**DETERMINING THE ECONOMIC RESPONSE OF SODIC SOILS TO REMEDIATION BY GYPSUM, ELEMENTAL SULFUR AND VERSALIME IN NORTHEAST NORTH DAKOTA ON TILED FIELDS**

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**INTRODUCTION**

Saline and sodic soils have been reported in North Dakota since the 1960s. NDSU Extension Bulletin No. 2 reported more than one million acres affected by high salt levels and more than two million acres, which had excessive levels of sodicity (Salt Affected Problem Soils in North Dakota, Their Properties and Management by Gordon A. Johnsgard, reprinted in 1974) in 1967. Another study by Brennan J. and M. Ulmer estimated 5.8 million saline acres in North Dakota (Salinity in the Northern Great Plains, Natural Resources Conservation Service, Bismarck, N.D. 2010). That is 15% of the 39 million acres of cropland in North Dakota. Soil salinity and sodicity are a result of high salt and sodium (Na+) levels in the soil parent material and the underlying sodium-rich shale present in the bedrock below the soil sediments. Rising groundwater depths and resulting capillary rise of soil water leads to the accumulation of excessive soluble salts (salinity) and Na+ causing sodicity in the topsoil.

Saline soils will have excessive levels of soluble salts in the soil water, which are a combination of positively and negatively charged ions (for example, table salt; Na+Cl-). High levels of ions (positive and negative) from soluble salts restrict normal water uptake by plant roots, even when soils are visibly wet, resulting in drought-stressed plants (osmotic effect).

Saline soils having higher levels of calcium (Ca2+)-based salts will have good structure. That happens as Ca2+ ions encourage aggregation of soil particles called flocculation (clumping together), resulting in well-defined pores facilitating free water movement through the soil profile.

In contrast to saline soils, sodic soils are highly saturated with Na+ ions at the soil cation exchange sites (negative charges of clay and humus particles that attract positively charged chemical ions). High Na+ levels compared to Ca2+ in combination with low salt levels can promote “soil dispersion”, which is the opposite of flocculation. Soil dispersion causes the breakdown of soil aggregates, resulting in poor soil structure (low “tilth” qualities). Due to the poor soil structure, sodic soils have dense soil layers, resulting in very slow permeability of water through the soil profile. Due to poor soil structure, when wet, sodic soils will be gummy and may seem as if they have “no bottom” to them, and when dry, they can be very hard.

Note:

* If Na+ is present as a salt, it will not cause dispersion as the positive charges of Na+ ions will be neutralized by the negatively charged chemical ions such as sulfates (SO42-) or chloride (Cl-).
* However, due to the constant exchange of positively charged ions like Ca2+, Mg2+ and Na+ between soil water and the soil clay and humus particle negative charges, high levels of Na+ based salts in the soil water can result in sodicity as more negative charges will be saturated with Na+.

**OBJECTIVES**

Remediation of soil sodicity requires application of amendments that add Ca2+ to the soil, followed by salinity remediation practices of lowering the groundwater depths to desirable levels by promptly draining the excess soil water under wet conditions. Ca2+ displaces Na+ from the clay and humus particles (cation exchange sites) and Na+ moves into soil water where it converts into a salt (Na2SO4) and leaches out with rain or irrigation water.

An effective way to lower groundwater depths is to install a field tile drainage system. Since tiles are generally three to four-feet below the surface, the efficiency of a tile drainage system depends upon how excess water infiltrates through the soil layers above the tiles. This requires analyzing soils for salts and Na+ causing sodicity. In cases of high Na+ levels causing sodicity, not adding Ca2+ can render tiling ineffective. Salinity and sodicity levels can be determined by sampling the areas in question and getting the samples analyzed by a soil laboratory for Electrical Conductivity (EC) and Sodium Adsorption Ratio (SAR). For detailed information on sampling and testing soils for salts and sodicity, please refer to the NDSU Publication: SF-1809; “Soil Testing Unproductive Areas.” Another NDSU publication that provides detailed information regarding the suitability of soils for tiling is: SF-1617; “Evaluation of Soils for Suitability for Tile Drainage Performance.”

Challenges for landowners considering tiling could be:

1. **What if soil sodicity levels are high in the fields they would like to tile?**
2. **In cases of high sodicity levels, what should they do first, tile or apply the amendments?**

In July 2014, the Langdon Research Extension Center (LREC) tiled a field that had excessive levels of sodicity and moderately high levels of soluble salts. This consisted of 12 research plots with three replications (Figure 1). In order to replicate field conditions, the project site was tiled in July 2014 prior to starting sodicity remediation by applying soil amendments that are suitable and easily available to northeast North Dakota growers. Soil amendments were applied in July and August of 2015, one year after tiling.

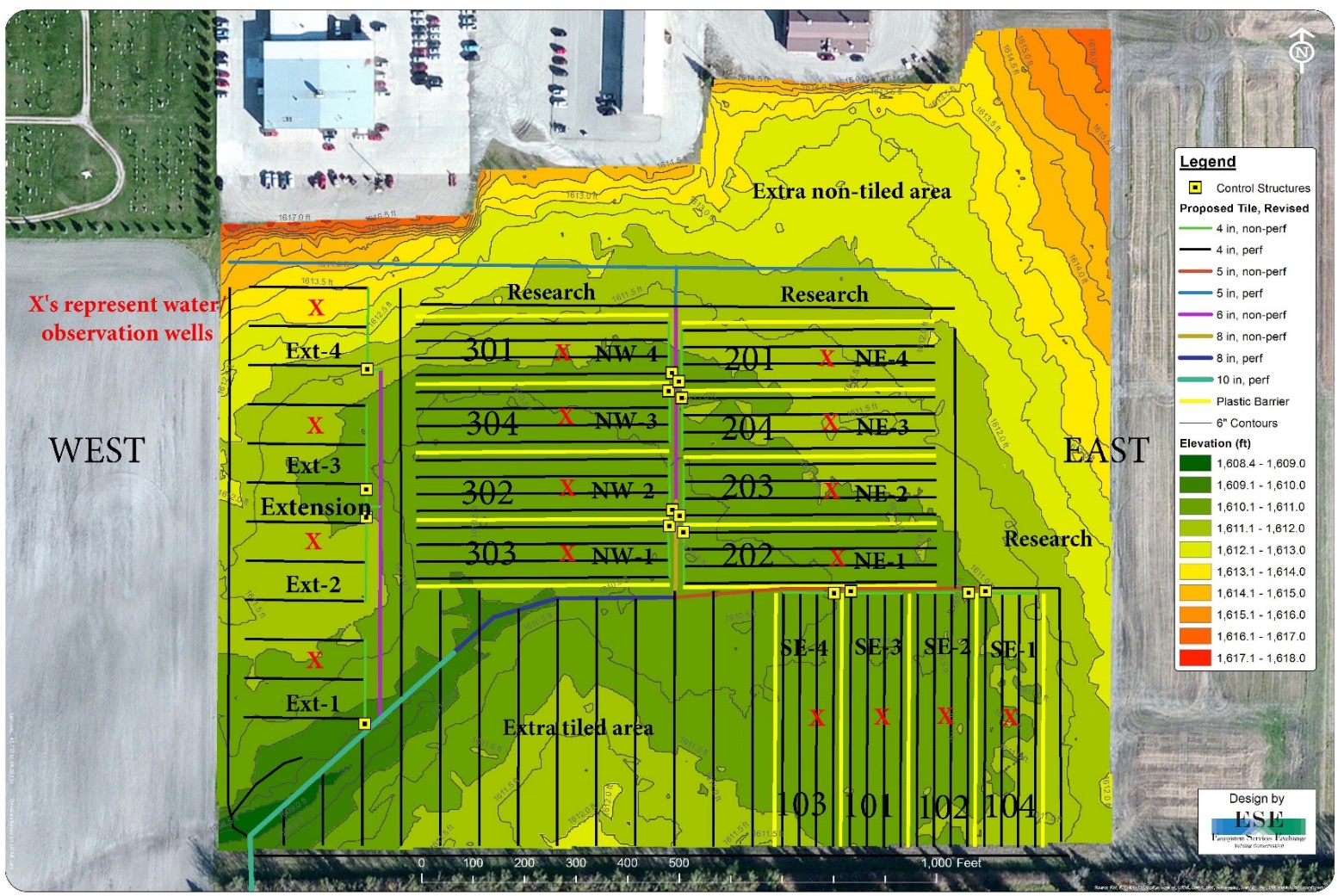


Figure 1. Final layout of the Langdon Research Extension Center Groundwater Management Research Project that has twelve research plots and three replications. Replication 1 is on the southeast and includes SE-1, SE-2, SE-3 and SE-4 plots, replication 2 is on the northeast and includes NE-1, NE-2, NE-3 and NE-4 plots and replication 3 includes NW-1, NW-2, NW-3 and NW-4 plots on the northwest. Treatments range from 101 to 104, 201 to 204 and 301 to 304. The red color axes represent the seven-foot deep observation wells.

The following objectives were set in order to achieve the research goals.

* Can tiling be successful on sodic or saline-sodic soils prior to starting sodicity remediation?
* Comparing the relationship between varying groundwater depths and resulting soil salt and sodicity levels.
* Analyzing water samples from the lift station, upstream and downstream for human and livestock health.

**TRIAL LOCATION AND SITE DESCRIPTION**

This trial site is located at the NDSU Langdon Research Extension Center, Langdon, North Dakota. As per the USDA Web Soil Survey, soil series are a mix of Cavour-Cresbard and Hamerly-Cresbard loams (Figure 2).



Hamerly-Cresbard loams

Cavour-Cresbard loams

Figure 2. USDA Web Soil Survey map of the Langdon Research Extension Center Groundwater Management Research Project before tiling the site along with the soil series descriptions.

**TRIAL DESIGN AND PLOT SIZE**

Trial design is split-block. Each plot is 325 X 80 feet (0.6 acre).

**METHODOLOGY**

**Soil Chemical Analysis**

Four-foot deep soil samples in 12” increments were collected from each plot in September 2014, right after tiling. Using the same protocol, the site was sampled again in June 2016 (two years after tiling and one year after applying the amendments), in June 2017 (three years after tiling and two years after applying the amendments) and in June of 2018 (four years after tiling and three years after applying the amendments). Sampling depths were separated in 12-inch increments and each sampling activity included 48 soil samples (12 plots x 4 depths = 48 samples). All samples were analyzed for Electrical Conductivity or EC (salts), Sodium Adsorption Ratio or SAR (sodicity), pH, calcium carbonate equivalent or CCE, bicarbonates (HCO3-), chlorides (Cl-), sulfates (SO42-), saturation percentage, calcium (Ca2+), magnesium (Mg2+), sodium (Na+), potassium (K+) and nitrate-nitrogen (NO3-N-) for zero to four-foot depths. Soil phosphorus (P) and organic matter percent (O.M. %) were analyzed for the 0-12 inch and 12-24 inch depths. In addition, cation exchange capacity (CEC) was analyzed for the first foot.

**Soil Physical Analysis:**

Eighteen-inch deep soil compaction measurements were taken in one-inch increments with the Field Scout SC 900 meter penetrometer in 2015, 2016, 2017 and 2018. At the time of penetrometer measurements, gravimetric water content was also measured for the eighteen-inch depths in six-inch increments. Soil bulk density was measured for the top ten-inch depths in five-inch increments by taking undisturbed soil cores using a Humboldt Density Sampler in 2015, 2016, 2017 and 2018.

**Weekly Groundwater Depth Measurements**

Seven and one-half foot deep observation wells were installed in each treatment (research plot) in May 2015. In 2015, weekly groundwater depths were measured from June to October, whereas, in 2016, 2017 and 2018 groundwater depths were measured on a weekly basis from May to October by using a Solinst TLC 107 Meter.

**Water Sample Analysis**

Water samples were collected from the lift station, upstream and downstream, in November of 2015, May, July and September of 2016, May and August of 2017, and June 2018. These samples were analyzed by the ND Department of Health for Group 2 complete mineral chemistry, Group 7 trace metals and Group 30 nutrients.

**Treatments and Replications**

Soil amendment rates were calculated to bring the SAR (SAR-final) numbers to an acceptable level of 3 in the first-foot. This was done by deducting three from the actual SAR numbers (SAR-initial). SAR-final values were converted into Exchangeable Sodium Percentage (ESP) by using the formula below:

ESP =

(Diagnosis and Improvement of Saline and Alkali Soils. USDA Salinity Laboratory Staff, Agriculture Handbook No. 60, 1954, Page-26).

ESP and cation exchange capacity (CEC) values of the 1st foot were used to calculate the milliequivalent of exchangeable Na/100 grams of soil by using the following formula:

(Diagnosis and Improvement of Saline and Alkali Soils, Agriculture Handbook No. 60, P-49 1954. United States Salinity Laboratory Staff).

The milliequivalent of exchangeable Na/100 grams of soil numbers were then multiplied by 1.7 to get tons of 100% pure gypsum/acre foot.

For each ton of 100% pure gypsum, 0.19 tons of 100% pure elemental sulfur were applied (Reclaiming Saline, Sodic, and Saline-Sodic Soils. University of California, ANR Publication 8519, August 2015). Considering the very low solubility of Versalime, for each ton of 100% pure gypsum, three tons of VersaLime were applied. Differences in amendment purities were compensated by using the following formula:

(Reclaiming Sodic and Saline/Sodic Soils. Drought Tips Number 92-33, University of California Cooperative Extension, 1993).

Following were the final treatments that were applied in three replications.

1. Control.
2. Full rate of 99.5% pure gypsum to lower soil SAR-final levels to 3.
3. Full rate of VersaLime (locally known as beetlime) to lower the soil SAR-final levels to 3.
4. Full rate of 90% pure elemental sulfur (S°) to lower the soil SAR-final levels to 3.

Details of amendment rates for each treatment and replication are in Table 1.

Table 1. Details of amendment rates for each treatment.

|  |  |  |  |
| --- | --- | --- | --- |
| **Treatments and** | **99.5% Gypsum** | **90% Elemental Sulfur** | **VersaLime** |
| **Replications** | **tons/plot** | **tons/plot** | **tons/plot** |
| R1T1 (101) | 0 | 0 | 0 |
| R1T2 (102) | 4.47 | 0 | 0 |
| R1T3 (103) | 0 | 0 | 8.74 |
| R1T4 (104) | 0 | 2.10 | 0 |
| R2T1 (201) | 0 | 0 | 0 |
| R2T2 (202) | 7.25 | 0 | 0 |
| R2T3 (203) | 0 | 0 | 30.45 |
| R2T4 (204) | 0 | 0.61 | 0 |
| R3T1 (301) | 0 | 0 | 0 |
| R3T2 (302) | 10.67 | 0 | 0 |
| R3T3 (303) | 0 | 0 | 22.93 |
| R3T4 (304) | 0 | 2.16 | 0 |
| Total | 22.40 | 4.87 | 62.14 |

Note:

* Gypsum and elemental sulfur were applied on June 29th, 2015, whereas, VersaLime was applied on July 23rd, 2015. After spreading, all of the amendments were rototilled into the soil. Control plots were also rototilled for uniformity purposes.
* Control structures for all of the treatments were fully opened right after the incorporation of the amendments in order to simulate free drainage and achieve maximum leaching conditions.
* Right after applying soil amendments, an equal mix of Tall, Slender, Intermediate and Green wheatgrasses and Russian Wildrye were hand broadcasted and harrowed in on August 28th, 2015 at the rate of 7 lbs/acre on all treatments. That was done to minimize the evapotranspiration. This perennial vegetative cover has been mowed since 2016.

**RESULTS AND DISCUSSION**

The findings below are based on the statistical analysis of the 2014, 2016, 2017 and 2018 soil chemical properties, 2015, 2016, 2017 and 2018 soil physical properties and 2016, 2017 and 2018 groundwater depths. That was done to compare the differences in soil chemical and physical properties due to the effects of treatments (soil amendments) and average annual growing-season groundwater depths combined with soil amendments by using SAS package 9.4 at 95% confidence interval. The treatment means of EC, SAR, pH, NO3-N, saturation, CCE, HCO3-, Cl-, SO42-, Ca2+, Mg2+, Na+, and K+ represent annual results of three replications for the zero to four-foot depths. The treatment means of P and O.M. represent annual results of three replications for zero to two-foot depths, whereas, the treatment means of CEC represent annual results of three replications for zero to one-foot depths. The treatment means of soil bulk density represent annual results of three replications for zero to ten-inch depths. The treatment means of soil penetrometer resistance represent annual results of three replications for zero to eighteen-inch depths. The treatment means of groundwater depths represent annual results of three replications measured for zero to seven and a half-foot depths.

**Soil Chemical Analysis Results at the Time of Tiling (2014)**

At the time of tiling, all plots had moderately high EC levels with control plots having the lowest levels (mean = 7.39 dS/m) and gypsum plots having the highest levels (mean = 9.58 dS/m). The soil SAR levels in all of the plots were high to very high with control plots having the lowest levels (mean = 12.58) and gypsum plots having the highest levels (mean = 18.36). Soil pH of all plots were close to neutral. Soil NO3--N and P levels were medium, whereas O.M. levels were moderately high in all plots. Soil CEC and saturation % were in the higher range in all plots. In terms anions, SO42- levels were very high followed by HCO3- and Cl-. The CCE levels also remained high. For major cations, Na+ levels remained the highest followed by Ca2+, Mg2+ and K+. Details are in Table 2.

Table 2. The Treatment means of the Soil Chemical Analysis at the time of Tiling (2014).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Soil Property** | **2014 Treatment Means** | | | |
| Control | Gypsum | VersaLime | E-Sulfur |
| EC (dS/m) | 7.39 | 9.58 | 9.19 | 8.91 |
| SAR | 12.58 | 18.36 | 16.33 | 16.58 |
| pH | 7.05 | 7.04 | 7.14 | 6.94 |
| NO3--N (pounds/acre) | 33.16 | 33.83 | 26.00 | 34.66 |
| P (ppm) | 13.50 | 12.33 | 14.00 | 13.50 |
| O.M. (%) | 3.61 | 3.73 | 3.55 | 3.25 |
| CEC (meq/100 g of soil) | 42.70 | 47.20 | 44.93 | 39.96 |
| Saturation (%) | 69.41 | 79.77 | 80.26 | 69.90 |
| CCE (%) | 7.25 | 8.90 | 9.35 | 9.75 |
| HCO3- (mg/L) | 105.97 | 110.64 | 104.44 | 103.93 |
| Cl- (mg/L) | 123.30 | 88.71 | 89.62 | 67.76 |
| SO42- (mg/L) | 4398.51 | 5439.34 | 5476.92 | 5622.24 |
| Ca2+ (mg/L) | 508.58 | 422.41 | 529.08 | 578.25 |
| Mg2+ (mg/L) | 189.25 | 215.08 | 218.91 | 209.33 |
| Na+ (mg/L) | 1280.00 | 1807.50 | 1694.16 | 1710.83 |
| K+ (mg/L) | 6.75 | 6.83 | 6.75 | 7.16 |

**Effect of Soil Amendments on Soil Chemical Properties**

**Differences in Soil EC Levels**

Statistically, there were significant differences in the soil EC levels in years, treatments and replications (Table 3).

Table 3. Statistical Differences in Soil EC (dS/m) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 202.87 | <.0001 |
| Treatments | 43.48 | <.0001 |
| Replications | 40.91 | <.0001 |
| Soil Depths | 8.50 | 0.1584 |
| Years vs Treatments | 1.11 | 0.9799 |
| Treatments vs Soil Depths | 2.27 | 0.8924 |
| Years vs Treatments vs Soil Depths | 1.12 | 1.0000 |

The 2016, 2017 and 2018 soil EC levels were significantly lower than 2014. However, EC levels increased in 2017 and 2018 significantly compared to 2016 due to drier weather and resulting capillary rise (wicking up) of soil water. In addition, soil EC levels of gypsum, E-Sulfur (elemental sulfur) and VersaLime treatments were significantly higher than the control treatments. There were no significant differences among the rest of the treatments. There were significant EC differences among replications as well. Replication 2 EC levels were significantly higher than replication 1 and replication 3. In addition, replication 1 EC levels were significantly higher than replication 3. In terms of subsurface salinity, EC levels in the 12-24 inch depths remained significantly higher than the EC levels in 36-48 inch depths. Overall, highest EC levels were measured in 12-24 inch depths, followed by 24-36 inch, 0-12 inch and 36-48 inch depths. Details are in Table 4.

Table 4. Soil EC (dS/m) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 8.77 |
| 2016 | 3.75 |
| 2017 | 6.59 |
| 2018 | 6.24 |
| Treatment Means | |
| Control | 4.92 |
| E-Sulfur | 6.74 |
| Gypsum | 6.77 |
| VersaLime | 6.93 |
| Replication Means | |
| Replication 1 (SE) | 6.33 |
| Replication 2 (NE) | 7.14 |
| Replication 3 (NW) | 5.54 |
| Means for Soil Depths | |
| 0-12 inch | 6.17 |
| 12-24 inch | 6.85 |
| 24-36 inch | 6.46 |
| 36-48 inch | 5.87 |

Based on the differences in the annual means of soil EC levels (Table 5), in 2016, EC levels dropped significantly compared to 2014 despite higher rainfall and shallower average annual growing-season groundwater depths. That could be attributed to improved drainage due to tiling under excess soil moisture. In 2017, EC levels remained lower than 2014, however, compared to 2016, EC levels increased despite lower average annual growing-season groundwater depths due to drier weather. That could be attributed to the increased capillary rise of soil water due to increased evapotranspiration. In 2018, EC levels remained similar to 2017.

Table 5. Annual Differences in the Means of Soil EC (dS/m) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 2.59 | 4.39 | 3.98 | 4.03 |
| 2014 | 7.39 | 8.91 | 9.58 | 9.19 |
| Difference | -4.80 | -4.52 | -5.60 | -5.16 |
| 2017 | 4.81 | 7.17 | 7.01 | 7.37 |
| 2014 | 7.39 | 8.91 | 9.58 | 9.19 |
| Difference | -2.58 | -1.74 | -2.57 | -1.82 |
| 2018 | 4.86 | 6.47 | 6.52 | 7.11 |
| 2014 | 7.39 | 8.91 | 9.58 | 9.19 |
| Difference | -2.53 | -2.44 | -3.06 | -2.08 |
| 2017 | 4.81 | 7.17 | 7.01 | 7.37 |
| 2016 | 2.59 | 4.39 | 3.98 | 4.03 |
| Difference | 2.22 | 2.78 | 3.03 | 3.34 |
| 2018 | 4.86 | 6.47 | 6.52 | 7.11 |
| 2016 | 2.59 | 4.39 | 3.98 | 4.03 |
| Difference | 2.27 | 2.08 | 2.54 | 3.08 |
| 2018 | 4.86 | 6.47 | 6.52 | 7.11 |
| 2017 | 4.81 | 7.17 | 7.01 | 7.37 |
| Difference | 0.05 | -0.70 | -0.49 | -0.26 |

The chart below (Figure 3) has the annual soil EC means for the four treatments.

Figure 3. Annual Means of Soil EC (dS/m) Levels for all Four Treatments.

**Differences in Soil SAR Levels**

Statistically, there were significant differences in the soil SAR (sodicity) levels in years, treatments and soil depths (Table 6).

Table 6. Statistical Differences in Soil SAR Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 119.38 | 0.0147 |
| Treatments | 370.94 | <.0001 |
| Replications | 9.23 | 0.7573 |
| Soil Depths | 456.08 | <.0001 |
| Years vs Treatments | 39.54 | 0.3023 |
| Treatments vs Soil Depths | 20.54 | 0.6901 |
| Years vs Treatments vs Soil Depths | 17.13 | 0.9611 |

In 2018, soil SAR levels increased significantly versus rest of the years. The soil SAR levels of control treatments remained significantly lower than the rest of the treatments. In addition, SAR levels in the gypsum treatments remained significantly higher than the rest of the treatments. The 0-12 and 12-24 inch soil depths had significantly lower SAR levels than the 24-36 and 36-48 inch depths. Overall, soil SAR levels increased with soil depths. Details are in Table 7. There were no significant differences between the three replications.

Table 7. Soil SAR Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 15.96 |
| 2016 | 16.45 |
| 2017 | 15.15 |
| 2018 | 18.82 |
| Treatment Means | |
| Control | 13.00 |
| E-Sulfur | 16.88 |
| Gypsum | 19.79 |
| VersaLime | 16.72 |
| Replication Means | |
| Replication 1 (SE) | 16.64 |
| Replication 2 (NE) | 16.20 |
| Replication 3 (NW) | 16.96 |
| Means for Soil Depths | |
| 0-12 inch | 13.69 |
| 12-24 inch | 14.78 |
| 24-36 inch | 17.28 |
| 36-48 inch | 20.63 |

Based on the differences in the annual means of soil SAR levels (Table 8), in 2018 SAR levels increased in all treatments, notably in control versus 2014, 2016 and 2017. Whereas, in 2016 and 2017, SAR levels fluctuated irrespective of the treatments.

Table 8. Annual Differences in the Means of Soil SAR (sodicity) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 10.72 | 18.26 | 21.51 | 15.32 |
| 2014 | 12.58 | 16.58 | 18.36 | 16.33 |
| Difference | -1.86 | 1.68 | 3.15 | -1.01 |
| 2017 | 10.77 | 14.71 | 17.64 | 17.48 |
| 2014 | 12.58 | 16.58 | 18.36 | 16.33 |
| Difference | -1.81 | -1.87 | -0.72 | 1.15 |
| 2018 | 17.95 | 17.95 | 21.64 | 17.75 |
| 2014 | 12.58 | 16.58 | 18.36 | 16.33 |
| Difference | 5.37 | 1.37 | 3.28 | 1.42 |
| 2017 | 10.77 | 14.71 | 17.64 | 17.48 |
| 2016 | 10.72 | 18.26 | 21.51 | 15.32 |
| Difference | 0.05 | -3.55 | -3.87 | 2.16 |
| 2018 | 17.95 | 17.95 | 21.64 | 17.75 |
| 2016 | 10.72 | 18.26 | 21.51 | 15.32 |
| Difference | 7.23 | -0.31 | 0.13 | 2.43 |
| 2018 | 17.95 | 17.95 | 21.64 | 17.75 |
| 2017 | 10.77 | 14.71 | 17.64 | 17.48 |
| Difference | 7.18 | 3.24 | 4.00 | 0.27 |

The chart below (Figure 4) has the annual soil SAR means for the four treatments.

Figure 4. Annual Means of Soil SAR Levels for all Four Treatments.

**Differences in Soil pH Levels**

Statistically, there were significant differences in the soil pH levels (Table 9) in years. In addition, pH levels significantly differed for soil depths.

Table 9. Statistical Differences in Soil pH Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 9.82 | <.0001 |
| Treatments | 0.07 | 0.4395 |
| Replications | 0.14 | 0.1987 |
| Soil Depths | 1.65 | <.0001 |
| Years vs Treatments | 0.03 | 0.9327 |
| Treatments vs Soil Depths | 0.04 | 0.6892 |
| Years vs Treatments vs Soil Depths | 0.03 | 0.9809 |

The 2016, 2017 and 2018 soil pH levels were significantly higher than the pH levels in 2014. However, there were no significant differences in soil pH during 2016, 2017 and 2018. The lower soil pH levels in 2014 can be attributed to the lower soil moisture levels at the time of sampling (September 2014) compared to the rest of the years. There were no significant differences in soil pH among the four treatments. In addition, there were no significant differences in soil pH between replications. Soil pH in the 36-48 inch depth remained significantly higher than the 0-12 and 12-24 inch depths. Overall, soil pH levels increased with soil depths due to the increased soil moisture levels. Details are in Table 10.

Table 10. Annual Differences in Soil pH Levels.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 7.04 |
| 2016 | 7.90 |
| 2017 | 7.92 |
| 2018 | 8.01 |
| Treatment Means | |
| Control | 7.72 |
| E-Sulfur | 7.66 |
| Gypsum | 7.74 |
| VersaLime | 7.75 |
| Replication Means | |
| Replication 1 (SE) | 7.70 |
| Replication 2 (NE) | 7.68 |
| Replication 3 (NW) | 7.77 |
| Means for Soil Depths | |
| 0-12 inch | 7.48 |
| 12-24 inch | 7.67 |
| 24-36 inch | 7.81 |
| 36-48 inch | 7.91 |

Based on the differences in the annual means of soil pH (Table 11), 2014 pH levels were significantly lower than the rest of the years due to the lower soil moisture conditions at the time of sampling (September 2014). In 2016, 2017 and 2018, soil samples were collected in June when moisture levels were higher.

Table 11. Annual Differences in the Means of Soil pH Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 7.87 | 7.94 | 7.91 | 7.89 |
| 2014 | 7.05 | 6.94 | 7.04 | 7.14 |
| Difference | 0.82 | 1.00 | 0.87 | 0.75 |
| 2017 | 7.90 | 7.87 | 7.95 | 7.99 |
| 2014 | 7.05 | 6.94 | 7.04 | 7.14 |
| Difference | 0.85 | 0.93 | 0.91 | 0.85 |
| 2018 | 8.05 | 7.90 | 8.06 | 8.00 |
| 2014 | 7.05 | 6.94 | 7.04 | 7.14 |
| Difference | 1.00 | 0.96 | 1.02 | 0.86 |
| 2017 | 7.90 | 7.87 | 7.95 | 7.99 |
| 2016 | 7.87 | 7.94 | 7.91 | 7.89 |
| Difference | 0.03 | -0.07 | 0.04 | 0.10 |
| 2018 | 8.05 | 7.90 | 8.06 | 8.00 |
| 2016 | 7.87 | 7.94 | 7.91 | 7.89 |
| Difference | 0.18 | -0.04 | 0.15 | 0.11 |
| 2018 | 8.05 | 7.90 | 8.06 | 8.00 |
| 2017 | 7.90 | 7.87 | 7.95 | 7.99 |
| Difference | 0.15 | 0.03 | 0.11 | 0.01 |

The chart below has the annual soil pH means for the four treatments (Figure 5).

Figure 5. Annual Means of Soil pH Levels for all Four Treatments.

**Differences in Soil NO3--N Levels**

Statistically, there were significant differences in the soil NO3--N levels in years, soil depths and year vs treatment vs soil depths (Table 12).

Table 12. Statistical Differences in Soil NO3--N (pounds/acre) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 8157.07 | <.0001 |
| Treatments | 211.18 | 0.7452 |
| Replications | 360.06 | 0.4975 |
| Soil Depths | 7082.68 | <.0001 |
| Years vs Treatments | 135.44 | 0.9834 |
| Treatments vs Soil Depths | 81.35 | 0.8698 |
| Years vs Treatments vs Soil Depths | 1306.76 | <.0001 |

The 2014 soil NO3--N levels were significantly higher than the NO3--N levels in 2016, 2017 and 2018. Since 2016, soil NO3--N levels decreased steadily with time, however, there were no significant differences between 2016, 2017 and 2018. Highest decrease in NO3--N levels was observed in 2016 versus 2014. That could be due to excessive leaching under wet weather and improved drainage conditions. Prior to tiling, the site received annual fertilization at the time of seeding. After tiling (since 2014), no fertilizer has been applied to the site. There were no significant annual differences in NO3--N levels among treatments.

Replication 2 had significantly higher NO3--N levels versus replication 1. There were no significant differences between replication 1 versus replication 3 and replication 2 versus replication 3. The 0-12 inch soil depth had significantly higher NO3--N levels versus rest of the depths and 12-24 inch depth had significantly higher NO3--N levels than 24-36 and 36-48 inch depths. There were no significant differences between 24-36 inch and 36-48 inch depths. Highest decrease in NO3--N levels was observed in 12-24 inch depth versus 0-12 inch depth. Details are in Table 13.

Table 13. Soil NO3--N (pounds/acre) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 31.91 |
| 2016 | 12.00 |
| 2017 | 6.87 |
| 2018 | 2.33 |
| Treatment Means | |
| Control | 13.83 |
| E-Sulfur | 15.50 |
| Gypsum | 13.33 |
| VersaLime | 10.45 |
| Replication Means | |
| Replication 1 (SE) | 10.78 |
| Replication 2 (NE) | 15.50 |
| Replication 3 (NW) | 13.56 |
| Means for Soil Depths | |
| 0-12 inch | 30.95 |
| 12-24 inch | 11.45 |
| 24-36 inch | 6.12 |
| 36-48 inch | 4.58 |

Based on the differences in the annual means of soil NO3--N (pounds/acre) levels (Table 14), in 2016, 2017 and 2018 NO3--N levels decreased significantly compared to 2014. In 2017 and 2018, NO3--N decreased further and remained lower than the levels in 2016.

Table 14. Annual Differences in the Means of Soil NO3--N (pounds/acre) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 11.50 | 20.00 | 10.50 | 6.00 |
| 2014 | 33.16 | 34.66 | 33.83 | 26.00 |
| Difference | -21.66 | -14.66 | -23.33 | -20.00 |
| 2017 | 7.83 | 5.33 | 6.83 | 7.50 |
| 2014 | 33.16 | 34.66 | 33.83 | 26.00 |
| Difference | -25.33 | -29.33 | -27.00 | -18.50 |
| 2018 | 2.83 | 2.00 | 2.16 | 2.33 |
| 2014 | 33.16 | 34.66 | 33.83 | 26.00 |
| Difference | -30.33 | -32.66 | -31.67 | -23.67 |
| 2017 | 7.83 | 5.33 | 6.83 | 7.50 |
| 2016 | 11.50 | 20.00 | 10.50 | 6.00 |
| Difference | -3.67 | -14.67 | -3.67 | 1.50 |
| 2018 | 2.83 | 2.00 | 2.16 | 2.33 |
| 2016 | 11.50 | 20.00 | 10.50 | 6.00 |
| Difference | -8.67 | -18.00 | -8.34 | -3.67 |
| 2018 | 2.83 | 2.00 | 2.16 | 2.33 |
| 2017 | 7.83 | 5.33 | 6.83 | 7.50 |
| Difference | -5.00 | -3.33 | -4.67 | -5.20 |

The chart below (Figure 6) has the annual soil NO3--N (pounds/acre) means for the four treatments.

Figure 6. Annual Means of Soil NO3--N (pounds/acre) Levels for all Four Treatments.

**Differences in Soil P Levels**

The only statistically significant differences observed in soil P levels were in soil depths (Table 15).

Table 15. Statistical Differences in Soil P (ppm) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 52.57 | 0.7441 |
| Treatments | 121.06 | 0.4202 |
| Replications | 200.27 | 0.2139 |
| Soil Depths | 5967.68 | <.0001 |
| Years vs Treatments | 32.10 | 0.9850 |
| Treatments vs Soil Depths | 31.73 | 0.5350 |
| Years vs Treatments vs Soil Depths | 85.92 | 0.0403 |

There were no statistically significant differences in soil P levels in 2016, 2017 and 2018 versus 2014. However, soil P levels numerically decreased steadily with time. That again could be due to no fertilizer application since 2014. Before 2014, site was planted with annual crops and commercial fertilizer was applied annually. In addition, drier weather in 2017 and 2018 probably resulted in limited P solubility and mobility. There were no significant differences between treatments and replications. However, the 0-12 inch soil depths had significantly higher P levels versus 12-24 inch depths. Details are in Table 16.

Table 16. Soil P (ppm) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 13.33 |
| 2016 | 12.28 |
| 2017 | 10.70 |
| 2018 | 10.08 |
| Treatment Means | |
| Control | 11.41 |
| E-Sulfur | 10.20 |
| Gypsum | 9.95 |
| VersaLime | 14.83 |
| Replication Means | |
| Replication 1 (SE) | 9.01 |
| Replication 2 (NE) | 11.12 |
| Replication 3 (NW) | 14.30 |
| Means for Soil Depths | |
| 0-12 inch | 19.37 |
| 12-24 inch | 3.60 |

Based on the differences in the annual means of soil P (ppm) levels (Table 17), there were no significant differences in 2016, 2017 and 2018 versus 2014. However, a steady decrease in soil P levels was observed with time.

Table 17. Annual Differences in the Means of Soil P (ppm) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 12.83 | 10.00 | 6.98 | 19.33 |
| 2014 | 13.50 | 13.50 | 12.33 | 14.00 |
| Difference | -0.67 | -3.50 | -5.35 | 5.33 |
| 2017 | 9.00 | 9.50 | 11.16 | 13.16 |
| 2014 | 13.50 | 13.50 | 12.33 | 14.00 |
| Difference | -4.50 | -4.00 | -1.17 | -0.84 |
| 2018 | 10.33 | 7.83 | 9.33 | 12.83 |
| 2014 | 13.50 | 13.50 | 12.33 | 14.00 |
| Difference | -3.17 | -5.67 | -3.00 | -1.17 |
| 2017 | 9.00 | 9.50 | 11.16 | 13.16 |
| 2016 | 12.83 | 10.00 | 6.98 | 19.33 |
| Difference | -3.83 | -0.50 | 4.18 | -6.17 |
| 2018 | 10.33 | 7.83 | 9.33 | 12.83 |
| 2016 | 12.83 | 10.00 | 6.98 | 19.33 |
| Difference | -2.50 | -2.17 | 2.35 | -6.50 |
| 2018 | 10.33 | 7.83 | 9.33 | 12.83 |
| 2017 | 9.00 | 9.50 | 11.16 | 13.16 |
| Difference | 1.33 | -1.67 | -1.83 | -0.33 |

The chart below (Figure 7) has the annual soil P (ppm) means for the four treatments.

Figure 7. Annual Means of Soil P (ppm) Levels for all Four Treatments.

**Differences in Soil O.M. Levels**

Statistically, there were significant differences in the O.M. levels in years and soil depths (Table 18).

Table 18. Statistical Differences in Soil O.M. (%) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 11.12 | <.0001 |
| Treatments | 0.12 | 0.9616 |
| Replications | 2.10 | 0.2089 |
| Soil Depths | 77.94 | <.0001 |
| Years vs Treatments | 0.21 | 0.9970 |
| Treatments vs Soil Depths | 0.15 | 0.6629 |
| Years vs Treatments vs Soil Depths | 0.49 | 0.0821 |

The 2017 soil O.M. levels were significantly lower than the O.M. levels in 2014, 2016 and 2018. That could be due to a slightly drier June 2017 when soil samples were collected. In June 2017, Langdon North Dakota Agricultural Weather Network (NDAWN) recorded 2.94 inches of rain, whereas in June 2014, June 2016 and June 2018, NDAWN recorded 3.20 inches, 3.97 inches and 3.38 inches of rain respectively. Also, higher O.M. levels in 2018 versus 2017 could be due to the establishment of the perennial salt-tolerant grass mix planted in 2015 and mowed since 2016. Replication 1 had numerically higher O.M. levels versus replication 2 and replication 3. Being the least saline-sodic replication, replication 1 has produced more biomass than replication 2 and 3. That could be the reason for the higher O.M. levels. In addition, 0-12 inch soil depths had significantly higher O.M. levels than 12-24 inch depths. There were no significant different in O.M. levels among the treatments. Details are in Table 19.

Table 19. Soil O.M. (%) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 3.53 |
| 2016 | 3.76 |
| 2017 | 2.30 |
| 2018 | 3.64 |
| Treatment Means | |
| Control | 3.36 |
| E-Sulfur | 3.33 |
| Gypsum | 3.33 |
| VersaLime | 3.20 |
| Replication Means | |
| Replication 1 (SE) | 3.58 |
| Replication 2 (NE) | 3.30 |
| Replication 3 (NW) | 3.05 |
| Means for Soil Depths | |
| 0-12 inch | 4.21 |
| 12-24 inch | 2.41 |

Based on the differences in the annual means of soil O.M. (%) levels (Table 20), 2017 levels were significantly lower than 2014, 2016 and 2018. Again, that could be due to a slightly drier June-2017 when soil samples were collected compared to June 2014, June 2016 and June 2018.

Table 20. Annual Differences in the Means of Soil O.M. (%) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 3.90 | 3.90 | 3.88 | 3.38 |
| 2014 | 3.61 | 3.25 | 3.73 | 3.55 |
| Difference | 0.29 | 0.65 | 0.15 | -0.17 |
| 2017 | 2.33 | 2.45 | 2.18 | 2.23 |
| 2014 | 3.61 | 3.25 | 3.73 | 3.55 |
| Difference | -1.28 | -0.80 | -1.55 | -1.32 |
| 2018 | 3.61 | 3.75 | 3.55 | 3.65 |
| 2014 | 3.61 | 3.25 | 3.73 | 3.55 |
| Difference | -1.57 | 0.50 | -0.18 | 0.10 |
| 2017 | 2.33 | 2.45 | 2.18 | 2.23 |
| 2016 | 3.90 | 3.90 | 3.88 | 3.38 |
| Difference | -1.57 | -1.45 | -1.70 | -1.15 |
| 2018 | 3.61 | 3.75 | 3.55 | 3.65 |
| 2016 | 3.90 | 3.90 | 3.88 | 3.38 |
| Difference | -0.29 | -0.15 | -0.33 | 0.27 |
| 2018 | 3.61 | 3.75 | 3.55 | 3.65 |
| 2017 | 2.33 | 2.45 | 2.18 | 2.23 |
| Difference | 1.28 | 1.30 | 1.37 | 1.42 |

The chart below (Figure 8) has the annual soil O.M. (%) means for the four treatments.

Figure 8. Annual Means of Soil O.M. (%) Levels for all Four Treatments.

**Differences in Soil CEC Levels**

Statistically, there were no significant differences in soil CEC levels in years, treatments, replications and year vs treatment (Table 21).

Table 21. Statistical Differences in Soil CEC (meq/100 g of soil) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 135.25 | 0.0748 |
| Treatments | 23.54 | 0.7241 |
| Replications | 172.85 | 0.0527 |
| Years vs Treatments | 34.14 | 0.7522 |

There were no significant differences between CEC levels between years, treatments, replications and 0-12 inch soil depth. Details are in Table 22.

Table 22. Soil CEC (meq/100 g of soil) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 43.70 |
| 2016 | 36.95 |
| 2017 | 36.28 |
| 2018 | 38.49 |
| Treatment Means | |
| Control | 37.25 |
| E-Sulfur | 39.74 |
| Gypsum | 40.28 |
| VersaLime | 38.14 |
| Replication Means | |
| Replication 1 (SE) | 35.80 |
| Replication 2 (NE) | 40.67 |
| Replication 3 (NW) | 40.83 |
| Means for Soil Depths | |
| 0-12 inch | 39.10 |

Based on the differences in the annual means of soil CEC (meq/100 g of soil) levels (Table 23), there were no statistically significant differences.

Table 23. Annual Differences in the Means of Soil CEC (meq/100 g of soil) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 33.40 | 42.83 | 38.06 | 33.53 |
| 2014 | 42.70 | 39.96 | 47.20 | 44.93 |
| Difference | -9.30 | 2.87 | -9.14 | -11.40 |
| 2017 | 36.93 | 33.83 | 38.90 | 35.46 |
| 2014 | 42.70 | 39.96 | 47.20 | 44.93 |
| Difference | -5.77 | -6.13 | -8.30 | -9.47 |
| 2018 | 36.00 | 42.32 | 36.99 | 38.66 |
| 2014 | 42.70 | 39.96 | 47.20 | 44.93 |
| Difference | -6.70 | 2.36 | -10.21 | -6.27 |
| 2017 | 36.93 | 33.83 | 38.90 | 35.46 |
| 2016 | 33.40 | 42.83 | 38.06 | 33.53 |
| Difference | 3.53 | -9.00 | 0.84 | 1.93 |
| 2018 | 36.00 | 42.32 | 36.99 | 38.66 |
| 2016 | 33.40 | 42.83 | 38.06 | 33.53 |
| Difference | 2.60 | -0.51 | -1.07 | 5.13 |
| 2018 | 36.00 | 42.32 | 36.99 | 38.66 |
| 2017 | 36.93 | 33.83 | 38.90 | 35.46 |
| Difference | -0.93 | 8.49 | -1.91 | 3.20 |

The chart below (Figure 9) has the annual soil CEC (meq/100 g of soil) means for the four treatments.

Figure 9. Annual Means of Soil CEC (meq/100 g of soil) Levels for all Four Treatments.

**Differences in Soil Saturation Levels**

Statistically, there were significant differences in the soil saturation levels in years, treatments, replications and treatment vs soil depths (Table 24).

Table 24. Statistical Differences in Soil Saturation (%) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 289.10 | 0.0050 |
| Treatments | 893.01 | <.0001 |
| Replications | 253.80 | 0.0222 |
| Soil Depths | 71.97 | 0.3073 |
| Years vs Treatments | 87.89 | 0.2152 |
| Treatments vs Soil Depths | 153.26 | 0.0091 |
| Years vs Treatments vs Soil Depths | 63.29 | 0.3835 |

The 2018 soil saturation levels were significantly higher than 2014, 2016 and 2017. The gypsum and VersaLime treatments had significantly higher saturation levels versus control and E-sulfur treatments. Replication 2 had significantly lower saturation levels than replication 3. There were no significant differences between soil depths. Details are in Table 25.

Table 25. Soil Saturation (%) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 74.84 |
| 2016 | 74.00 |
| 2017 | 75.40 |
| 2018 | 79.52 |
| Treatment Means | |
| Control | 71.73 |
| E-Sulfur | 73.04 |
| Gypsum | 80.98 |
| VersaLime | 78.00 |
| Replication Means | |
| Replication 1 (SE) | 75.81 |
| Replication 2 (NE) | 74.01 |
| Replication 3 (NW) | 77.99 |
| Means for Soil Depths | |
| 0-12 inch | 75.05 |
| 12-24 inch | 75.80 |
| 24-36 inch | 77.71 |
| 36-48 inch | 75.19 |

Based on the differences in the annual means of soil saturation (%) levels (Table 26), 2018 soil saturation levels were significantly higher than 2014, 2016 and 2017.

Table 26. Annual Differences in the Means of Soil Saturation (%) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 69.81 | 75.01 | 76.09 | 75.08 |
| 2014 | 69.41 | 69.90 | 79.77 | 80.26 |
| Difference | 0.40 | 5.11 | -3.68 | -5.18 |
| 2017 | 73.30 | 70.22 | 80.70 | 77.39 |
| 2014 | 69.41 | 69.90 | 79.77 | 80.26 |
| Difference | 3.89 | 0.32 | 0.93 | -2.87 |
| 2018 | 74.40 | 77.03 | 87.37 | 79.27 |
| 2014 | 69.41 | 69.90 | 79.77 | 80.26 |
| Difference | 4.99 | 7.13 | 7.60 | -0.99 |
| 2017 | 73.30 | 70.22 | 80.70 | 77.39 |
| 2016 | 69.81 | 75.01 | 76.09 | 75.08 |
| Difference | 3.49 | -4.79 | 4.61 | 2.31 |
| 2018 | 74.40 | 77.03 | 87.37 | 79.27 |
| 2016 | 69.81 | 75.01 | 76.09 | 75.08 |
| Difference | 4.59 | 2.02 | 11.28 | 4.19 |
| 2018 | 74.40 | 77.03 | 87.37 | 79.27 |
| 2017 | 73.30 | 70.22 | 80.70 | 77.39 |
| Difference | 1.10 | 6.81 | 6.67 | 1.38 |

The chart below (Figure 10) has the annual soil saturation (%) means for the four treatments.

Figure 10. Annual Means of Soil Saturation (%) Levels for all Four Treatments.

**Differences in Soil CCE Levels**

Statistically, there were significant differences in the soil CCE levels in soil depths (Table 27).

Table 27. Statistical Differences in Soil CCE (%) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 4.51 | 0.9375 |
| Treatments | 6.82 | 0.8907 |
| Replications | 62.39 | 0.1523 |
| Soil Depths | 1335.40 | <.0001 |
| Years vs Treatments | 14.62 | 0.9083 |
| Treatments vs Soil Depths | 17.22 | 0.0931 |
| Years vs Treatments vs Soil Depths | 7.70 | 0.8222 |

The 0-12 inch soil depths had significantly lower CCE levels compared to rest of the depths, whereas 24-36 inch depths had the highest CCE levels versus the rest of the depths. There were no significant differences in CCE levels between years, treatments and replications. Details are in Table 28.

Table 28. Soil CCE (%) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 8.81 |
| 2016 | 8.87 |
| 2017 | 9.41 |
| 2018 | 9.32 |
| Treatment Means | |
| Control | 8.99 |
| E-Sulfur | 9.66 |
| Gypsum | 8.95 |
| VersaLime | 8.82 |
| Replication Means | |
| Replication 1 (SE) | 8.00 |
| Replication 2 (NE) | 9.90 |
| Replication 3 (NW) | 9.42 |
| Means for Soil Depths | |
| 0-12 inch | 1.62 |
| 12-24 inch | 9.84 |
| 24-36 inch | 13.92 |
| 36-48 inch | 11.03 |

Based on the differences in the annual means of soil CCE (%) levels (Table 29), there were no significant differences in 2016, 2017 and 2018 versus 2014.

Table 29. Annual Differences in the Means of Soil CCE (%) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 7.70 | 9.94 | 9.01 | 8.83 |
| 2014 | 7.25 | 9.75 | 8.90 | 9.35 |
| Difference | 0.45 | 0.19 | 0.11 | -0.52 |
| 2017 | 10.07 | 9.15 | 8.95 | 9.45 |
| 2014 | 7.25 | 9.75 | 8.90 | 9.35 |
| Difference | 2.82 | -0.60 | 0.05 | 0.10 |
| 2018 | 10.93 | 9.80 | 8.95 | 7.63 |
| 2014 | 7.25 | 9.75 | 8.90 | 9.35 |
| Difference | 3.68 | 0.05 | 0.05 | -1.72 |
| 2017 | 10.07 | 9.15 | 8.95 | 9.45 |
| 2016 | 7.70 | 9.94 | 9.01 | 8.83 |
| Difference | 2.37 | -0.79 | -0.06 | 0.62 |
| 2018 | 10.93 | 9.80 | 8.95 | 7.63 |
| 2016 | 7.70 | 9.94 | 9.01 | 8.83 |
| Difference | 3.23 | -0.14 | -0.06 | -1.20 |
| 2018 | 10.93 | 9.80 | 8.95 | 7.63 |
| 2017 | 10.07 | 9.15 | 8.95 | 9.45 |
| Difference | 0.86 | 0.65 | 0.00 | -1.82 |

The chart below (Figure 11) has the annual soil CCE (%) means for the four treatments.

Figure 11. Annual Means of Soil CCE (%) Levels for all Four Treatments.

**Differences in Soil HCO3- Levels**

Statistically, there were significant differences in the HCO3- levels in years, soil depths and year vs treatment vs soil depths (Table 30).

Table 30. Statistical Differences in Soil HCO3- (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 9622.14 | 0.0063 |
| Treatments | 1029.74 | 0.7140 |
| Replications | 6349.98 | 0.0631 |
| Soil Depths | 59476.79 | <.0001 |
| Years vs Treatments | 1448.56 | 0.7614 |
| Treatments vs Soil Depths | 1003.73 | 0.5305 |
| Years vs Treatments vs Soil Depths | 1808.48 | 0.0278 |

The soil HCO3- levels in 2017 were significantly higher than rest of the years, whereas HCO3- levels in 2016 were significantly higher than the HCO3- levels in 2018. There were no significant differences in HCO3- levels among treatments. Replication 3 had significantly higher HCO3- levels than replication 2. The 0-12 inch soil depths had significantly higher HCO3- levels versus rest of the depths, whereas 36-48 inch depths had significantly higher HCO3- levels versus 24-36 inch depths. Details are in Table 31.

Table 31. Soil HCO3- (mg/L) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 106.25 |
| 2016 | 118.02 |
| 2017 | 134.14 |
| 2018 | 102.76 |
| Treatment Means | |
| Control | 120.56 |
| E-Sulfur | 113.21 |
| Gypsum | 117.38 |
| VersaLime | 110.01 |
| Replication Means | |
| Replication 1 (SE) | 114.20 |
| Replication 2 (NE) | 105.92 |
| Replication 3 (NW) | 125.75 |
| Means for Soil Depths | |
| 0-12 inch | 166.78 |
| 12-24 inch | 95.57 |
| 24-36 inch | 90.13 |
| 36-48 inch | 108.69 |

Based on the differences in the annual means of soil HCO3- (mg/L) levels (Table 32), 2017 levels were significantly higher than 2014, 2016 and 2018.

Table 32. Annual Differences in the Means of Soil HCO3- (mg/L) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 121.83 | 109.83 | 139.32 | 101.08 |
| 2014 | 105.97 | 103.93 | 110.64 | 104.44 |
| Difference | 15.86 | 5.90 | 28.68 | -3.36 |
| 2017 | 136.68 | 134.04 | 125.70 | 140.14 |
| 2014 | 105.97 | 103.93 | 110.64 | 104.44 |
| Difference | 30.71 | 30.11 | 15.06 | 35.70 |
| 2018 | 117.76 | 105.05 | 93.86 | 94.37 |
| 2014 | 105.97 | 103.93 | 110.64 | 104.44 |
| Difference | 11.79 | 1.12 | -16.78 | -10.07 |
| 2017 | 136.68 | 134.04 | 125.70 | 140.14 |
| 2016 | 121.83 | 109.83 | 139.32 | 101.08 |
| Difference | 14.85 | 24.21 | -13.62 | 39.06 |
| 2018 | 117.76 | 105.05 | 93.86 | 94.37 |
| 2016 | 121.83 | 109.83 | 139.32 | 101.08 |
| Difference | -4.07 | -4.78 | -45.46 | -6.71 |
| 2018 | 117.76 | 105.05 | 93.86 | 94.37 |
| 2017 | 136.68 | 134.04 | 125.70 | 140.14 |
| Difference | -18.92 | -28.99 | -31.84 | -45.77 |

The chart below (Figure 12) has the annual soil HCO3- (mg/L) means for the four treatments.

Figure 12. Annual Means of Soil HCO3- (mg/L) Levels for all Four Treatments.

**Differences in Soil Cl- Levels**

Statistically, there were significant differences in the Cl- levels in years and replications (Table 33).

Table 33. Statistical Differences in Soil Cl- (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 64879.15 | <.0001 |
| Treatments | 1902.21 | 0.8147 |
| Replications | 63809.07 | <.0001 |
| Soil Depths | 9345.18 | 0.1962 |
| Years vs Treatments | 4247.82 | 0.7058 |
| Treatments vs Soil Depths | 7435.87 | 0.2643 |
| Years vs Treatments vs Soil Depths | 5945.85 | 0.4673 |

The soil Cl- levels in 2018 were significantly higher than rest of the years. In addition, 2014 Cl- levels were significantly higher than the 2017 levels. There were no significant differences in Cl- levels among treatments. Replication 2 had significantly higher Cl- levels than replications 1 and 3, whereas, replication 3 had significantly higher Cl- levels than replication 1. There were no significant differences Cl- in levels between soil depths. Details are in Table 34.

Table 34. Soil Cl- (mg/L) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 92.35 |
| 2016 | 69.06 |
| 2017 | 48.56 |
| 2018 | 134.23 |
| Treatment Means | |
| Control | 95.13 |
| E-Sulfur | 81.50 |
| Gypsum | 82.13 |
| VersaLime | 85.44 |
| Replication Means | |
| Replication 1 (SE) | 55.74 |
| Replication 2 (NE) | 118.76 |
| Replication 3 (NW) | 83.67 |
| Means for Soil Depths | |
| 0-12 inch | 104.53 |
| 12-24 inch | 71.09 |
| 24-36 inch | 86.79 |
| 36-48 inch | 81.81 |

Based on the differences in the annual means of soil Cl- (mg/L) levels (Table 35), 2018 levels were significantly higher than 2014, 2016 and 2017. In addition, 2014 Cl- levels were significantly higher than the 2017 levels.

Table 35. Annual Differences in the Means of Soil Cl- (mg/L) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 54.71 | 66.04 | 71.18 | 84.31 |
| 2014 | 123.30 | 67.76 | 88.71 | 89.62 |
| Difference | -68.59 | -1.72 | -17.53 | -5.31 |
| 2017 | 38.32 | 54.59 | 49.22 | 52.12 |
| 2014 | 123.30 | 67.76 | 88.71 | 89.62 |
| Difference | -84.98 | -13.17 | -39.49 | -37.50 |
| 2018 | 164.19 | 137.60 | 119.41 | 115.72 |
| 2014 | 123.30 | 67.76 | 88.71 | 89.62 |
| Difference | 40.89 | 69.84 | 30.70 | 26.10 |
| 2017 | 38.32 | 54.59 | 49.22 | 52.12 |
| 2016 | 54.71 | 66.04 | 71.18 | 84.31 |
| Difference | -16.39 | -11.45 | -21.96 | -32.19 |
| 2018 | 164.19 | 137.60 | 119.41 | 115.72 |
| 2016 | 54.71 | 66.04 | 71.18 | 84.31 |
| Difference | 109.48 | 71.56 | 48.23 | 31.41 |
| 2018 | 164.19 | 137.60 | 119.41 | 115.72 |
| 2017 | 38.32 | 54.59 | 49.22 | 52.12 |
| Difference | 125.87 | 83.01 | 70.19 | 63.60 |

The chart below (Figure 13) has the annual soil Cl- (mg/L) means for the four treatments.

Figure 13. Annual Means of Soil Cl- (mg/L) Levels for all Four Treatments.

**Differences in Soil SO42- Levels**

Statistically, there were significant differences in the SO42- levels in years, treatments, replications and soil depths (Table 36).

Table 36. Statistical Differences in Soil SO42- (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 12615410.16 | 0.0058 |
| Treatments | 33086403.76 | <.0001 |
| Replications | 14568859.96 | 0.0079 |
| Soil Depths | 11878700.81 | 0.0186 |
| Years vs Treatments | 2097852.01 | 0.6934 |
| Treatments vs Soil Depths | 1104882.17 | 0.9668 |
| Years vs Treatments vs Soil Depths | 847169.54 | 1.0000 |

The soil SO42- levels in 2014 were significantly higher than the 2017 levels. Among treatments, control had significantly lower SO42- levels than rest of the treatments. Replication 2 had significantly higher SO42- levels than replication 3. The 12-24 inch soil depth had significantly higher SO42- levels the 36-48 inch depth. Details are in Table 37.

Table 37. Soil SO42- (mg/L) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 5234.25 |
| 2016 | 4555.01 |
| 2017 | 3985.67 |
| 2018 | 4688.05 |
| Treatment Means | |
| Control | 3380.48 |
| E-Sulfur | 5174.94 |
| Gypsum | 4933.83 |
| VersaLime | 4973.73 |
| Replication Means | |
| Replication 1 (SE) | 4613.70 |
| Replication 2 (NE) | 5093.90 |
| Replication 3 (NW) | 4139.70 |
| Means for Soil Depths | |
| 0-12 inch | 4667.30 |
| 12-24 inch | 5153.30 |
| 24-36 inch | 4693.60 |
| 36-48 inch | 3948.80 |

Based on the differences in the annual means of soil SO42- (mg/L) levels (Table 38), 2014 levels were significantly higher than the SO42- levels in 2017, whereas, numerically 2014 SO42- levels remained higher than the SO42- levels in rest of the years.

Table 38. Annual Differences in the Means of Soil SO42- (mg/L) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 2652.50 | 5677.07 | 5288.47 | 4602.01 |
| 2014 | 4398.51 | 5622.24 | 5439.34 | 5476.92 |
| Difference | -1746.01 | 54.83 | -150.87 | -874.91 |
| 2017 | 2807.04 | 4496.02 | 4184.71 | 4454.90 |
| 2014 | 4398.51 | 5622.24 | 5439.34 | 5476.92 |
| Difference | -1591.47 | -1126.22 | -1254.63 | -1022.02 |
| 2018 | 3663.89 | 4904.42 | 4822.79 | 5361.10 |
| 2014 | 4398.51 | 5622.24 | 5439.34 | 5476.92 |
| Difference | -734.62 | -717.82 | -616.55 | -115.82 |
| 2017 | 2807.04 | 4496.02 | 4184.71 | 4454.90 |
| 2016 | 2652.50 | 5677.07 | 5288.47 | 4602.01 |
| Difference | 154.54 | -1181.05 | -1103.76 | -147.11 |
| 2018 | 3663.89 | 4904.42 | 4822.79 | 5361.10 |
| 2016 | 2652.50 | 5677.07 | 5288.47 | 4602.01 |
| Difference | 1011.39 | -772.65 | -465.68 | 759.09 |
| 2018 | 3663.89 | 4904.42 | 4822.79 | 5361.10 |
| 2017 | 2807.04 | 4496.02 | 4184.71 | 4454.90 |
| Difference | 856.85 | 408.40 | 638.08 | 906.20 |

The chart below (Figure 14) has the annual soil SO42- (mg/L) means for the four treatments.

Figure 14. Annual Means of Soil SO42- (mg/L) Levels for all Four Treatments.

**Differences in Soil Ca2+ Levels**

Statistically, there were significant differences in the Ca2+ levels in years and soil depths (Table 39).

Table 39. Statistical Differences in Soil Ca2+ (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 511070.54 | <.0001 |
| Treatments | 71545.17 | 0.2252 |
| Replications | 81435.64 | 0.1912 |
| Soil Depths | 574732.83 | <.0001 |
| Years vs Treatments | 12618.05 | 0.9844 |
| Treatments vs Soil Depths | 19436.85 | 0.9183 |
| Years vs Treatments vs Soil Depths | 23772.25 | 0.9868 |

The soil Ca2+ levels in 2014 were significantly higher than rest of the years, whereas the Ca2+ levels in 2016 were significantly lower than rest of the years. There were no differences between treatments and replications. The lower soil Ca2+ levels in 2016 versus 2014 could be due to the leaching of Ca2+ under wet weather and improved drainage conditions (tiling). In addition, the gradual increase in Ca2+ levels in 2017 and 2018 could be due to the upward movement of Ca2+-based salts under drier weather and resulting capillary rise of soil water. The 12-24 inch soil depth had significantly higher Ca2+ levels than the 24-36 inch and 36-48 inch depths, whereas, 36-48 inch depths had significantly lower Ca2+ levels than rest of the treatments. Details are in Table 40.

Table 40. Soil Ca2+ (mg/L) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 509.58 |
| 2016 | 282.65 |
| 2017 | 311.24 |
| 2018 | 324.76 |
| Treatment Means | |
| Control | 321.26 |
| E-Sulfur | 402.83 |
| Gypsum | 329.20 |
| VersaLime | 374.93 |
| Replication Means | |
| Replication 1 (SE) | 316.98 |
| Replication 2 (NE) | 385.32 |
| Replication 3 (NW) | 368.89 |
| Means for Soil Depths | |
| 0-12 inch | 397.62 |
| 12-24 inch | 463.41 |
| 24-36 inch | 361.63 |
| 36-48 inch | 205.58 |

Based on the differences in the annual means of soil Ca2+ (mg/L) levels (Table 41), 2014 levels were significantly higher than rest of the years and the Ca2+ levels in 2016 were significantly lower than rest of the years.

Table 41. Annual Differences in the Means of Soil Ca2+ (mg/L) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 224.40 | 331.65 | 271.42 | 303.14 |
| 2014 | 508.58 | 578.25 | 422.41 | 529.08 |
| Difference | -284.18 | -246.60 | -150.99 | -225.94 |
| 2017 | 292.73 | 345.58 | 301.40 | 305.25 |
| 2014 | 508.58 | 578.25 | 422.41 | 529.08 |
| Difference | -215.85 | -232.67 | -121.01 | -223.83 |
| 2018 | 259.35 | 355.85 | 321.58 | 362.26 |
| 2014 | 508.58 | 578.25 | 422.41 | 529.08 |
| Difference | -249.23 | -222.40 | -100.83 | -166.82 |
| 2017 | 292.73 | 345.58 | 301.40 | 305.25 |
| 2016 | 224.40 | 331.65 | 271.42 | 303.14 |
| Difference | 68.33 | 13.93 | 29.98 | 2.11 |
| 2018 | 259.35 | 355.85 | 321.58 | 362.26 |
| 2016 | 224.40 | 331.65 | 271.42 | 303.14 |
| Difference | 34.95 | 24.20 | 50.16 | 59.12 |
| 2018 | 259.35 | 355.85 | 321.58 | 362.26 |
| 2017 | 292.73 | 345.58 | 301.40 | 305.25 |
| Difference | -33.38 | 10.27 | 20.18 | 57.01 |

The chart below (Figure 15) has the annual soil Ca2+ (mg/L) means for the four treatments.

Figure 15. Annual Means of Soil Ca2+ (mg/L) Levels for all Four Treatments.

**Differences in Soil Mg2+ Levels**

Statistically, there were significant differences in the Mg2+ levels in treatments, replications and soil depths (Table 42).

Table 42. Statistical Differences in Soil Mg2+ (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 16789.97 | 0.0968 |
| Treatments | 63790.30 | <.0001 |
| Replications | 123016.06 | <.0001 |
| Soil Depths | 89021.19 | <.0001 |
| Years vs Treatments | 8350.34 | 0.3911 |
| Treatments vs Soil Depths | 4627.46 | 0.7837 |
| Years vs Treatments vs Soil Depths | 2925.11 | 0.9992 |

There were no significant differences in the annual soil Mg2+ levels. Control treatment had the lowest Mg2+ levels versus rest of the treatments. Replication 2 had significantly higher Mg2+ levels, whereas, replication 3 had significantly lower Mg2+ levels. The 0-12 inch and 12-24 inch soil depths had significantly higher Mg2+ levels than the 24-36 inch and 36-48 inch soil depths. Overall, Mg2+ levels numerically decreased with increasing soil depths. Details are in Table 43.

Table 43. Soil Mg2+ (mg/L) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 208.14 |
| 2016 | 234.27 |
| 2017 | 189.00 |
| 2018 | 215.18 |
| Treatment Means | |
| Control | 160.08 |
| E-Sulfur | 237.07 |
| Gypsum | 211.69 |
| VersaLime | 237.76 |
| Replication Means | |
| Replication 1 (SE) | 208.65 |
| Replication 2 (NE) | 256.92 |
| Replication 3 (NW) | 169.39 |
| Means for Soil Depths | |
| 0-12 inch | 249.75 |
| 12-24 inch | 239.65 |
| 24-36 inch | 202.54 |
| 36-48 inch | 154.68 |

Based on the differences in the annual means of soil Mg2+ (mg/L) levels (Table 44), there were no significant differences the annual Mg2+ soil levels.

Table 44. Annual Differences in the Means of Soil Mg2+ (mg/L) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 148.00 | 285.17 | 245.41 | 258.50 |
| 2014 | 189.25 | 209.33 | 215.08 | 218.91 |
| Difference | -41.25 | 75.84 | 30.33 | 39.59 |
| 2017 | 145.61 | 230.34 | 182.51 | 197.56 |
| 2014 | 189.25 | 209.33 | 215.08 | 218.91 |
| Difference | -43.64 | 21.01 | -32.57 | -21.35 |
| 2018 | 157.48 | 223.43 | 203.75 | 276.08 |
| 2014 | 189.25 | 209.33 | 215.08 | 218.91 |
| Difference | -31.77 | 14.10 | -11.33 | 57.17 |
| 2017 | 145.61 | 230.34 | 182.51 | 197.56 |
| 2016 | 148.00 | 285.17 | 245.41 | 258.50 |
| Difference | -2.39 | -54.83 | -62.90 | -60.94 |
| 2018 | 157.48 | 223.43 | 203.75 | 276.08 |
| 2016 | 148.00 | 285.17 | 245.41 | 258.50 |
| Difference | 9.48 | -61.74 | -41.66 | 17.58 |
| 2018 | 157.48 | 223.43 | 203.75 | 276.08 |
| 2017 | 145.61 | 230.34 | 182.51 | 197.56 |
| Difference | 11.87 | -6.91 | 21.24 | 78.52 |

The chart below (Figure 16) has the annual soil Mg2+ (mg/L) means for the four treatments.

Figure 16. Annual Means of Soil Mg2+ (mg/L) Levels for all Four Treatments.

**Differences in Soil Na+ Levels**

Statistically, there were significant differences in the Na+ levels between years, treatments and replications (Table 45).

Table 45. Statistical Differences in Soil Na+ (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 1129023.18 | 0.0206 |
| Treatments | 4415560.48 | <.0001 |
| Replications | 1395717.73 | 0.0177 |
| Soil Depths | 205282.16 | 0.6931 |
| Years vs Treatments | 317068.99 | 0.4937 |
| Treatments vs Soil Depths | 155787.26 | 0.9482 |
| Years vs Treatments vs Soil Depths | 97565.73 | 1.0000 |

The 2017 Na+ levels were significantly lower than the Na+ levels in 2014 and 2018. Among treatments, control treatment had the lowest Na+ levels versus rest of the treatments. Replication 2 had significantly higher Na+ levels than replication 3. There were no significant differences in soil depths for Na+ levels. Details are in Table 46.

Table 46. Soil Na+ (mg/L) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 1623.12 |
| 2016 | 1498.06 |
| 2017 | 1269.81 |
| 2018 | 1555.85 |
| Treatment Means | |
| Control | 1034.35 |
| E-Sulfur | 1650.88 |
| Gypsum | 1668.68 |
| VersaLime | 1592.93 |
| Replication Means | |
| Replication 1 (SE) | 1521.80 |
| Replication 2 (NE) | 1613.70 |
| Replication 3 (NW) | 1324.70 |
| Means for Soil Depths | |
| 0-12 inch | 1419.50 |
| 12-24 inch | 1559.50 |
| 24-36 inch | 1522.60 |
| 36-48 inch | 1445.30 |

Based on the differences in the annual means of soil Na+ (mg/L) levels (Table 47), in 2017, Na+ levels were significantly lower than the Na+ levels in 2014 and 2018.

Table 47. Annual Differences in the Means of Soil Na+ (mg/L) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 810.15 | 1876.60 | 1850.75 | 1454.75 |
| 2014 | 1280.00 | 1710.83 | 1807.50 | 1694.16 |
| Difference | -469.85 | 165.77 | 43.50 | -239.41 |
| 2017 | 803.00 | 1399.75 | 1386.00 | 1490.50 |
| 2014 | 1280.00 | 1710.83 | 1807.50 | 1694.16 |
| Difference | -477.00 | -311.08 | -421.50 | -203.66 |
| 2018 | 1244.28 | 1616.35 | 1630.47 | 1732.31 |
| 2014 | 1280.00 | 1710.83 | 1807.50 | 1694.16 |
| Difference | -35.72 | -94.48 | -177.03 | 38.15 |
| 2017 | 803.00 | 1399.75 | 1386.00 | 1490.50 |
| 2016 | 810.15 | 1876.60 | 1850.75 | 1454.75 |
| Difference | -7.15 | -476.85 | -464.75 | 35.75 |
| 2018 | 1244.28 | 1616.35 | 1630.47 | 1732.31 |
| 2016 | 810.15 | 1876.60 | 1850.75 | 1454.75 |
| Difference | 434.13 | -260.25 | -220.28 | 277.56 |
| 2018 | 1244.28 | 1616.35 | 1630.47 | 1732.31 |
| 2017 | 803.00 | 1399.75 | 1386.00 | 1490.50 |
| Difference | 441.28 | 216.60 | 244.47 | 241.81 |

The chart below (Figure 17) has the annual soil Na+ (mg/L) means for the four treatments.

Figure 17. Annual Means of Soil Na+ (mg/L) Levels for all Four Treatments.

**Differences in Soil K+ Levels**

Statistically, there were significant differences in the K+ levels in years (Table 48).

Table 48. Statistical Differences in Soil K+ (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 31019.42 | 0.0001 |
| Treatments | 5121.91 | 0.3126 |
| Replications | 2777.52 | 0.5239 |
| Soil Depths | 4769.82 | 0.3406 |
| Years vs Treatments | 5051.13 | 0.3105 |
| Treatments vs Soil Depths | 4548.16 | 0.3858 |
| Years vs Treatments vs Soil Depths | 4346.34 | 0.4402 |

The 2018 K+ levels were significantly higher than the K+ levels in rest of the years. There were no significant differences in K+ levels in treatments, replications and soil depths. Details are in Table 49.

Table 49. Soil K+ (mg/L) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2014 | 6.87 |
| 2016 | 7.31 |
| 2017 | 9.42 |
| 2018 | 58.66 |
| Treatment Means | |
| Control | 33.56 |
| E-Sulfur | 19.11 |
| Gypsum | 21.21 |
| VersaLime | 8.37 |
| Replication Means | |
| Replication 1 (SE) | 13.08 |
| Replication 2 (NE) | 23.15 |
| Replication 3 (NW) | 25.47 |
| Means for Soil Depths | |
| 0-12 inch | 28.67 |
| 12-24 inch | 7.57 |
| 24-36 inch | 28.09 |
| 36-48 inch | 17.95 |

Based on the differences in the annual means of soil K+ (mg/L) levels (Table 50), in 2018, K+ levels were significantly higher than the K+ levels in 2014, 2016 and 2017.

Table 50. Annual Differences in the Means of Soil K+ (mg/L) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 6.59 | 8.95 | 6.52 | 7.18 |
| 2014 | 6.75 | 7.16 | 6.83 | 6.75 |
| Difference | -0.16 | 1.79 | -0.31 | 0.43 |
| 2017 | 9.84 | 10.54 | 9.25 | 8.05 |
| 2014 | 6.75 | 7.16 | 6.83 | 6.75 |
| Difference | 3.09 | 3.38 | 2.42 | 1.30 |
| 2018 | 111.08 | 49.79 | 62.25 | 11.52 |
| 2014 | 6.75 | 7.16 | 6.83 | 6.75 |
| Difference | 104.33 | 42.63 | 55.42 | 4.77 |
| 2017 | 9.84 | 10.54 | 9.25 | 8.05 |
| 2016 | 6.59 | 8.95 | 6.52 | 7.18 |
| Difference | 3.25 | 1.59 | 2.73 | 0.87 |
| 2018 | 111.08 | 49.79 | 62.25 | 11.52 |
| 2016 | 6.59 | 8.95 | 6.52 | 7.18 |
| Difference | 104.49 | 40.84 | 55.73 | 4.34 |
| 2018 | 111.08 | 49.79 | 62.25 | 11.52 |
| 2017 | 9.84 | 10.54 | 9.25 | 8.05 |
| Difference | 101.24 | 39.25 | 53.00 | 3.47 |

The chart below (Figure 18) has the annual soil K+ (mg/L) means for the four treatments.

Figure 18. Annual Means of Soil K+ (mg/L) Levels for all Four Treatments.

**Effect of Soil Amendments on Soil Physical Properties**

**Differences in Soil Bulk Density Levels**

Statistically, there were significant differences in the soil bulk density levels in years and soil depths (Table 51).

Table 51. Statistical Differences in Soil Bulk Density (g/cm3) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 0.86 | <.0001 |
| Treatments | 0.01 | 0.2691 |
| Replications | 0.01 | 0.1130 |
| Soil Depths | 0.06 | 0.0083 |
| Years vs Treatments | 0.01 | 0.0833 |
| Treatments vs Soil Depths | 0.01 | 0.2812 |
| Years vs Treatments vs Soil Depths | 0.00 | 0.9810 |

The 2015 soil bulk densitylevels were significantly lower than the bulk density levels in the rest of the years. The lower bulk density levels in 2015 are consistent with the significantly lower gravimetric and volumetric soil water contents in 2015 versus the rest of the years. In 2015, gravimetric water content was 0.28%, whereas, volumetric water content was 0.34%. The gravimetric and volumetric water contents were 0.33% and 0.53% in 2016, 0.29% and 0.48% in 2017 and 0.30% and 0.49% in 2018. In addition, bulk density levels in 2016 were significantly lower than the bulk density levels in 2017. The 0-5 inch soil depths had significantly lower bulk density levels than the 5-10 inch soil depths. There were no significant differences in bulk densitylevels in treatments, replications, year vs treatment, treatment vs soil depth and year vs treatment vs soil depths. Details are in Table 52.

Table 52. Soil Bulk Density (g/cm3) Level Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2015 | 1.23 |
| 2016 | 1.58 |
| 2017 | 1.64 |
| 2018 | 1.61 |
| Treatment Means | |
| Control | 1.48 |
| E-Sulfur | 1.53 |
| Gypsum | 1.51 |
| VersaLime | 1.52 |
| Replication Means | |
| Replication 1 (SE) | 1.49 |
| Replication 2 (NE) | 1.53 |
| Replication 3 (NW) | 1.53 |
| Means for Soil Depths | |
| 0-5 inch | 1.49 |
| 5-10 inch | 1.54 |

Based on the differences in the annual means of soil bulk density (g/cm3) levels (Table 53), in 2015, bulk densitylevels were significantly lower than the bulk density levels in 2016, 2017 and 2018. In addition, bulk density levels in 2016 were significantly lower than the bulk density levels in 2017.

Table 53. Annual Differences in the Means of Soil Bulk Density (g/cm3) Levels among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 1.52 | 1.57 | 1.58 | 1.64 |
| 2015 | 1.26 | 1.22 | 1.20 | 1.24 |
| Difference | 0.26 | 0.35 | 0.38 | 0.40 |
| 2017 | 1.57 | 1.73 | 1.68 | 1.58 |
| 2015 | 1.26 | 1.22 | 1.20 | 1.24 |
| Difference | 0.31 | 0.51 | 0.48 | 0.34 |
| 2018 | 1.58 | 1.62 | 1.59 | 1.63 |
| 2015 | 1.26 | 1.22 | 1.20 | 1.24 |
| Difference | 0.32 | 0.40 | 0.39 | 0.39 |
| 2017 | 1.57 | 1.73 | 1.68 | 1.58 |
| 2016 | 1.52 | 1.57 | 1.58 | 1.64 |
| Difference | 0.05 | 0.16 | 0.10 | -0.06 |
| 2018 | 1.58 | 1.62 | 1.59 | 1.63 |
| 2016 | 1.52 | 1.57 | 1.58 | 1.64 |
| Difference | 0.06 | 0.05 | 0.01 | -0.01 |
| 2018 | 1.58 | 1.62 | 1.59 | 1.63 |
| 2017 | 1.57 | 1.73 | 1.68 | 1.58 |
| Difference | 0.01 | -0.11 | -0.09 | 0.05 |

The chart below (Figure 19) has the annual soil Bulk Density (g/cm3) means for the four treatments.

Figure 19. Annual Means of Soil Bulk Density (g/cm3) Levels for all Four Treatments.

**Differences in Soil Penetrometer Meter Resistance Levels**

Statistically, there were significant differences in the soil penetrometer resistance levels measured in pounds of force per square inch (psi) in years (Table 54).

Table 54. Statistical Differences in Soil Penetrometer Resistance Levels (Psi).

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 5695615.57 | <.0001 |
| Treatments | 798.16 | 0.0504 |
| Replications | 477.41 | 0.1238 |
| Soil Depths | 181.84 | 0.5747 |
| Years vs Treatments | 771.73 | 0.0295 |
| Treatments vs Soil Depths | 71.08 | 0.8999 |
| Years vs Treatments vs Soil Depths | 84.89 | 0.8914 |

The 2018 soil penetrometer measurements showed significantly less resistance than the resistance recorded in the rest of the years. That could be due to the saturated soil conditions because of an unexpected snow event in early October. In addition, penetrometer measured highest resistance in 2017, followed by in 2015, 2016 and 2018. The higher resistance to penetration in 2015 could be due to 19.14% gravimetric soil moisture levels compared to 31.39%, 30.12% and 29.18% moisture levels in 2016, 2017 and 2018 respectively. There were no significant differences in penetrometer resistance levels in treatments, replications, soil depths, year vs treatment, treatment vs soil depth and year vs treatment vs soil depths. Details are in Table 55.

Table 55. Soil Penetrometer Resistance Level (Psi) Differences between Years, Treatments and Soil Depths.

|  |  |
| --- | --- |
| Annual Means | |
| 2015 | 533.25 |
| 2016 | 521.28 |
| 2017 | 534.06 |
| 2018 | 204.98 |
| Treatment Means | |
| Control | 446.50 |
| E-Sulfur | 447.61 |
| Gypsum | 450.71 |
| VersaLime | 448.75 |
| Replication Means | |
| Replication 1 (SE) | 447.14 |
| Replication 2 (NE) | 448.66 |
| Replication 3 (NW) | 449.37 |
| Means for Soil Depths | |
| 1 inch | 442.77 |
| 2 inch | 447.12 |
| 3 inch | 448.64 |
| 4 inch | 448.62 |
| 5 inch | 448.59 |
| 6 inch | 448.72 |
| 7 inch | 448.73 |
| 8 inch | 448.73 |
| 9 inch | 448.72 |
| 10 inch | 448.83 |
| 11 inch | 448.81 |
| 12 inch | 448.86 |
| 13 inch | 448.86 |
| 14 inch | 448.98 |
| 15 inch | 449.06 |
| 16 inch | 448.88 |
| 17 inch | 448.95 |
| 18 inch | 449.09 |

Based on the differences in the annual means of soil penetrometer resistance (psi) levels (Table 56), in 2018, resistance levels were significantly lower than the resistance levels in 2016, 2017 and 2018.

Table 56. Annual Differences in the Means of Soil Penetrometer Resistance Levels (Psi) among Treatments.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Least Square Means** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2016 | 513.57 | 518.35 | 530.02 | 523.18 |
| 2015 | 533.17 | 532.38 | 534.16 | 533.26 |
| Difference | -1.96 | -14.03 | -4.14 | -10.08 |
| 2017 | 534.19 | 534.59 | 533.40 | 534.08 |
| 2015 | 533.17 | 532.38 | 534.16 | 533.26 |
| Difference | 1.02 | 2.21 | -0.76 | 0.82 |
| 2018 | 205.06 | 205.11 | 205.25 | 204.49 |
| 2015 | 533.17 | 532.38 | 534.16 | 533.26 |
| Difference | -328.11 | -327.27 | -328.91 | -328.77 |
| 2017 | 534.19 | 534.59 | 533.40 | 534.08 |
| 2016 | 513.57 | 518.35 | 530.02 | 523.18 |
| Difference | 20.62 | 16.24 | 3.38 | 10.90 |
| 2018 | 205.06 | 205.11 | 205.25 | 204.49 |
| 2016 | 513.57 | 518.35 | 530.02 | 523.18 |
| Difference | -308.51 | -313.24 | -324.77 | -318.69 |
| 2018 | 205.06 | 205.11 | 205.25 | 204.49 |
| 2017 | 534.19 | 534.59 | 533.40 | 534.08 |
| Difference | -329.13 | -329.48 | -328.15 | -329.59 |

The chart below (Figure 20) has the annual soil penetrometer resistance (psi) levels means for the four treatments.

Figure 20. Annual Means of Soil Penetrometer Resistance Levels (Psi) Levels for all Four Treatments.

**Effect of Average Annual Growing-Season Groundwater Depths**

**On Soil Chemical Properties**

The average annual growing-season groundwater depths in 2016 were shallower than the depths in 2015, 2017 and 2018 (Table 57).

Table 57. Average Annual Growing-Season Groundwater Depth Differences among Treatments in feet.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Average Annual Growing-Season Groundwater Depths in feet** | | | |
| **Year** | **Control** | **E-Sulfur** | **Gypsum** | **VersaLime** |
| 2015 | 4.45 | 3.99 | 4.53 | 4.96 |
| 2016 | 3.78 | 3.55 | 3.49 | 4.09 |
| Difference | 0.67 | 0.44 | 1.04 | 0.87 |
| 2015 | 4.45 | 3.99 | 4.53 | 4.96 |
| 2017 | 4.98 | 5.11 | 5.21 | 5.76 |
| Difference | -0.53 | -1.12 | -0.68 | -0.80 |
| 2015 | 4.45 | 3.99 | 4.53 | 4.96 |
| 2018 | 5.74 | 5.56 | 5.87 | 6.24 |
| Difference | -1.29 | -1.57 | -1.34 | -1.28 |
| 2016 | 3.78 | 3.55 | 3.49 | 4.09 |
| 2017 | 4.98 | 5.11 | 5.21 | 5.76 |
| Difference | -1.20 | -1.56 | -1.72 | -1.67 |
| 2016 | 3.78 | 3.55 | 3.49 | 4.09 |
| 2018 | 5.74 | 5.56 | 5.87 | 6.24 |
| Difference | -1.96 | -2.01 | -2.38 | -2.15 |
| 2017 | 4.98 | 5.11 | 5.21 | 5.76 |
| 2018 | 5.74 | 5.56 | 5.87 | 6.24 |
| Difference | -0.76 | -0.45 | -0.66 | -0.48 |

Figure 21 has the average annual growing-season groundwater depths for the four treatments in feet.

Figure 21. Annual Means of Average Growing-Season Groundwater Depths for all Four Treatments in feet.

That was a direct result of a very wet 2016 versus 2015, 2017 and 2018. In addition, the difference between evapotranspiration and annual rainfall in 2016 was much lower (10.38-inches) compared to the differences in 2015 (22.91-inches), 2017 (28.48-inches) and 2018 (26.87-inches). Details are in Table 58. In addition, 2015 average annual growing-season groundwater depths were shallower than the depths in 2017 and 2018.

Table 58. Four-year Rainfall versus Evapotranspiration Data of the NDSU Langdon Research Extension Center, North Dakota Agricultural Weather Network (NDAWN) Station.

|  |  |  |  |
| --- | --- | --- | --- |
| Time Period | Total Potential Evapotranspiration (Penman) | Total Rainfall (inches) | Total Normal Rainfall (inches) |
| April 1 – Oct. 31, 2015 | 41.37” | 18.46” | 16.68” |
| April 1 – Oct. 31, 2016 | 35.29” | 24.91” |
| April 1 – Oct. 31, 2017 | 38.72” | 10.24” |
| April 1 – Oct. 31, 2018 | 38.28” | 11.41” |

**Differences in Soil EC Levels**

Statistically, there were significant differences in the soil EC levels in years due to the changes in the average annual growing-season groundwater depths. The 2016 soil EC levels were significantly lower than the EC levels in 2017 and 2018 (Table 59).

Table 59. Statistical Differences in Soil EC (dS/m) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 23.54 | 0.0032 |
| Replications | 4.77 | 0.2994 |
| Groundwater Depths | 5.05 | 0.2584 |

**Differences in Soil SAR Levels**

Statistically, there were significant differences in the soil SAR levels in years due to the changes in the average annual growing-season groundwater depths. The SAR levels in 2017 remained lower than the SAR levels in 2016 and 2018 (Table 60).

Table 60. Statistical Differences in Soil SAR Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 138.17 | 0.0315 |
| Replications | 73.99 | 0.1537 |
| Groundwater Depths | 33.11 | 0.3583 |

**Differences in Soil pH Levels**

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil pH levels (Table 61).

Table 61. Statistical Differences in Soil SAR Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 0.05 | 0.4737 |
| Replications | 0.07 | 0.3363 |
| Groundwater Depths | 0.12 | 0.1749 |

**Differences in Soil NO3--N (pounds/acre) Levels**

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil NO3--N levels (Table 62).

Table 62. Statistical Differences in Soil NO3--N (pounds/acre) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 74.07 | 0.5227 |
| Replications | 220.23 | 0.1479 |
| Groundwater Depths | 189.88 | 0.1983 |

**Differences in Soil P (ppm) Levels**

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil P levels (Table 63).

Table 63. Statistical Differences in Soil P (ppm) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 37.23 | 0.7365 |
| Replications | 45.36 | 0.6892 |
| Groundwater Depths | 34.70 | 0.5943 |

**Differences in Soil O.M. (%) Levels**

Statistically, there were significant differences in the soil O.M. levels in years due to the changes in the average annual growing-season groundwater depths as O.M. levels in 2017 remained lower than the O.M. levels in 2018 (Table 64).

Table 64. Statistical Differences in Soil O.M. (%) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 14.22 | 0.0001 |
| Replications | 2.50 | 0.1662 |
| Groundwater Depths | 0.77 | 0.4522 |

**Differences in Soil CEC (meq/100 g of soil) Levels**

Statistically, there were significant differences in the soil CEC levels in replications due to the changes in the average annual growing-season groundwater depths as replication 1 had the lowest CEC levels versus replication 2 and 3 (Table 65).

Table 65. Statistical Differences in Soil CEC (meq/100 g of soil) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 13.33 | 0.7094 |
| Replications | 159.13 | 0.0257 |
| Groundwater Depths | 9.19 | 0.6282 |

**Differences in Soil Saturation (%) Levels**

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil saturation levels (Table 66).

Table 66. Statistical Differences in Soil Saturation (%) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 128.38 | 0.1661 |
| Replications | 64.47 | 0.4036 |
| Groundwater Depths | 7.85 | 0.7393 |

**Differences in Soil CCE (%) Levels**

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil CCE levels (Table 67).

Table 67. Statistical Differences in Soil CCE (%) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 0.92 | 0.9724 |
| Replications | 59.39 | 0.1704 |
| Groundwater Depths | 0.14 | 0.9476 |

**Differences in Soil HCO3- (mg/L) Levels**

Statistically, there were significant differences in the soil HCO3- levels in years due to the changes in the average annual growing-season groundwater depths as 2017 HCO3- levels were higher than the HCO3- levels in 2018 (Table 68).

Table 68. Statistical Differences in Soil HCO3- (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 11056.58 | 0.0180 |
| Replications | 1083.84 | 0.6674 |
| Groundwater Depths | 433.90 | 0.6876 |

**Differences in Soil Cl- (mg/L) Levels**

Statistically, there were significant differences in the soil Cl- levels in years and replications due to the changes in the average annual growing-season groundwater depths. The 2018 Cl- levels were significantly higher than the Cl- levels in 2016 and 2017, whereas, replication 2 had significantly higher Cl- levels than replication 1 and 3. In addition, replication 3 had significantly higher Cl- levels than replication 1 (Table 69).

Table 69. Statistical Differences in Soil Cl- (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 84721.52 | <.0001 |
| Replications | 37000.21 | 0.0001 |
| Groundwater Depths | 8238.13 | 0.1457 |

**Differences in Soil SO42- (mg/L) Levels**

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil SO42- levels (Table 70).

Table 70. Statistical Differences in Soil SO42- (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 6977510.25 | 0.1347 |
| Replications | 3561244.22 | 0.3569 |
| Groundwater Depths | 598928.05 | 0.6767 |

**Differences in Soil Ca2+ (mg/L) Levels**

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil Ca2+ levels (Table 71).

Table 71. Statistical Differences in Soil Ca2+ (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 3911.18 | 0.8453 |
| Replications | 63179.24 | 0.0695 |
| Groundwater Depths | 0.2126 | 0.9976 |

**Differences in Soil Mg2+ (mg/L) Levels**

Statistically, there were significant differences in the soil Mg2+ levels in replications due to the changes in the average annual growing-season groundwater depths (Table 72). Replication 3 had significantly lower Mg2+ levels than replication 1 and 2, whereas, replication 2 had significantly higher Mg2+ levels than replication 1.

Table 72. Statistical Differences in Soil Mg2+ (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 15173.45 | 0.2396 |
| Replications | 59452.86 | 0.0044 |
| Groundwater Depths | 1446.08 | 0.7113 |

**Differences in Soil Na+ (mg/L) Levels**

Statistically, there were significant differences in the soil Na+ levels in years due to the changes in the average annual growing-season groundwater depths (Table 73). The 2017 Na+ levels were significantly lower than the Na+ levels in 2014 and 2018.

Table 73. Statistical Differences in Soil Na+ (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 1192016.58 | 0.0573 |
| Replications | 55710.18 | 0.8726 |
| Groundwater Depths | 199218.28 | 0.4861 |

**Differences in Soil K+ (mg/L) Levels**

Statistically, there were significant differences in the soil K+ levels in years due to the changes in the average annual growing-season groundwater depths (Table 74). The 2018 K+ levels were significantly higher than the K+ levels in rest of the years.

Table 74. Statistical Differences in Soil K+ (mg/L) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 37685.33 | 0.0018 |
| Replications | 4603.00 | 0.4490 |
| Groundwater Depths | 14387.62 | 0.1149 |

**Effect of Average Annual Growing-Season Groundwater Depths**

**On Soil Physical Properties**

**Differences in Soil Bulk Density Levels**

Statistically, there were significant differences in the soil bulk densitylevels in years due to the changes in the average annual growing-season groundwater depths (Table 75). The 2015 soil bulk densitylevels were significantly lower than the bulk density levels in the rest of the years. In addition, bulk density levels in 2016 were significantly lower than the bulk density levels in 2017. The 0-5 inch soil depths had significantly lower bulk density levels than the 5-10 inch soil depths.

Table 75. Statistical Differences in Soil Bulk Density (g/cm3) Levels.

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 0.78 | <.0001 |
| Replications | 0.01 | 0.1214 |
| Groundwater Depths | 0.00 | 0.5312 |

**Differences in Soil Penetrometer Meter Resistance Levels**

Statistically, there were significant differences in the soil penetrometer resistance levels in years and replications due to the changes in the average annual growing-season groundwater depths (Table 76). The penetrometer resistance levels in 2018 were significantly lower than the resistance levels in 2016, 2017 and 2015. Replication 3 had higher resistance levels than replication 1.

Table 76. Statistical Differences in Soil Penetrometer Resistance Levels (Psi).

|  |  |  |
| --- | --- | --- |
| **Source** | **Mean Square** | **P > F** |
| Years | 3064639.55 | 0.0001 |
| Replications | 1428.69 | 0.0100 |
| Groundwater Depths | 4022.35 | 0.0003 |

**Quality of Water Draining from the Research Project Site for**

**Human and Livestock Health**

All minerals, trace elements and nutrients affecting human and livestock health, were found to be within the acceptable limits in the 2015, 2016, 2017 and 2018 samples draining out of the Langdon REC Groundwater Management Research Project site.

**SUMMARY**

Below is the summary for soil chemical and physical properties based on four-years of data.

**Soil EC levels:** have been directly related to the annual rainfall and moisture levels in the topsoil. That is evident from the significant decrease in 2016 EC levels despite shallow average annual growing-season groundwater depths due to excess rainfall and improved drainage under tiling. However, EC levels spiked up in 2017 and 2018 despite average annual growing-season groundwater depths being deeper than the depth of tiles (four-feet) and improved drainage. That was a result of increased capillary rise of soil water due to low rainfall and higher evapotranspiration. This defies the common belief that lowering the groundwater depths will cause excess salts to leach out. However, lowering soil EC levels will need an optimum combination of low enough groundwater depths combined with sufficient rain to push the salts into deeper depths. Sufficient rain will also result in improved moisture levels in the topsoil resulting in decrease in capillary rise. Based on soil test EC levels, establishing a salt-tolerant annual crop (barley, oat) or perennial grass mix is also very important as that will reduce evaporation and consequently capillary rise.

**Soil SAR levels:** have been inconsistent, irrespective of soil amendment application (even after three-years), average annual growing-season groundwater depths and improved drainage. It could be due to lack of soil water to dissolve the soil amendments and may take more time for the amendments to cause the desired chemical reaction. However, this could be a good insight that lowering SAR levels is more complex than lowering EC, which will take longer time (maybe 4-5 years or more) and decent annual rainfall.

**Soil pH levels:** were consistent with the soil moisture levels and have had no impact so far either due to the application of soil amendments or the fluctuations in the average annual growing-season groundwater depths.

**Soil NO3--N levels:** have been consistent with the annual rainfall, average annual growing-season groundwater depths, improved drainage condition and how much N is being applied through fertilizers. Soil NO3- -N levels will decrease if not added through commercial fertilizers, plant biomass, manure or compost.

**Soil P levels:** have been more stable than NO3- -N levels due to lower solubility, however, if there is some vegetation utilizing the soil available P with no addition, P levels may also decrease with time.

**Soil O.M. levels:** will also decrease under no or poor vegetation. This is especially crucial for areas with high EC (salinity) and SAR (sodicity) levels where most of the annual crops do not do well. Establishing something, which will grow there like a mix of perennial salt-tolerant grasses will keep adding above-the ground and below-the-ground plant biomass. Adding plant biomass will result in the increase of soil microorganism’s populations. When microbes die it will result in microbial biomass. Both plant and microbial biomass will help increase soil organic matter levels.

**Soil CEC levels:** have had no effect due to the application of soil amendments or average annual growing-season groundwater depths. That is understandable as soil texture does not change (except under an extreme event like flood deposits) and there has been no drastic changes in the soil organic matter (O.M.) levels.

**Soil Saturation levels:** did increase in 2018 versus the rest of the years, however, it is bit early to read too much into it.

**Soil CCE levels:** have had no impact due to the application of soil amendments or average annual growing-season groundwater depths. However, once beetlime (VersaLime) starts dissolving, CCE levels may increase. Being the least soluble salt, highest levels of CCE have been observed in 12-24 inch soil depths.

**Soil HCO3- levels:** also have had no impact due to the application of soil amendments or average annual growing-season groundwater depths so far. However, like CCE, HCO3- levels may spike once beetlime (VersaLime) starts dissolving.

**Soil Cl- levels:** have not shown a consistent trend due to the application of soil amendments or average annual growing-season groundwater depths. Being a very soluble chemical ion (anion), the significant increase in Cl- levels in 2018 may be an indication of high Cl- levels in the groundwater.

**Soil SO42- levels:** have been consistent with the average annual growing-season groundwater depth and annual rainfall. The SO42- Levels decreased in 2016 under higher rainfall and improved drainage and remained low in 2017. However, in 2018 levels increased, which may be due to the increased capillary rise of soil water under drier weather that brought SO42- ions back.

**Soil Ca2+ levels:** have been consistent with the average annual growing-season groundwater depth and annual rainfall. Levels decreased in 2016 under higher rainfall and improved drainage and remained low in 2017 and 2018. That is one apprehension about tiling sodic or saline-sodic soils before applying the amendments that it may lead to the leaching of Ca2+ before it would displace the excess Na+ from the cation exchange sites. Leaching the Ca2+ already present in the soil may require extra application of amendments. So far there has been no indication that amendments have had any effect on soil Ca2+ levels.

**Soil Mg2+ levels:** have had no major impact due to the application of soil amendments or average annual growing-season groundwater depths despite some changes annually.

**Soil Na+ levels:** have been inconsistent like SAR levels despite some annual changes. There was an increase in Na+ levels in 2018, which maybe an indication of high Na+ levels in the groundwater.

**Soil K+ levels:** mostly remained stable, however, there has been a significant increase in K+ levels in 2018. That could be an outlier, however, it needs to be verified in the future.

**Soil Bulk Density levels:** have been consistent with the available soil moisture levels and have had no effect due to the application of soil amendments or average annual growing-season groundwater depths so far.

**Soil Penetrometer Resistance levels:** were significantly lower in 2018 compared to rest of the years. That could be due to the unexpected snow event in early October and the saturated conditions. However, the average gravimetric soil moisture levels in 2018 (29.18%) was roughly the same like the average gravimetric soil moisture levels in 2016 and 2017 (31.40% and 30.13% respectively). The 2015 average gravimetric soil moisture levels were the lowest (19.14%). It will be very interesting if this trend continues.

**CONCLUSIONS**

Though the data and the observations so far are not conclusive, however, producers and landowners, who have unproductive areas and are thinking about tiling entire fields as a single-step strategy to reclaim potential saline-sodic areas, may want to consider the following points before making a final decision:

**Under Wet Weather**

* Tiling may drain excess water timely **“under good soil water infiltration or permeability”.**
* If the potential fields have unproductive or marginal areas, **“they may want to sample these areas three to four-feet deep and analyze for EC (salinity) and SAR (sodicity) levels.”** That will be a very cheap activity compared to tiling and will help them make informed decisions.
* Based on the soil SAR results, if sodicity is established **“they may want to consider applying the soil amendments before tiling as amendments will convert sodicity into a salinity issue”.** Once sodicity levels are lowered, soil water infiltration will also improve and tiling will help drain excess water and leach salts.
* Based on soil EC levels, **“it will be beneficial to plant a salt-tolerant annual crop or a perennial grass mix on the saline or saline-sodic areas”**. That will use excess soil water, reduce evaporation, and minimize capillary rise of soil water as well as upward movement of excess water soluble salts.

**Under Drier Weather**

* Under drier weather, **“tiling entire fields may not be necessary as average annual growing-season groundwater depths may lower naturally.”**
* Tiling alone under drier weather **“may not lower salinity** **as moving the excess water soluble salts into the deeper soil depths will require sufficient rain resulting in free or gravitational water.”**
* Under drier weather, **“salinity levels can actually increase despite tiling** **due to the increased evaporation and resulting capillary rise of soil water.”**
* If the potential fields have unproductive or marginal areas, **“they may still be sampled three to four-feet deep and analyzed for EC (salinity) and SAR (sodicity) levels.”** Again, that will be a very cheap activity compared to tiling.
* Based on the soil SAR results, if sodicity is established **“they may still want to consider applying the soil amendments, before tiling as amendments will convert sodicity into a salinity issue”.** Once sodicity levels are lowered, soil water infiltration will also improve, which will help leach salts during spring-melt or decent rain event.
* Under drier weather, despite applying amendments, conversion of sodicity into salinity **“will take longer time and may take several years.”**
* Tiling sodic or saline-sodic fields alone **“will not remediate sodicity and will require application of amendments at some point in time.”**
* Based on soil EC levels, **“it will be beneficial to plant a salt-tolerant annual crop or a perennial grass mix on the saline or saline-sodic areas”** which will reduce evaporation, minimize capillary rise of soil water and minimize upward movement of excess soluble salts.