9 had a statistically significant difference ($p = 0.0008$).

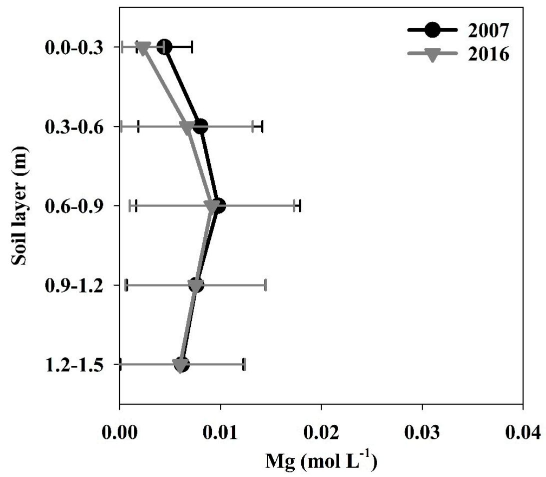


Figure 6. Mean Mg for each soil layer at the two sampling dates in 2007 and 2016. Error bars represent one standard deviation from the mean.

3.1.6. Electrical Conductivity

The sub-cores collected from different locations/depths at two sampling times had a wide range of electrical conductivity (EC), varying from 0.3 to 26.0 dS m^{-1}. In 2007, the average EC of all sampling locations was smallest at the top layer with a value of 5.7 dS m^{-1} (Figure 7). Below this layer, EC increased to 11.0 dS m^{-1} at 0.6–0.9 m, then decreased and reached EC of 7.1 dS m^{-1} at the deepest level. The differences in EC between the first and the second layers and the first and the third layers were statistically significant according to Tukey's pairwise test ($p < 0.05$). In 2016, similar to 2007, the lowest average EC was observed at the shallowest layer at 4.3 dS m^{-1}. It then increased by depth to the maximum value of 11.1 dS m^{-1} at the depth of 0.6–0.9 m, followed by a decrease to 8.4 dS m^{-1} at the deepest soil layer. The differences in average EC were only statistically significant between the top soil layer and the layers 0.6–0.9 m and 0.9–1.2 m ($p < 0.05$).

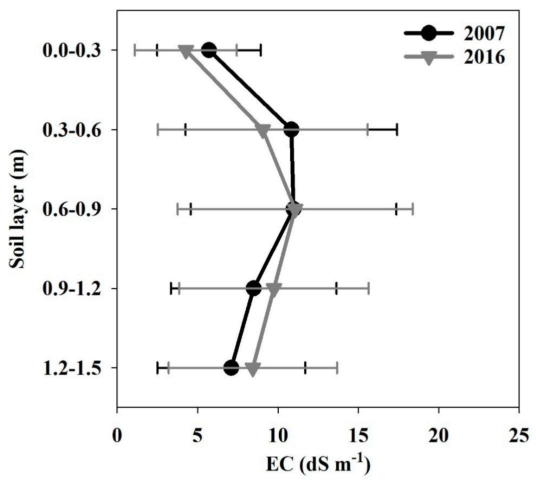


Figure 7. Mean EC for each soil layer at the two sampling dates in 2007 and 2016. Error bars represent one standard deviation from the mean.

The results from the two sampling times provided valuable information on how salinity changed with depth and time during the study period. When considering changes with depth, the lowest salinity observed was in the shallowest soil layer at both sampling times. This could be attributed to the effect of irrigation applications. The top soil salinity is more strongly impacted by the salinity of the irrigation water compared to deeper soil layers, where other factors such as soil type, salt type, and the method of water application play greater roles [33]. The EC of irrigation water measured at different times during the study period at a central location within LAID was 2.0 dS m^{-1} on average, smaller than the average EC at all soil layers/dates. Another contributing factor could be soil texture, which is coarser for the top layer and heavier for deeper layers in the study area. The percent clay content averaged for all sampling locations was 35, 42, 43, 43, and 42 for soil layers 0.0–0.3, 0.3–0.6, 0.6–0.9, 0.9–1.2, and 1.2–1.5, respectively. The change in soil texture affects permeability and thus the leaching potential.

In addition to observing the lowest EC at the shallowest layer, both sampling dates had similar EC patterns that first increased and then decreased with depth. This profile distribution of EC could be linked to the texture profile. Salts can accumulate in the B-horizon, which is typically associated with elevated clay content (the case with the Hollister soil profile). As a result, the salts tend to accumulate in this layer because they cannot be leached further down. A similar pattern of EC variations by depth was observed by Feikema and Baker [8] under irrigation with low-salinity water, where EC increased with depth to mid-layers of 0.8–1.0 m and then decreased to deepest sampling layer of 1.8 m. Under high-salinity irrigation application, however, they reported continuous increase in EC with depth [8]. The increasing EC pattern has been reported by several other researchers [11,34], especially under the presence of shallow groundwater [35,36].

The changes in EC during the study period varied largely among sampling locations/depths, from a decrease of 12.7 to an increase of 11.5 dS m^{-1}. The magnitude and direction of EC change was impacted by depth. The average EC decreased by time for the top two layers, remained unchanged for the third layer, and increased for the bottom two layers. This is similar to the temporal change in Na and indicates some downward movement of salts (leaching) during the study period. When considering all data points, EC decreased 2.8 dS m^{-1} from 2007 to 2016 on average. However, this difference was not statistically significant; suggesting that the net impact of dry and wet cycles on the salinity of soil profile was negligible at the district level.

Despite finding no significant change in EC at large scale, the high level of variability in salinity changes among studied locations deserves further investigation. Out of the 20 locations sampled in this study, 12 (60%) had experienced some level of leaching from 2007 to 2016. The remaining locations were divided equally between no significant change and increase in EC over time. Since these locations were similar in many characteristics (e.g., climate, soil type, irrigation source, crop type), different responses in soil EC is most likely caused by on-farm factors such as irrigation management and the effectiveness of removing excess water from the root zone using surface and subsurface drains. The dynamics of interrelationships between irrigation and soil salinity should be investigated further in future studies. While irrigation can leach salts from the top soil, high levels of EC can negatively impact the performance of soil moisture sensors, which can be used to develop precision irrigation scheduling for leaching salts [37].

Cotton is the dominant crop in the study area and plays a vital role in the local economy. Hence, it is of great importance to investigate potential impacts of soil salinity on cotton performance. In conducting such analysis, however, it should be taken into account that crop productivity is affected by the average salinity of the soil profile and elevated salinity in certain depths may not significantly affect productivity if other depths had low salt concentration. Cotton is considered a salt tolerant crop with the threshold EC of 7.7 dS m^{-1} [38]. Above this threshold, cotton yields start to decline at a rate of 5.2% per unit increase in EC [32]. When averaged over the entire sampling profile (1.5 m), the EC estimates for the 20 locations had a range of 3.4–14.0 dS m^{-1} in 2007 and 2.8–14.2 dS m^{-1} in 2016. At locations with the highest profile EC, yield declines of 33% and 34% in cotton are expected in 2007 and 2016, respectively. The average profile EC for all sampling locations was 8.8 dS m^{-1} in 2007 and 8.5 dS m^{-1} in 2016 in this study, which is about one unit larger than the threshold and may have a small potential impact on reducing cotton yield (5 and 4%, respectively) at district scale. For the top two layers (0.0–0.6 m), the average EC was 8.3 dS m^{-1} in 2007 (above the threshold) and 6.6 dS m^{-1} (below the threshold) in 2016.

3.1.7. Exchangeable Sodium Percentage

High levels of exchangeable sodium percentage (ESP) can have detrimental effects on soil physical and hydraulic properties such as aggregate stability, permeability, and hydraulic conductivity [30]. In addition, elevated ESP levels have been linked to lower cotton yield and fiber quality in studies conducted in Australia [39] and India [40]. In this study, ESP had a range of 2-65% in 2007 and 3-64% in 2016 when considering all samples. Despite observing large ESP levels in some soil samples, 80% of them had an ESP level less than 15% in both years. According to Abrol et al. (1988), the sodicity hazard is none to slight when ESP is smaller than 15%. About 18% of samples in both years had ESP levels larger than 15% but smaller than 30%, which is classified as light to moderate sodicity hazard. The average ESP was 12% and 13% in 2007 and 2016, respectively. However, this difference was not statistically significant.

The trend of ESP profiles was similar to those of Ca, Mg, Na, and EC. In 2007, the minimum ESP observed was in the top soil layer with the average of 9.9%. This value increased by depth and reached the maximum of 13.5% at 0.6–0.9 m depth, then decreased and reached 10.6% at the deepest layer (Figure 8). In 2016, the minimum ESP also was observed at the shallowest soil layer with the average value of 7.7%. ESP increased by depth below the top layer and reached the maximum of 16.4% at the deepest soil layer. Although these estimates show a decrease in ESP for the top soil layers and an increase for the bottom layers over time, the differences among layers were not statistically significant based on the Tukey's pairwise comparison.

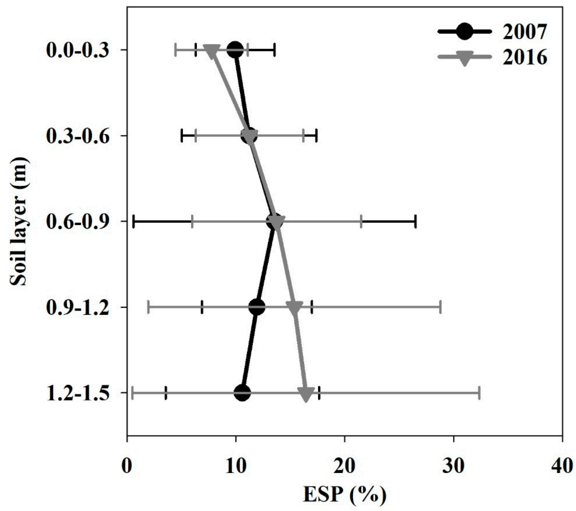


Figure 8. Mean ESP for each soil layer at the two sampling dates in 2007 and 2016. Error bars represent one standard deviation from the mean.

3.2. Soil Salinity Classification

Several classification systems have been proposed in the past for dividing soils into different categories for variable purposes. A classification commonly used in irrigated agriculture is based on soil salinity and sodicity [41]. In this system, an EC threshold of 4.0 dS m^{-1} is considered for salinity and an ESP of 15% is used for sodicity. Combining the two thresholds allows for classifying soil samples into four groups. Normal soils have both EC and ESP values less than the thresholds. Saline soils are identified with EC of greater than 4 dS m^{-1} and ESP of less than 15%. Nonsaline-sodic soils have EC levels of less than 4 dS m^{-1} and ESP of greater than 15%. If both thresholds are exceeded the soil is classified as saline-sodic. Figure 9 shows a scatterplot of EC vs. ESP for all collected samples in 2007 and 2016. The horizontal and vertical lines represent the thresholds. The majority of the soils were either normal or saline (see Table 2 for details). This classification is beneficial if reclamation is implemented. For saline soils, an adequate amount of water is needed to leach excess salts out of the soil profile, but gypsum and organic matter are required in addition to remove the excess sodium first by exchanging Na by Ca [42].

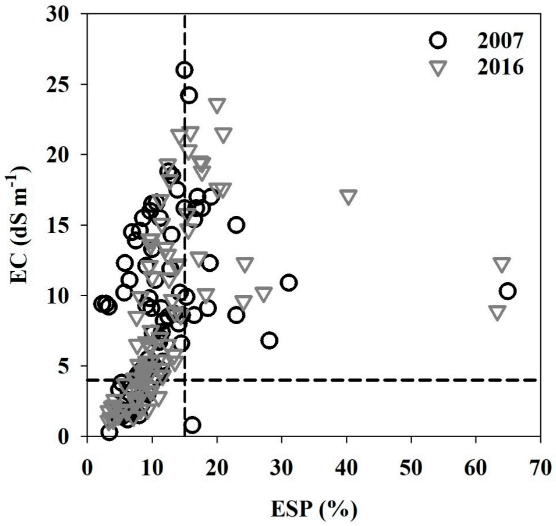


Figure 9. Distribution of all collected soil samples across four soil classes of normal (lower left), saline (upper left), saline-sodic (upper right), and sodic (lower right).

Table 2. Percentage of samples in each soil class in 2007 and 2016 reported for the entire soil profile and each of the five sub-layers.

Class	EC	ESP	Profile		0.0–0.3		0.3–0.6		0.6–0.9		0.9–1.2		1.2–1.5	
			2007	2016	2007	2016	2007	2016	2007	2016	2007	2016	2007	2016
Normal	<=4	<=15	22	29	35	60	20	20	15	20	18	18	25	25
Sodic	<=4	>15	1	0	0	0	0	0	0	0	1	0	0	0
Saline	>4	<=15	60	50	55	35	60	60	60	45	65	59	58	50
Saline-sodic	>4	>15	17	21	10	5	20	20	25	35	12	24	17	25

When considering the change in soil classification over the study period for all collected samples (profile), the largest difference observed was in the saline class. The percentage of samples belonging to this class decreased from 60% in 2007 to 50% in 2016 (Table 2). The majority of the points that were no longer classified as saline had moved to the normal class, represented by a frequency increase in this class from 22% in 2007 to 29% in 2016. Although this a considerable change in the right direction, it still shows that a significant portion (half) of all samples had salinity issues after the eight years of dry/wet cycles. In addition, the percentage of samples classified as saline-sodic increased from 17% in 2007 to 21% in 2016. The increase in saline-sodic soils deserves further investigation and continued monitoring since high sodicity results in aggregates dispersion and decrease in soil permeability to air and water, especially if salts are leached out of saline-sodic soils.

When studying each soil layer, the largest change was observed in the top layer (0.0-0.3), with an increase in the normal class from 35% of samples in 2007 to 60% in 2016. The largest decline of the saline class was observed as the same layer, from 55% in 2007 to 35% in 2016. The distribution of samples among classes remained unchanged over time for the second layer (0.3–0.6 m). The bottom three layers experienced a reduction in saline samples and an increase in saline-sodic ones.

3.3. Temporal Stability

To investigate the effect of wet and dry cycles experienced during the study period (2007–2016) on temporal stability of soil salinity, the nonparametric Spearman's test was performed on all studied soil parameters, averaged over the sampled soil profile (1.5 m). The Spearmen's rank correlation coefficient (r_s) varied from 0.761 for boron (B) to 0.935 for ESP (Table 3). All r_s values were close to unity and larger than the critical r_s values of 0.447 and 0.570, which represent 0.05 and 0.01 significance levels, respectively. This suggests the presence of a strong and statistically significant time stability in the ranks of sampling locations during the study period. The r_s for EC in this study was 0.875. Douaik et al. [42] reported similar r_s values for EC estimated at twenty sampling locations across a grassland in eastern Hungary over a span of about seven years.

Table 3. Spearman's rank correlation coefficients (r_s) for studied soil parameters.

Parameter	r_s
B	0.761
Ca	0.687
Mg	0.877
Na	0.814
pH	0.781
EC	0.875
ESP	0.935

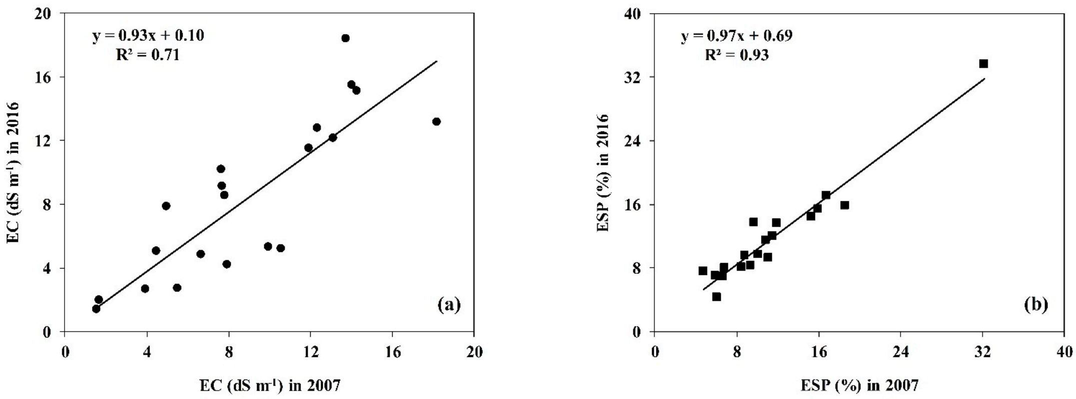
The static-dynamic nature of temporal changes in spatial patterns of the soil properties was evaluated by developing linear regression models for each measured property where the independent and dependent variables were the soil property of interest on the first (2007) and the second (2016) sampling dates, respectively. The intercept (I), slope (S), and the coefficient of determination (r^2) of developed regression models are presented in Table 4. All developed linear regression models were statistically significant at 0.01 level, according to the F-test. Except for Ca, the r^2 values were larger than 0.67, suggesting that more than two-thirds of the spatial variance observed at the end of the study can be explained by the variations at the beginning of the experiment.

Table 4. Temporal and spatial pattern of electrical conductivity between the two sampling dates of 2007 and 2016 for different soil layers.

Parameter	I	P (H_0: I = 0)	S	P (H_0: S = 1)	r^2
B	0.02	0.589	1.00	0.499	0.86
Ca	113.6	0.235	0.46	0.001 [1]	0.34
Mg	−14.1	0.580	0.93	0.292	0.78
Na	79.7	0.619	0.85	0.149	0.67
pH	4.11	0.000 [1]	0.51	0.000 [1]	0.72
EC	0.10	0.944	0.93	0.310	0.71
ESP	0.69	0.396	0.97	0.299	0.93

[1] These *P*-values are less than the 0.01 significance level, indicating that the corresponding null hypotheses can be rejected.

Statistical analyses were performed on the coefficients of the regression models (I and S) to identify the represented static-dynamic category among the four categories mentioned in the methodology section. The null hypotheses were that the intercept is zero and the slope is unity. In case of Ca, the null hypothesis was rejected only for S. This suggests that the changes in Ca concentration were not uniform across sampling sites (the spatial patterns were dynamic), but the mean Ca concentration did not change over the study period. In case of pH, null hypotheses were rejected for both I and S, meaning that the average pH changed with time and the magnitude of change between two dates was not uniform and differed from one location to the other. The means and the spatial patterns of all other parameters were static. The largest slope belonged to B at the value of unity, followed by the slopes of ESP, EC, and Mg. Figure 10 depicts the scatterplots and regression lines for EC and ESP between the two sampling dates.



(a) (b)

Figure 10. Linear regression models developed for EC (**a**) and ESP (**b**) on the two sampling dates in 2007 and 2016.

4. Conclusions

The top soil across an irrigation scheme in southwest Oklahoma was sampled before and after a period spanning eight growing seasons. This period was characterized by four years of exceptional drought when irrigation deliveries were terminated due to water scarcity, followed by a period of record precipitation. Except for pH and calcium (Ca), the district-wide mean of studied parameters did not experience a statistically significant change. The mean pH increased significantly from 7.7 to 8.1 and the mean Ca decreased from 1.3×10^{-2} to 8.9×10^{-3} mol L^{-1} over the study period. When investigating temporal changes at five sub-layers, a decrease in sodium (Na) and electrical conductivity (EC) for top layers and an increase for bottom layers were observed. Although this observation is an indication of shallow leaching, the net impact for the entire sampled profile was negligible. Analysis of time stability revealed that, except for the same two parameters (pH and Ca), spatial patterns of other parameters were static. Overall, four years of extreme drought with no irrigation application succeeded by a period of intensive rainfall reduced soil salinity in the surface layer, but moved salts downward to the middle section of soil profiles. This reduction in surface soil salinity is beneficial for seedling establishment. However, levels of pH, EC, and ESP appear to be high enough to cause yield loss, especially at some of the sampling locations.

Author Contributions: Conceptualization, S.T.; Methodology, S.T., H.Z., and J.G.W.; Formal analysis, S.C. and S.T.; Investigation, S.C., S.T., H.Z., and J.G.W.; Writing—original draft preparation, S.C. and S.T.; Writing—review and editing, S.T., H.Z., and J.G.W.; Supervision, S.T.; Project administration, S.T.; Funding acquisition, S.T.

Funding: This material is based upon work supported by the Oklahoma Water Resources Center through the U.S. Geological Survey 104(b) program and by Cotton Incorporated Oklahoma State program under project number 15-657OK.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ghassemi, F.; Jakeman, A.J.; Nix, H.A. *Salinisation of Land and Water Resources: Human Causes, Extent, Management and Case Studies*; CAB international: Wallingford, UK, 1995.
2. Hillel, D. *Salinity Management for Sustainable Irrigation: Integrating Science, Environment, and Economics*; World Bank Publications: Washington, DC, USA, 2000.
3. Tanji, K.K.; Kielen, N.C. *Agricultural Drainage Water Management in Arid and Semi-Arid Areas*; FAO: London, UK, 2002.

4. Kijne, J.W. *How to Manage Salinity in Irrigated Lands: A Selective Review with Particular Reference to Irrigation in Developing Countries*; IWMI: Battaramulla, Sri Lanka, 1998.
5. Oldeman, L.R.; Hakkeling, R.T.; Sombroek, W.G. *World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note*; International Soil Reference and Information Centre: Wageningen, The Netherlands; United Nations Environment Programme: Nairobi, Kenya, 2017.
6. Qadir, M.; Quillérou, E.; Nangia, V.; Murtaza, G.; Singh, M.; Thomas, R.J.; Drechsel, P.; Noble, A.D. Economics of salt-induced land degradation and restoration. *Nat. Resour. Forum* **2014**, *38*, 282–295. [CrossRef]
7. Wallender, W.W.; Hopmans, J.W.; Grismer, M.E. Scales and scaling as a framework for synthesizing irrigated agroecosystem research on the westside San Joaquin Valley. In *Salinity and Drainage in San Joaquin Valley, California*; Springer: Dordrecht, The Netherlands, 2014; pp. 99–122.
8. Feikema, P.M.; Baker, T.G. Effect of soil salinity on growth of irrigated plantation Eucalyptus in south-eastern Australia. *Agric. Water Manag.* **2011**, *98*, 1180–1188. [CrossRef]
9. Razzouk, S.; Whittington, W.J. Effects of salinity on cotton yield and quality. *Field Crops Res.* **1991**, *26*, 305–314. [CrossRef]
10. Tanton, W.T.; Rycroft, D.W.; Hashimi, M. Leaching of salt from a heavy clay subsoil under simulated rainfall conditions. *Agric. Water Manag.* **1995**, *27*, 321–329. [CrossRef]
11. Armstrong, A.S.B.; Rycroft, D.W.; Tanton, T.W. Seasonal movement of salts in naturally structured saline-sodic clay soils. *Agric. Water Manag.* **1996**, *32*, 15–27. [CrossRef]
12. Ballantyne, A.K. Movement of salts in agricultural soils of Saskatchewan 1964 to 1975. *Can. J. Soil Sci.* **1978**, *58*, 501–509. [CrossRef]
13. Herrero, J.; Pérez-Coveta, O. Soil salinity changes over 24 years in a Mediterranean irrigated district. *Geoderma* **2005**, *125*, 287–308. [CrossRef]
14. Wu, J.; Zhao, L.; Huang, J.; Yang, J.; Vincent, B.; Bouarfa, S.; Vidal, A. On the effectiveness of dry drainage in soil salinity control. *Sci. China Ser. E Technol. Sci.* **2009**, *52*, 3328–3334. [CrossRef]
15. Autobee, R. *The WC Austin Project*; United States Bureau of Reclamation: Austin, TX, USA, 1994.
16. USBR. *Appraisal Report Water Supply Augmentation W.C. Austin Project, Oklahoma*; United States Bureau of Reclamation: Austin, TX, USA, 2005.
17. Masasi, B.; Taghvaeian, S.; Boman, R.; Datta, S. Impacts of Irrigation Termination Date on Cotton Yield and Irrigation Requirement. *Agriculture* **2019**, *9*, 39. [CrossRef]
18. Evers, A.J.M.; Elliott, R.L.; Stevens, E.W. Integrated decision making for reservoir, irrigation, and crop management. *Agric. Syst.* **1998**, *58*, 529–554. [CrossRef]
19. Taghvaeian, S.; Fox, G.; Boman, R.; Warren, J. Evaluating the impact of drought on surface and groundwater dependent irrigated agriculture in western Oklahoma. In *2015 ASABE/IA Irrigation Symposium: Emerging Technologies for Sustainable Irrigation-A Tribute to the Career of Terry Howell, Sr. Conference Proceedings*; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2015; pp. 1–8.
20. Krueger, E.S.; Yimam, Y.T.; Ochsner, T.E. Human factors were dominant drivers of record low streamflow to a surface water irrigation district in the US southern Great Plains. *Agric. Water Manag.* **2017**, *185*, 93–104. [CrossRef]
21. Richards, L.A. *Diagnosis and Improvement of Saline and Alkali Soils*; United States Department of Agriculture: Washington, DC, USA, 1954.
22. Soltanpour, P.N.; Johnson, G.W.; Workman, S.M.; Jones, J.B.; Miller, R.O. Inductively coupled plasma emission spectrometry and inductively coupled plasma-mass spectrometry. In *Methods of Soil Analysis. Part 3—Chemical Methods*; Soil Science Society of America: Madison, WI, USA, 1996; pp. 91–139.
23. Vachaud, G.; Passerat de Silans, A.; Balabanis, P.; Vauclin, M. Temporal stability of spatially measured soil water probability density function. *Soil Sci. Soc. Am.* **1985**, *49*, 822–828. [CrossRef]
24. Ramsey, P.H. Critical values for Spearman's Rank Order correlation. *Educ. Stat.* **1989**, *14*, 245–253.
25. Kachanoski, R.G.; De Jong, E. Scale dependence and the temporal presistence of spatial patterns of soil water storgae. *Water Resour. Res.* **1989**, *24*, 85–91. [CrossRef]
26. Douaik, A.; Van Meirvenne, M.; Tóth, T. Statistical Methods for Evaluating Soil Salinity Spatial and Temporal Variability. *Soil Sci. Soc. Am. J.* **2007**, *71*, 1629–1635. [CrossRef]
27. Thomas, G.W. Soil pH and soil acidity. In *Methods of Soil Analysis Part 3—Chemical Methods*; Soil Science Society of America: Madison, WI, USA, 1996; pp. 475–490.

28. Kent, L.M.; Lauchli, A. Germination and seedling growth of cotton: Salinity-calcium interactions. *Plant Cell Environ.* **1985**, *8*, 155–159. [CrossRef]
29. Bohn, H.L.; Strawn, D.G.; O'Connor, G.A. *Soil Chemistry*; John Wiley and Sons: Hoboken, NJ, USA, 2001.
30. *Agricultural Salinity Assessment and Management*; Wallender, W.W., Tanji, K.K., Eds.; American Society of Civil Engineers: Reston, VA, USA, 2011. [CrossRef]
31. Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture*; Food and Agriculture Organization of the United Nations: Rome, Italy, 1985; p. 29.
32. Maas, E.V. Salt Tolerance of Plants. In *Handbook of Plant Science in Agriculture*; Christie, B.R., Ed.; CRC Press: Boca Raton, FL, USA, 1987.
33. Grattan, S.R. Irrigation with saline water. In *Management of Water Use in Agriculture*; Springer: Berlin, Germany, 1994.
34. Ayars, J.E.; Hutmacher, R.B.; Schoneman, R.A.; Vail, S.S.; Pflaum, T. Long term use of saline water for irrigation. *Irrig. Sci.* **1993**, *14*, 27–34. [CrossRef]
35. Moreno, F.; Cabrera, F.; Andrew, L.; Vaz, R.; Martin-Aranda, J.; Vachaud, G. Water movement and salt leaching in drained and irrigated marsh soils of southwest Spain. *Agric. Water Manag.* **1995**, *27*, 25–44. [CrossRef]
36. Datta, S.; Taghvaeian, S.; Ochsner, T.E.; Moriasi, D.; Gowda, P.; Steiner, J.L. Performance Assessment of Five Different Soil Moisture Sensors under Irrigated Field Conditions in Oklahoma. *Sensors* **2018**, *18*, 3786. [CrossRef]
37. Bernstein, L. *Salt Tolerance of Field Crops*; United States Department of Agriculture: Washington, DC, USA, 1960.
38. Dodd, K.; Guppy, C.N.; Lockwood, P.V.; Rochester, I.J. The effect of sodicity on cotton: Does soil chemistry or soil physical condition have the greater role? *Crop Pasture Sci.* **2013**, *64*, 806–815. [CrossRef]
39. Choudhary, O.P.; Josan, A.S.; Bajwa, M.S. Yield and fibre quality of cotton cultivars as affected by the build-up of sodium in the soils with sustained sodic irrigations under semi-arid conditions. *Agric. Water Manag.* **2001**, *49*, 1–9. [CrossRef]
40. Abrol, I.P.; Yadav, J.S.P.; Massoud, F.I. *Salt-Affected Soils and Their Management*; Food & Agriculture Organization: Rome, Italy, 1988.
41. Zhang, H. *Reclaiming Slick-Spots and Salty Soils*; Oklahoma Cooperative Extension Services Publication; Oklahoma State University: Stillwater, OK, USA, 2013; p. PSS-2226.
42. Douaik, A.; Van Meirvenne, M.; Toth, T. Temporal stability of spatial patterns of soil salinity determined from laboratory and field electrolytic conductivity. *Arid Land Res. Manag.* **2006**, *20*, 1–13. [CrossRef]