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 (Ca^{2+})-based salts will have good structure. That happens as Ca^{2+} 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 Ca^{2+} 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.

<u>Note:</u>

- 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 (SO_4^{2-}) or chloride (Cl^-).
- However, due to the constant exchange of positively charged ions like Ca^{2+}, Mg^{2+} 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 Ca^{2+} 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. Ca^{2+} displaces Na^{+} from the clay and humus particles (cation exchange sites) and Na^{+} moves into soil water where it converts into a salt (Na_2SO_4) 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 Ca^{2+} 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.

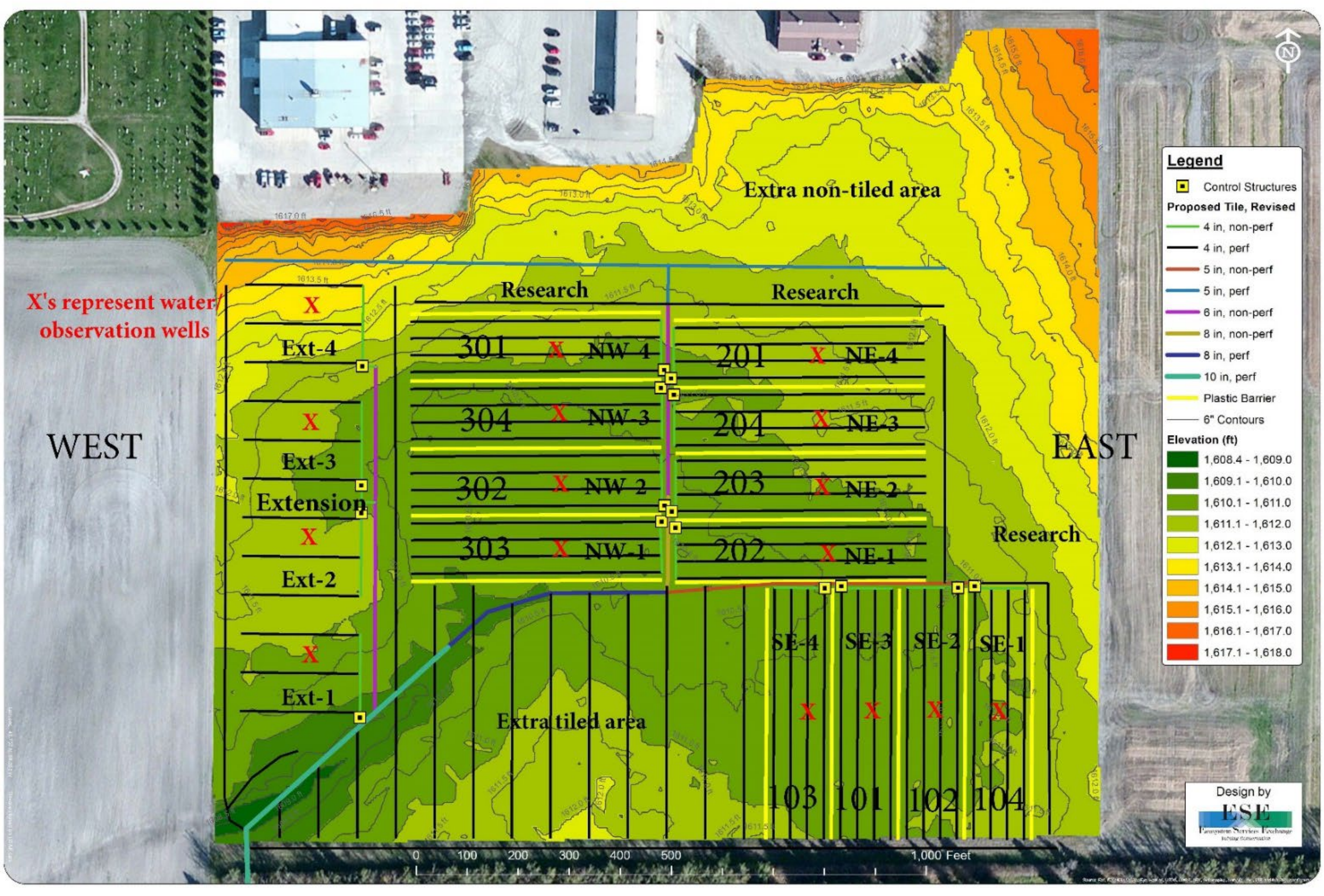


Figure 1. Final layout of the Langdon Research Extension Center Groundwater Management Research Project that has twelve research plots and three replications. Replication 1 is on the southeast and includes SE-1, SE-2, SE-3 and SE-4 plots, replication 2 is on the northeast and includes NE-1, NE-2, NE-3 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).

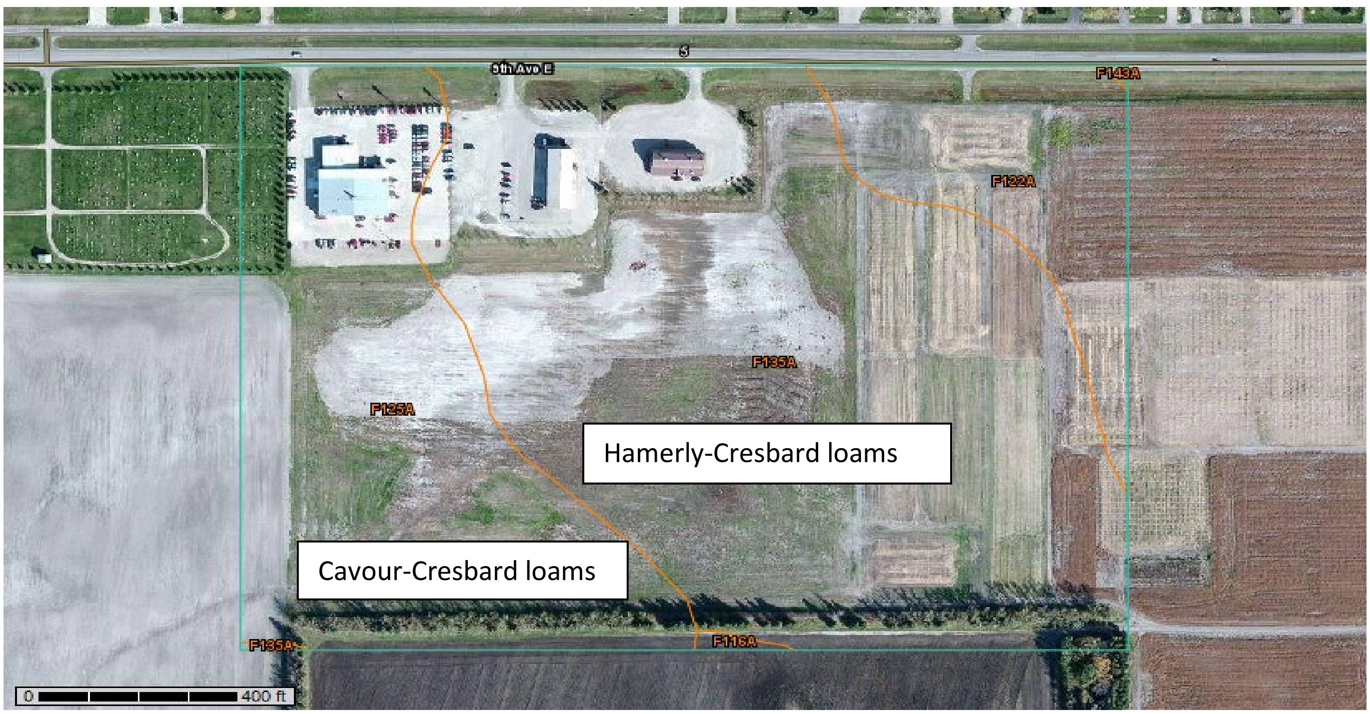


Figure 2. USDA Web Soil Survey map of the Langdon Research Extension Center Groundwater Management Research Project before tiling the site along with the soil series descriptions.

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 (HCO_3^-), chlorides (Cl^-), sulfates (SO_4^{2-}), saturation percentage, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+) and nitrate-nitrogen (NO_3-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:

$$ESP = \frac{(100(-0.0126+(0.01475*SAR)))}{(1+(-0.0126+(0.01475*SAR)))}$$

(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:

$$Exchangeable\ Na\ Meq\ per\ 100\ grams\ of\ soil = \frac{CEC * Ex.Na\%}{100}$$

(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:

$$\frac{100}{purity\%} * tons\ equivalent\ to\ 1\ ton\ of\ pure\ gypsum$$

(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 Replications	99.5% Gypsum tons/plot	90% Elemental Sulfur tons/plot	VersaLime 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, HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, 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 NO_3^--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, SO_4^{2-} levels were very high followed by HCO_3^- and Cl^-. The CCE levels also remained high. For major cations, Na^+ levels remained the highest followed by Ca^{2+}, 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
NO_3^--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
HCO_3^- (mg/L)	105.97	110.64	104.44	103.93
Cl^- (mg/L)	123.30	88.71	89.62	67.76
SO_4^{2-} (mg/L)	4398.51	5439.34	5476.92	5622.24
Ca^{2+} (mg/L)	508.58	422.41	529.08	578.25
Mg^{2+} (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

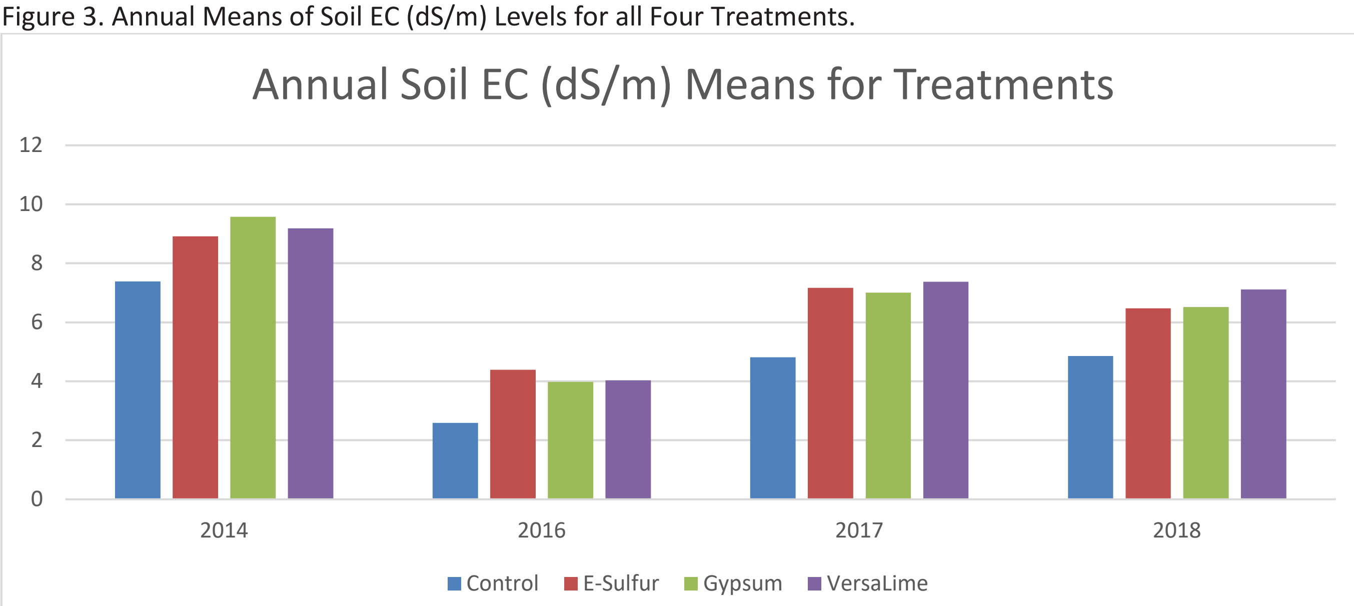
Based on the differences in the annual means of soil EC levels (Table 5), in 2016, EC levels dropped significantly compared to 2014 despite higher rainfall and shallower average annual growing-season groundwater depths. That could be attributed to improved drainage due to tiling under excess soil moisture. 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

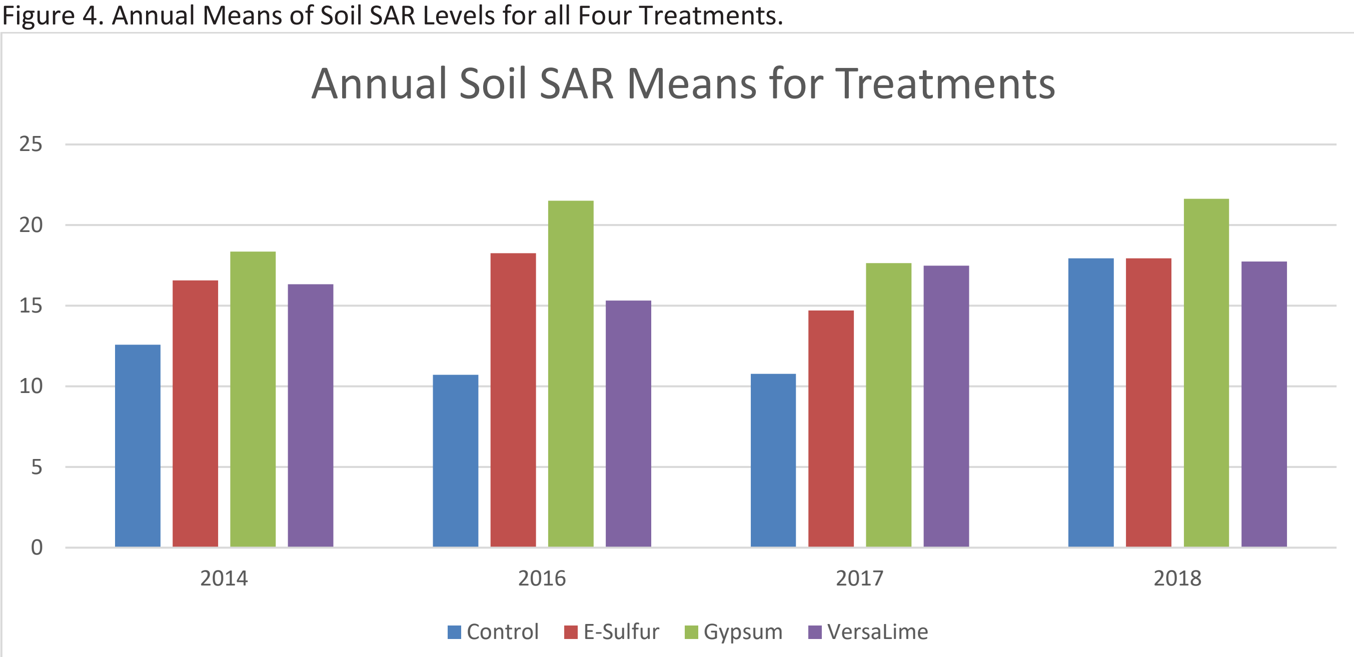
Based on the differences in the annual means of soil SAR levels (Table 8), in 2018 SAR levels increased in all treatments, notably in control versus 2014, 2016 and 2017. Whereas, in 2016 and 2017, SAR levels fluctuated irrespective of the treatments.

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

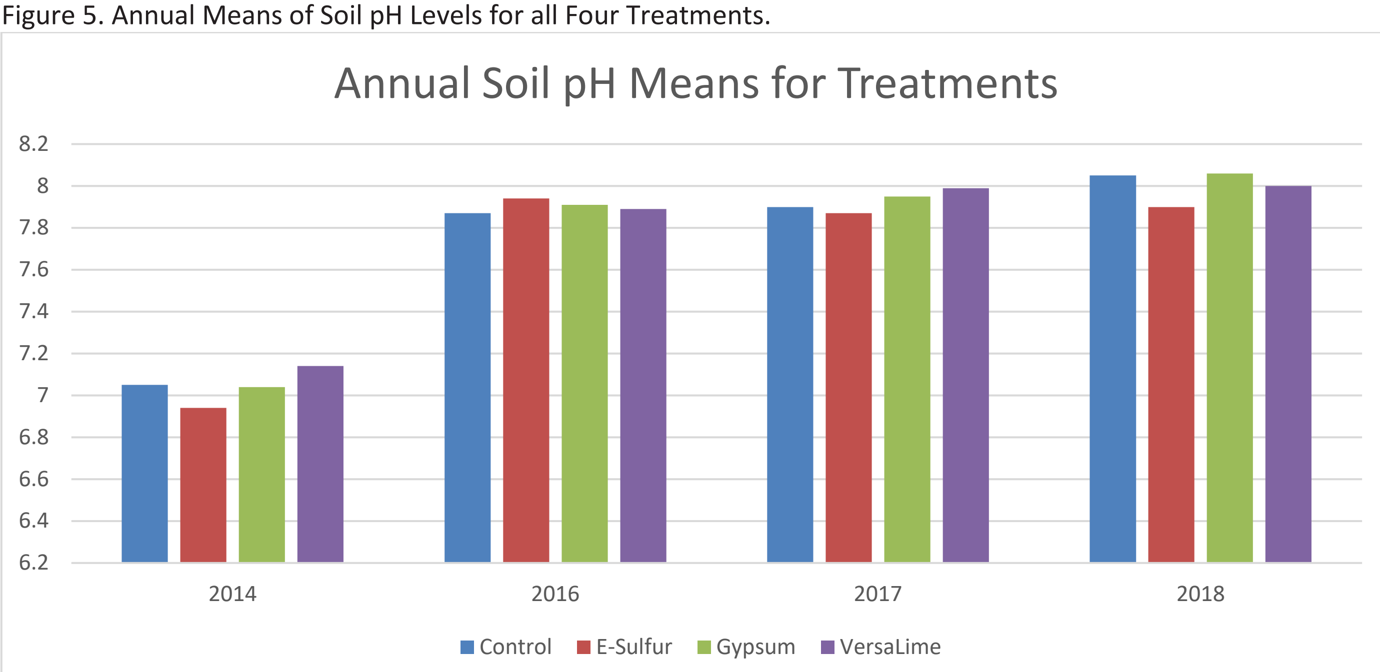
Based on the differences in the annual means of soil pH (Table 11), 2014 pH levels were significantly lower than the rest of the years due to the lower soil moisture conditions at the time of sampling (September 2014). In 2016, 2017 and 2018, soil samples were collected in June when moisture levels were 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 NO_3^--N Levels

Statistically, there were significant differences in the soil NO_3^--N levels in years, soil depths and year vs treatment vs soil depths (Table 12).

Table 12. Statistical Differences in Soil NO_3^--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 NO_3^--N levels were significantly higher than the NO_3^--N levels in 2016, 2017 and 2018. Since 2016, soil NO_3^--N levels decreased steadily with time, however, there were no significant differences between 2016, 2017 and 2018. Highest decrease in NO_3^--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 NO_3^--N levels among treatments.

Replication 2 had significantly higher NO_3^--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 NO_3^--N levels versus rest of the depths and 12-24 inch depth had significantly higher NO_3^--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 NO_3^--N levels was observed in 12-24 inch depth versus 0-12 inch depth. Details are in Table 13.

Table 13. Soil NO_3^--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

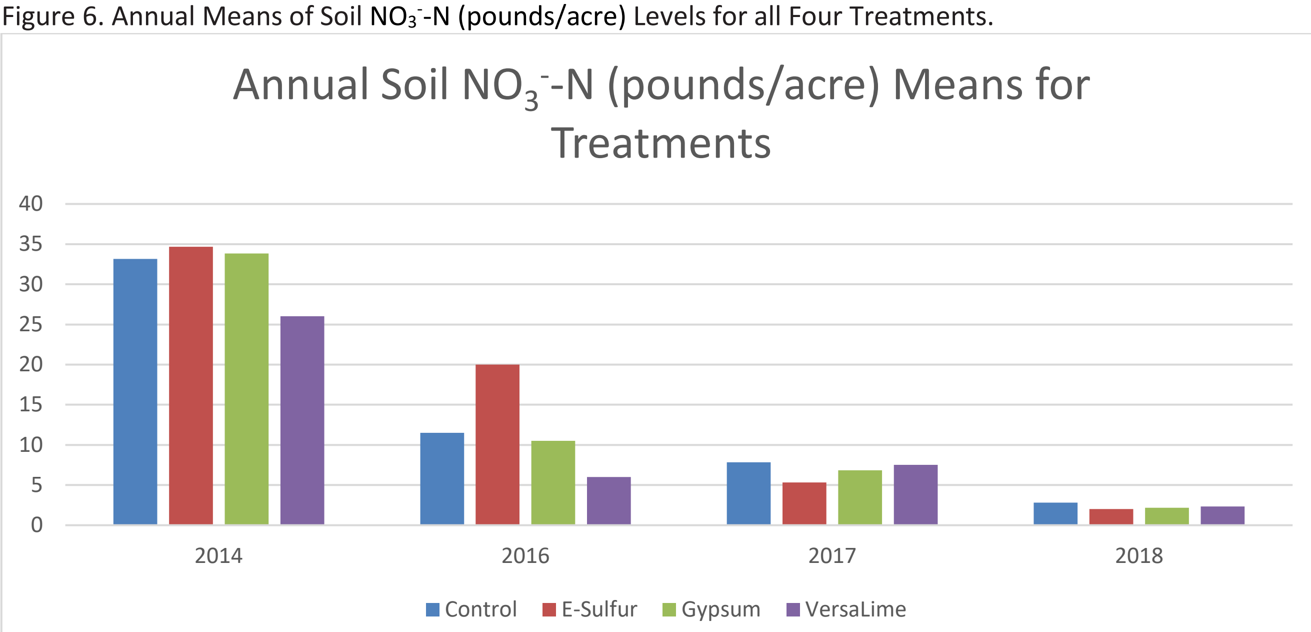
Based on the differences in the annual means of soil NO_3^--N (pounds/acre) levels (Table 14), in 2016, 2017 and 2018 NO_3^--N levels decreased significantly compared to 2014. In 2017 and 2018, NO_3^--N decreased further and remained lower than the levels in 2016.

Table 14. Annual Differences in the Means of Soil NO_3^--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 NO_3^--N (pounds/acre) means for the four treatments.

Figure 6. Annual Means of Soil NO_3^--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

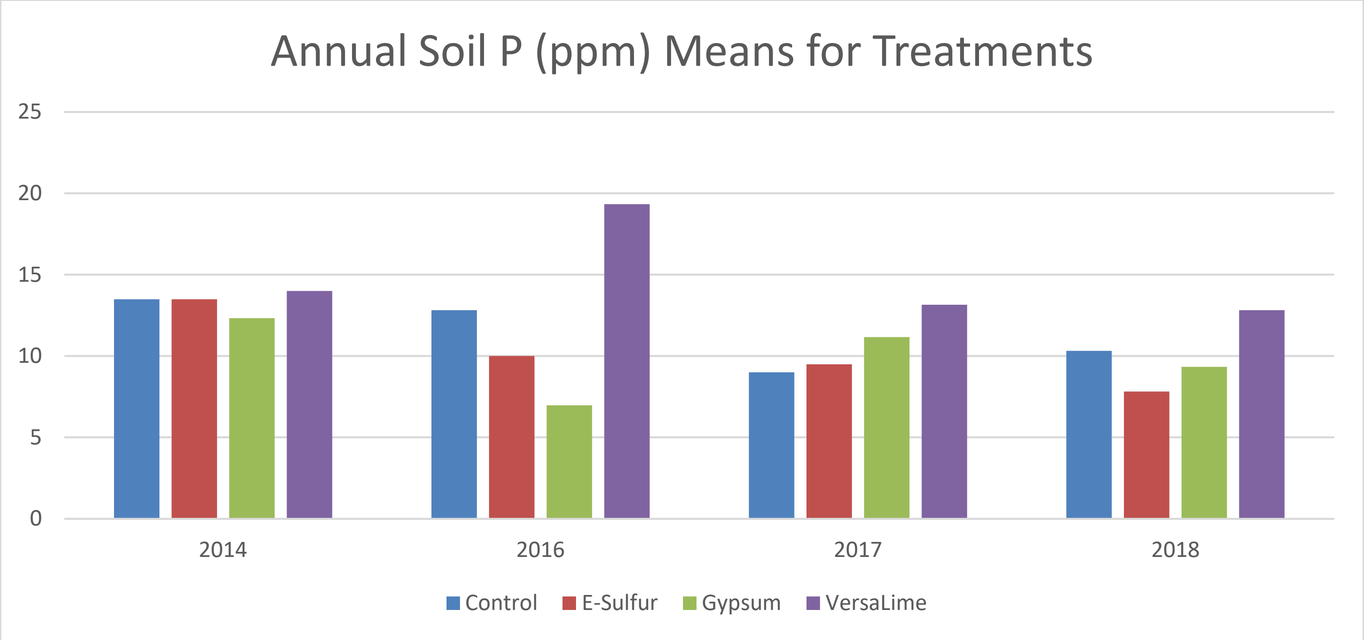
Based on the differences in the annual means of soil P (ppm) levels (Table 17), there were no significant differences in 2016, 2017 and 2018 versus 2014. However, a steady decrease in soil P levels was observed with time.

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

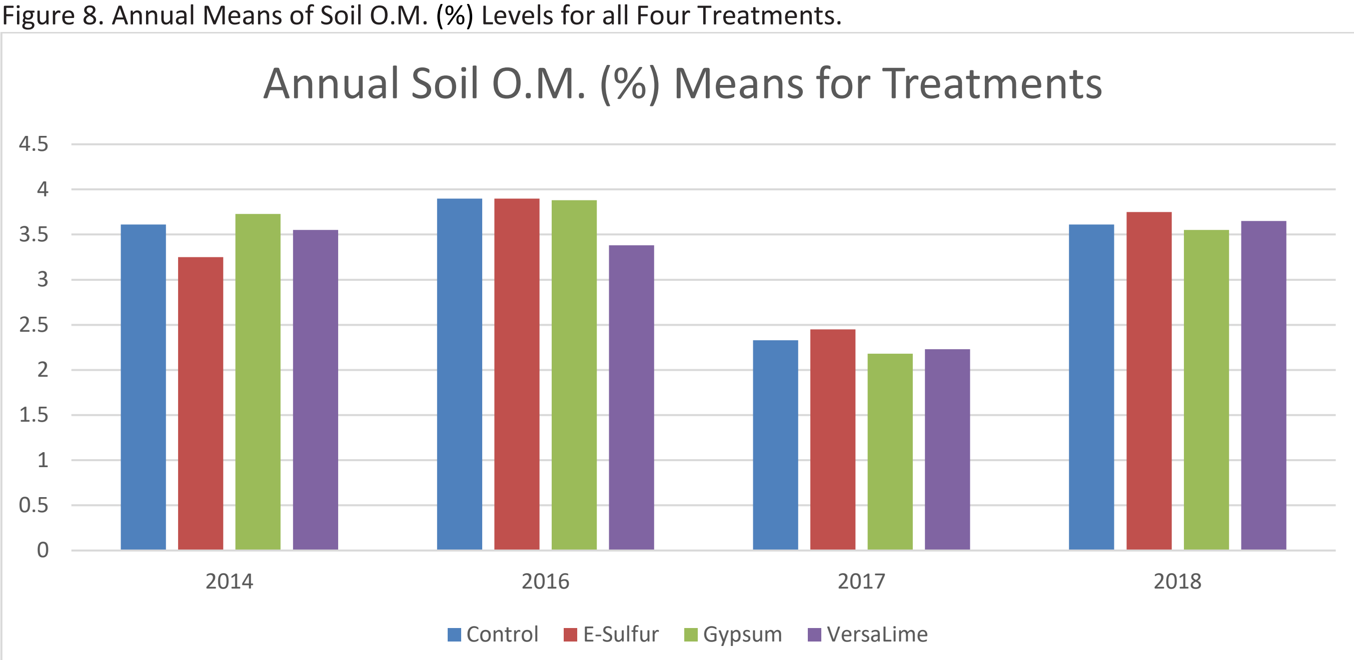
Based on the differences in the annual means of soil O.M. (%) levels (Table 20), 2017 levels were significantly lower than 2014, 2016 and 2018. Again, that could be due to a slightly drier June-2017 when soil samples were collected compared to June 2014, June 2016 and June 2018.

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

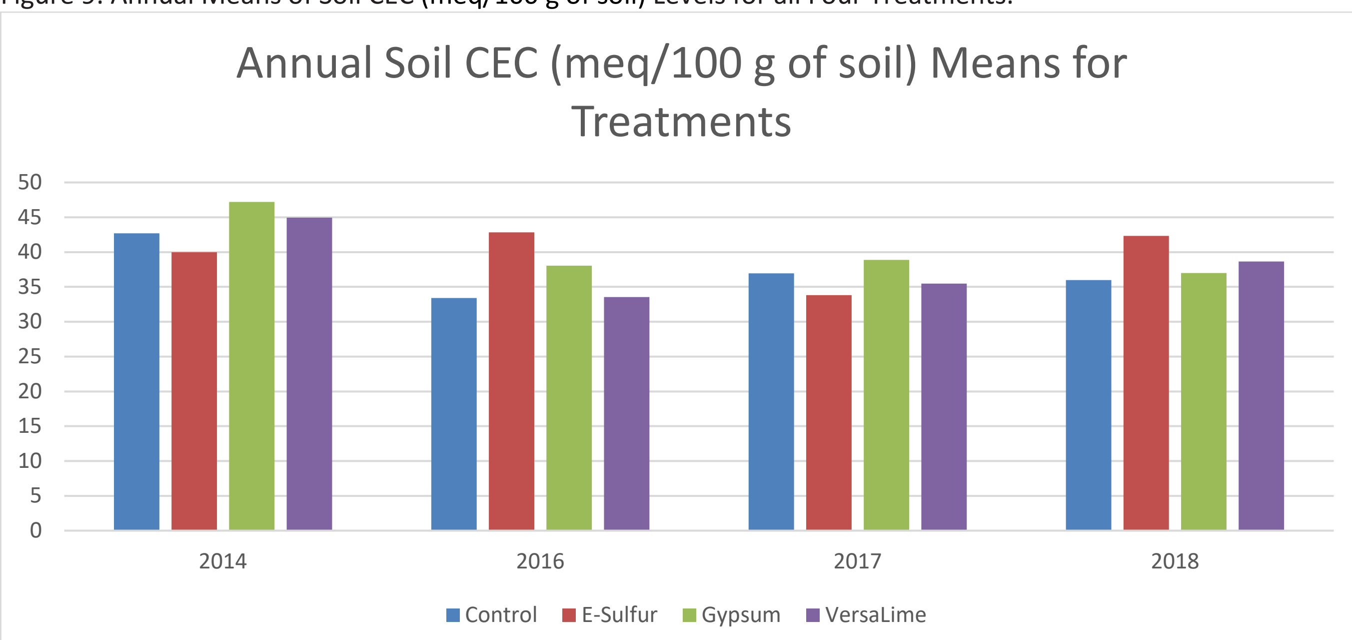
Based on the differences in the annual means of soil CEC (meq/100 g of soil) levels (Table 23), there were no statistically significant differences.

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

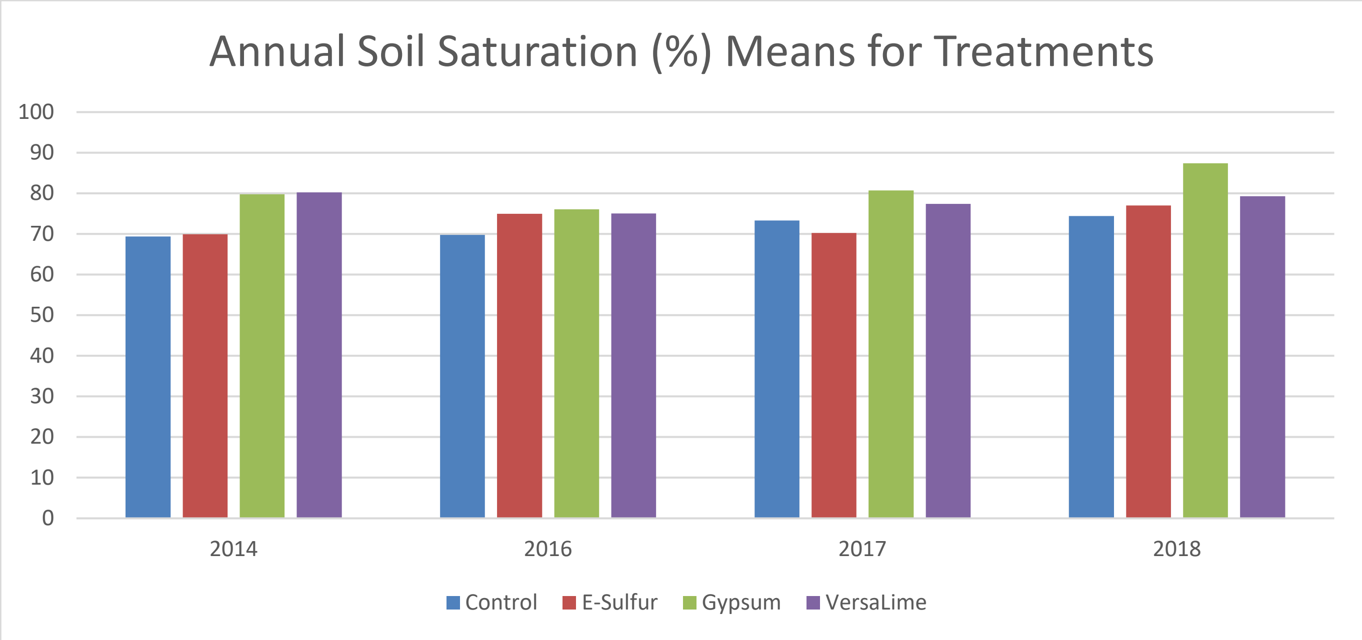
Based on the differences in the annual means of soil saturation (%) levels (Table 26), 2018 soil saturation levels were significantly higher than 2014, 2016 and 2017.

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

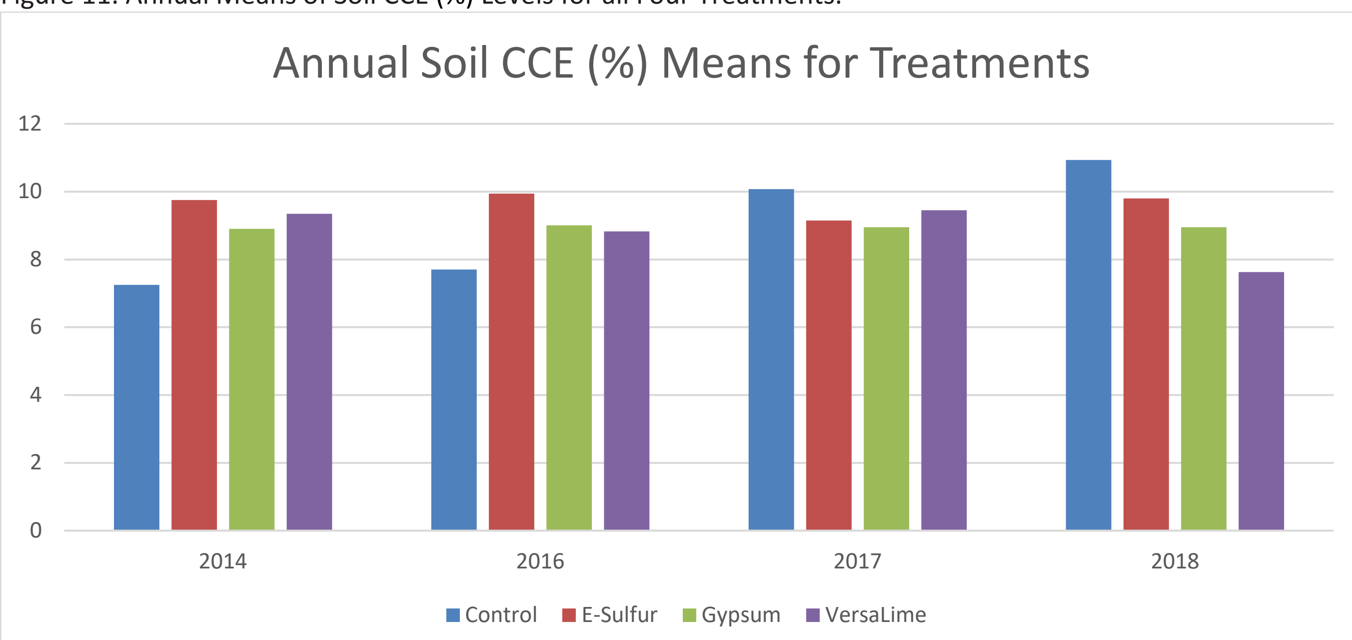
Based on the differences in the annual means of soil CCE (%) levels (Table 29), there were no significant differences in 2016, 2017 and 2018 versus 2014.

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 HCO_3^- Levels

Statistically, there were significant differences in the HCO_3^- levels in years, soil depths and year vs treatment vs soil depths (Table 30).

Table 30. Statistical Differences in Soil HCO_3^- (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 HCO_3^- levels in 2017 were significantly higher than rest of the years, whereas HCO_3^- levels in 2016 were significantly higher than the HCO_3^- levels in 2018. There were no significant differences in HCO_3^- levels among treatments. Replication 3 had significantly higher HCO_3^- levels than replication 2. The 0-12 inch soil depths had significantly higher HCO_3^- levels versus rest of the depths, whereas 36-48 inch depths had significantly higher HCO_3^- levels versus 24-36 inch depths. Details are in Table 31.

Table 31. Soil HCO_3^- (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

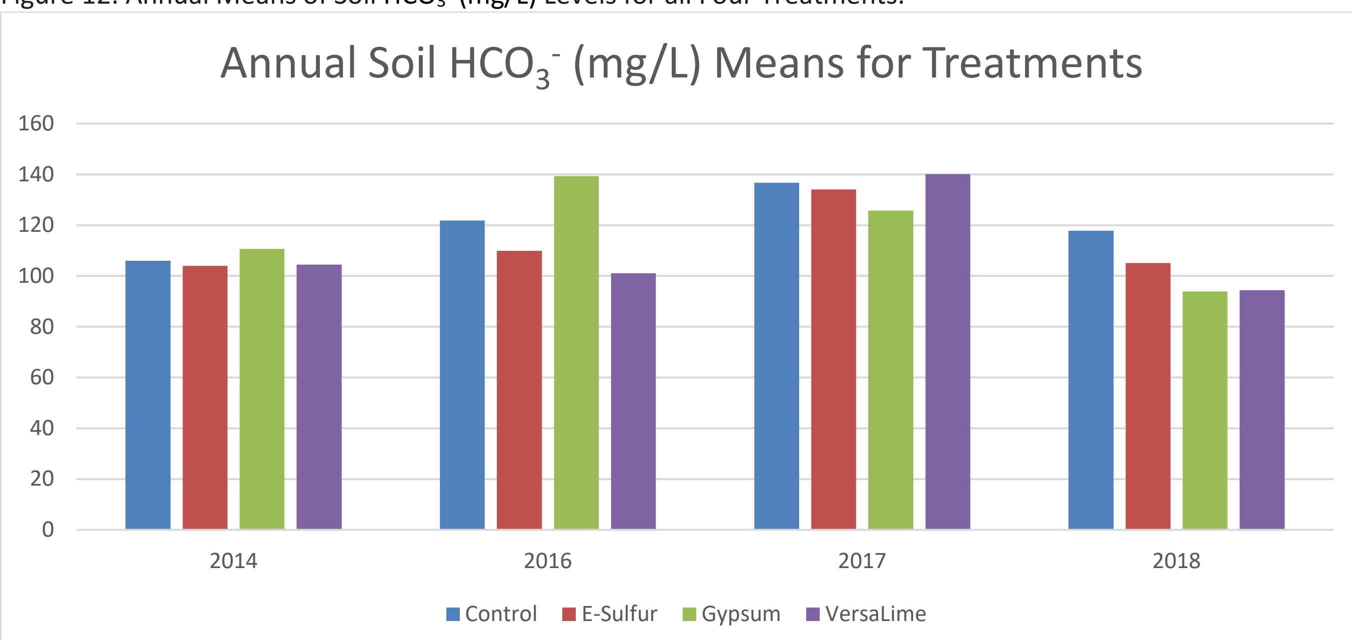
Based on the differences in the annual means of soil HCO_3^- (mg/L) levels (Table 32), 2017 levels were significantly higher than 2014, 2016 and 2018.

Table 32. Annual Differences in the Means of Soil HCO_3^- (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 HCO_3^- (mg/L) means for the four treatments.

Figure 12. Annual Means of Soil HCO_3^- (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

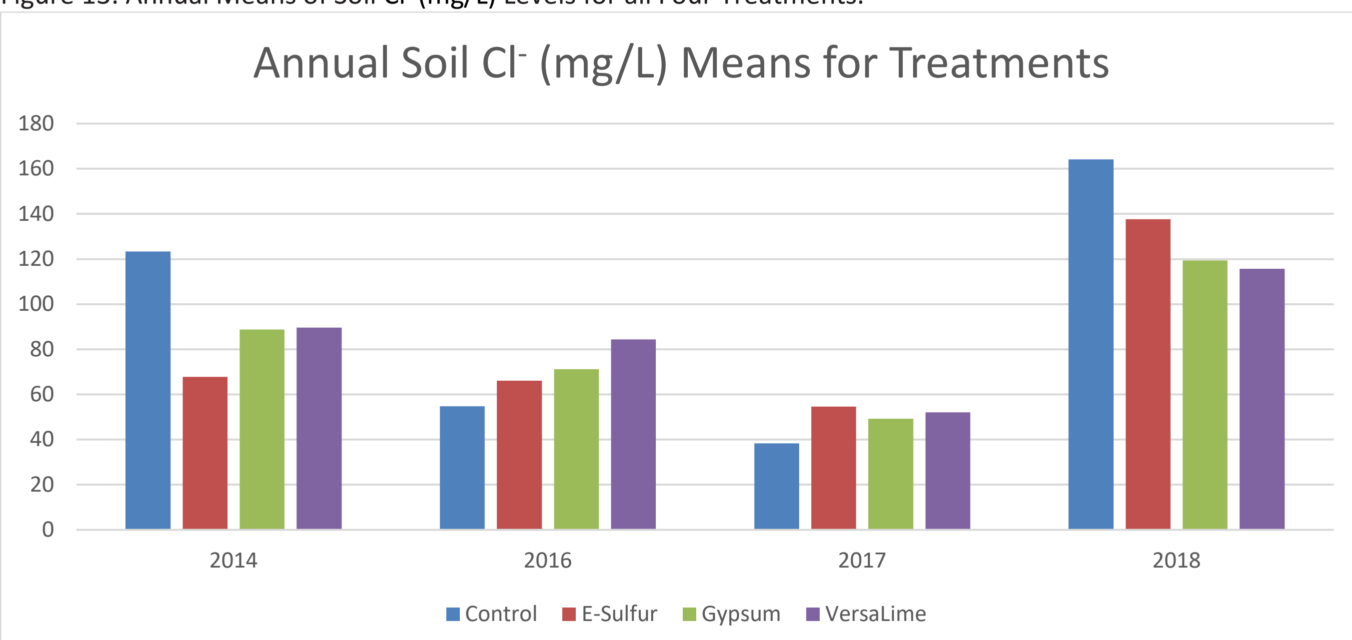
Based on the differences in the annual means of soil Cl^- (mg/L) levels (Table 35), 2018 levels were significantly higher than 2014, 2016 and 2017. In addition, 2014 Cl^- levels were significantly higher than the 2017 levels.

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 SO_4^{2-} Levels

Statistically, there were significant differences in the SO_4^{2-} levels in years, treatments, replications and soil depths (Table 36).

Table 36. Statistical Differences in Soil SO_4^{2-} (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 SO_4^{2-} levels in 2014 were significantly higher than the 2017 levels. Among treatments, control had significantly lower SO_4^{2-} levels than rest of the treatments. Replication 2 had significantly higher SO_4^{2-} levels than replication 3. The 12-24 inch soil depth had significantly higher SO_4^{2-} levels the 36-48 inch depth. Details are in Table 37.

Table 37. Soil SO_4^{2-} (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

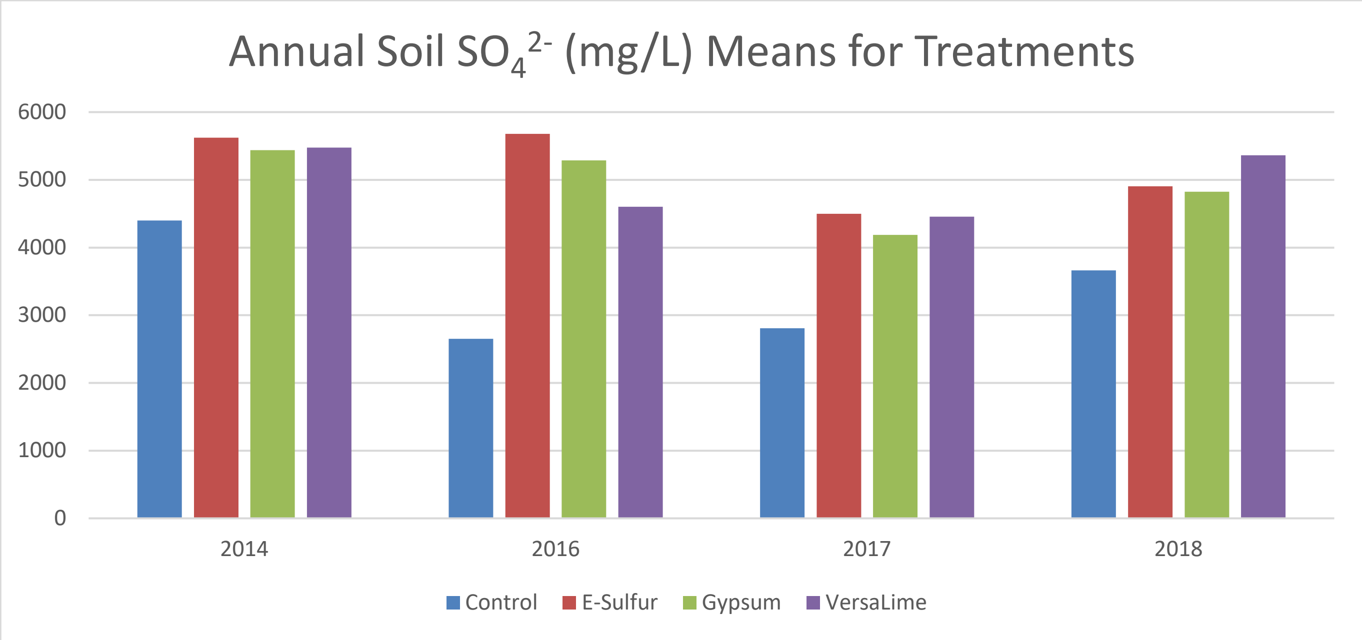
Based on the differences in the annual means of soil SO_4^{2-} (mg/L) levels (Table 38), 2014 levels were significantly higher than the SO_4^{2-} levels in 2017, whereas, numerically 2014 SO_4^{2-} levels remained higher than the SO_4^{2-} levels in rest of the years.

Table 38. Annual Differences in the Means of Soil SO_4^{2-} (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 SO_4^{2-} (mg/L) means for the four treatments.

Figure 14. Annual Means of Soil SO_4^{2-} (mg/L) Levels for all Four Treatments.



Differences in Soil Ca^{2+} Levels

Statistically, there were significant differences in the Ca^{2+} levels in years and soil depths (Table 39).

Table 39. Statistical Differences in Soil Ca^{2+} (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 Ca^{2+} levels in 2014 were significantly higher than rest of the years, whereas the Ca^{2+} levels in 2016 were significantly lower than rest of the years. There were no differences between treatments and replications. The lower soil Ca^{2+} levels in 2016 versus 2014 could be due to the leaching of Ca^{2+} under wet weather and improved drainage conditions (tiling). In addition, the gradual increase in Ca^{2+} levels in 2017 and 2018 could be due to the upward movement of Ca^{2+}-based salts under drier weather and resulting capillary rise of soil water. The 12-24 inch soil depth had significantly higher Ca^{2+} levels than the 24-36 inch and 36-48 inch depths, whereas, 36-48 inch depths had significantly lower Ca^{2+} levels than rest of the treatments. Details are in Table 40.

Table 40. Soil Ca^{2+} (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

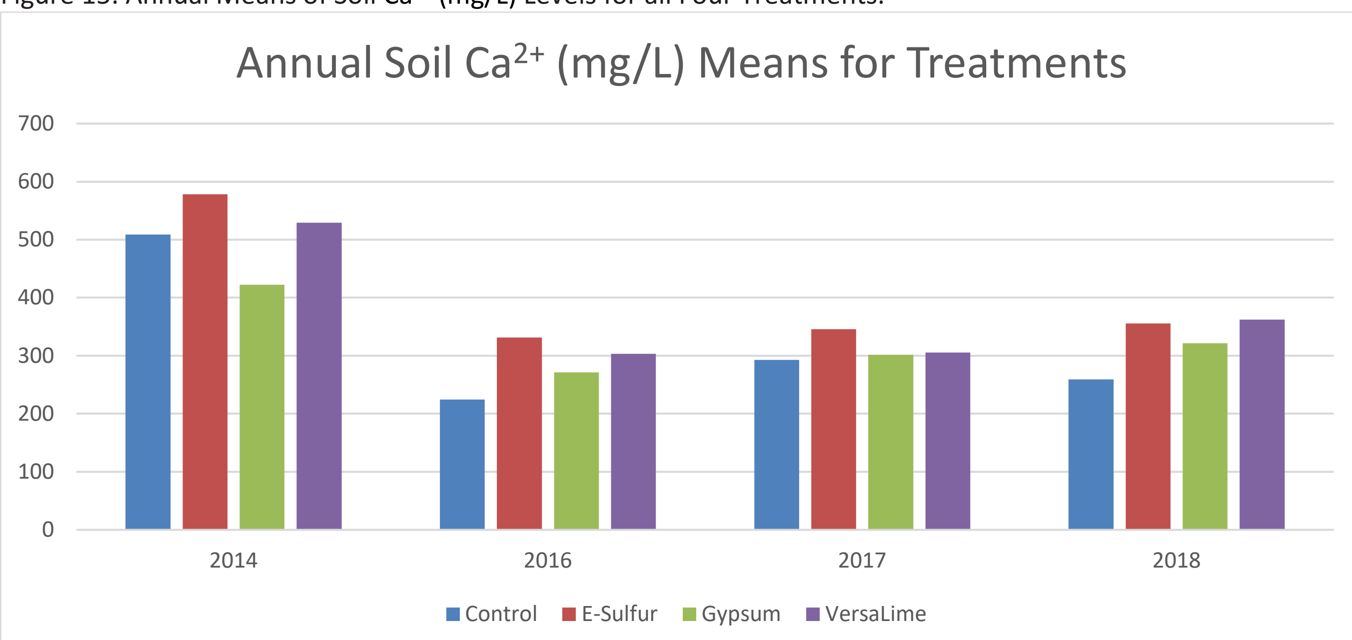
Based on the differences in the annual means of soil Ca^{2+} (mg/L) levels (Table 41), 2014 levels were significantly higher than rest of the years and the Ca^{2+} levels in 2016 were significantly lower than rest of the years.

Table 41. Annual Differences in the Means of Soil Ca^{2+} (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 Ca^{2+} (mg/L) means for the four treatments.

Figure 15. Annual Means of Soil Ca^{2+} (mg/L) Levels for all Four Treatments.



Differences in Soil Mg^{2+} Levels

Statistically, there were significant differences in the Mg^{2+} levels in treatments, replications and soil depths (Table 42).

Table 42. Statistical Differences in Soil Mg^{2+} (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 Mg^{2+} levels. Control treatment had the lowest Mg^{2+} levels versus rest of the treatments. Replication 2 had significantly higher Mg^{2+} levels, whereas, replication 3 had significantly lower Mg^{2+} levels. The 0-12 inch and 12-24 inch soil depths had significantly higher Mg^{2+} levels than the 24-36 inch and 36-48 inch soil depths. Overall, Mg^{2+} levels numerically decreased with increasing soil depths. Details are in Table 43.

Table 43. Soil Mg^{2+} (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

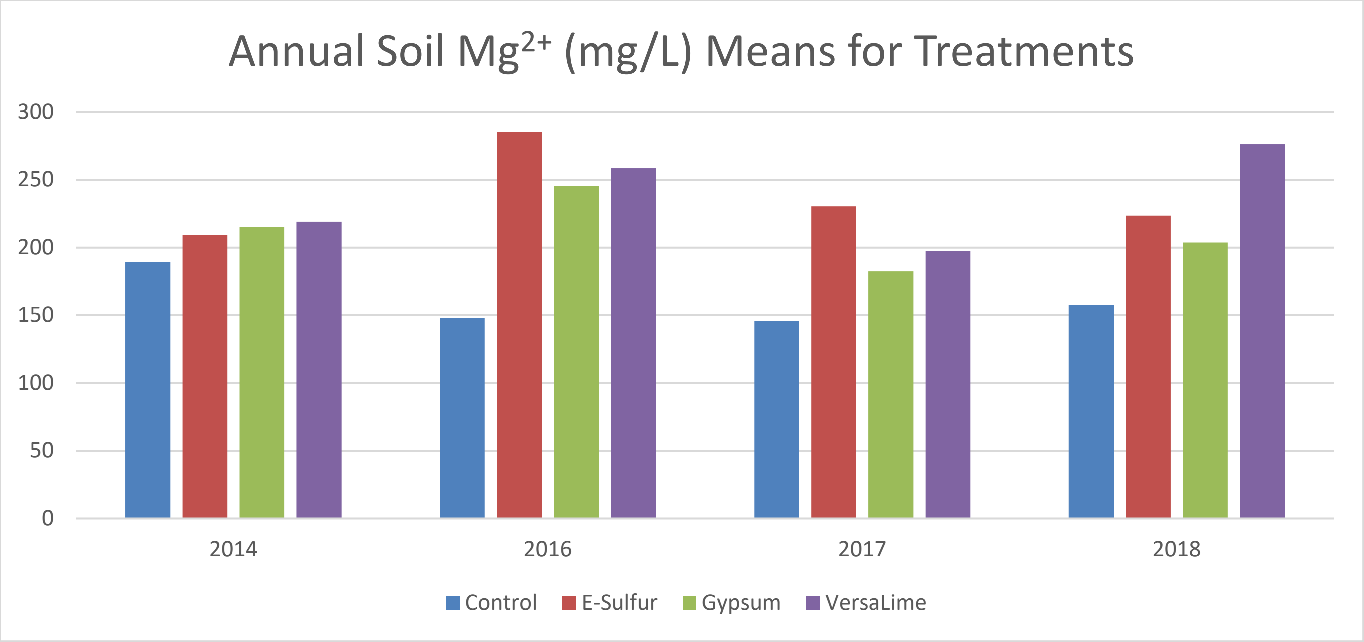
Based on the differences in the annual means of soil Mg^{2+} (mg/L) levels (Table 44), there were no significant differences the annual Mg^{2+} soil levels.

Table 44. Annual Differences in the Means of Soil Mg^{2+} (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 Mg^{2+} (mg/L) means for the four treatments.

Figure 16. Annual Means of Soil Mg^{2+} (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

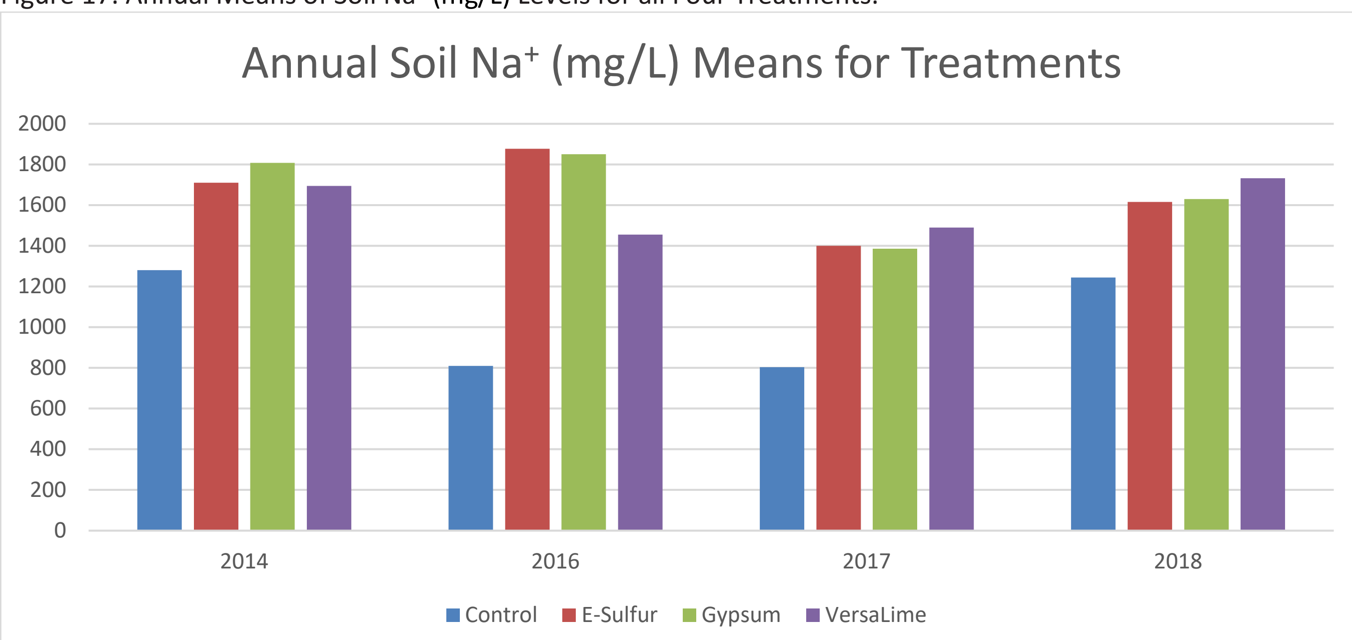
Based on the differences in the annual means of soil Na^+ (mg/L) levels (Table 47), in 2017, Na^+ levels were significantly lower than the Na^+ levels in 2014 and 2018.

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

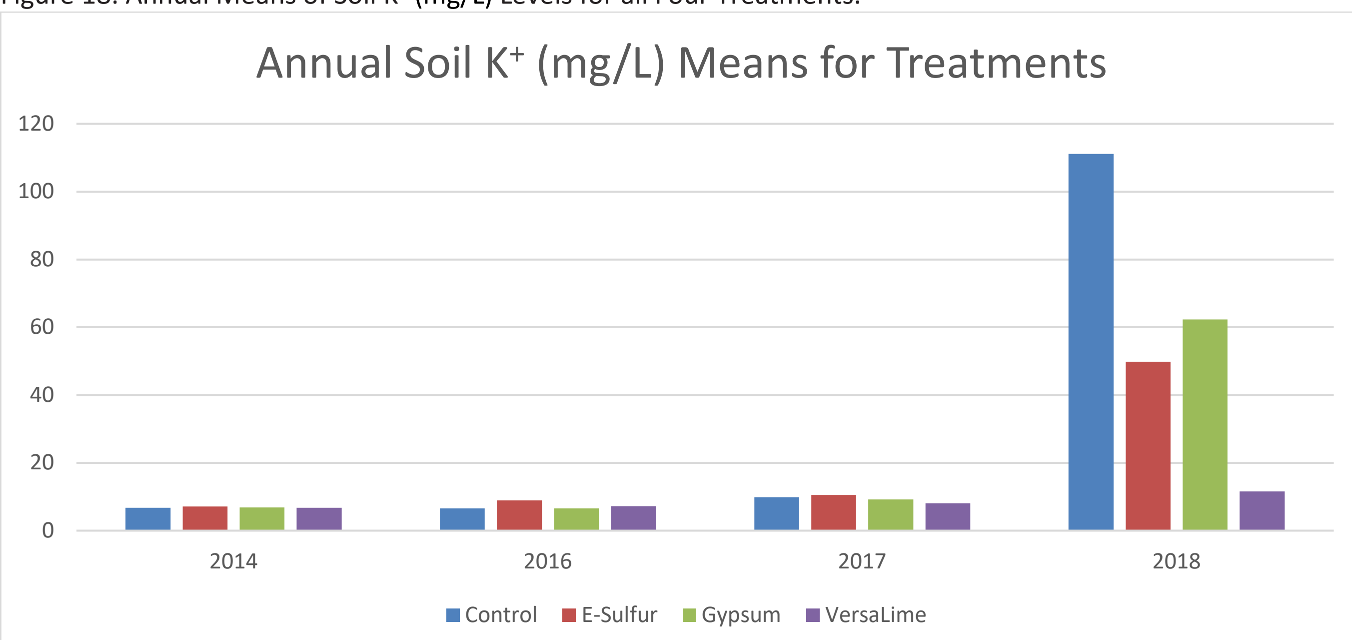
Based on the differences in the annual means of soil K^+ (mg/L) levels (Table 50), in 2018, K^+ levels were significantly higher than the K^+ levels in 2014, 2016 and 2017.

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/cm^3) 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 density levels 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 density levels 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/cm^3) 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

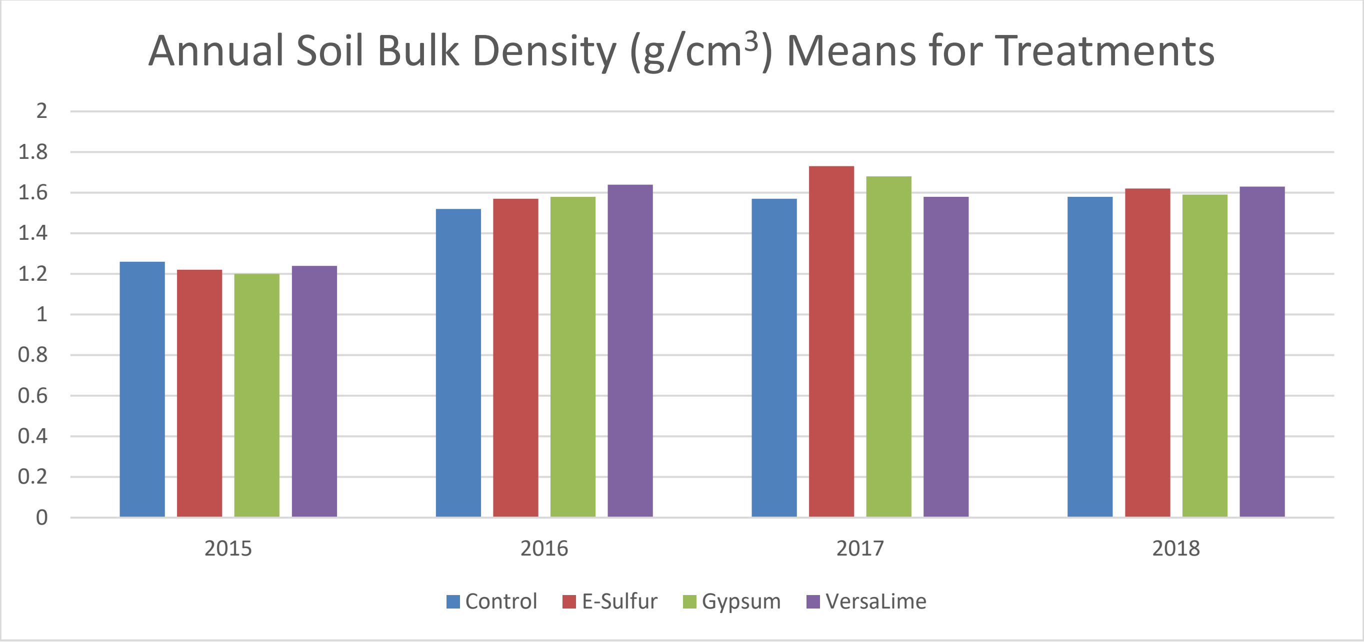
Based on the differences in the annual means of soil bulk density (g/cm^3) levels (Table 53), in 2015, bulk density levels were significantly lower than the bulk density levels in 2016, 2017 and 2018. In addition, bulk density levels in 2016 were significantly lower than the bulk density levels in 2017.

Table 53. Annual Differences in the Means of Soil Bulk Density (g/cm^3) 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/cm^3) means for the four treatments.

Figure 19. Annual Means of Soil Bulk Density (g/cm^3) 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

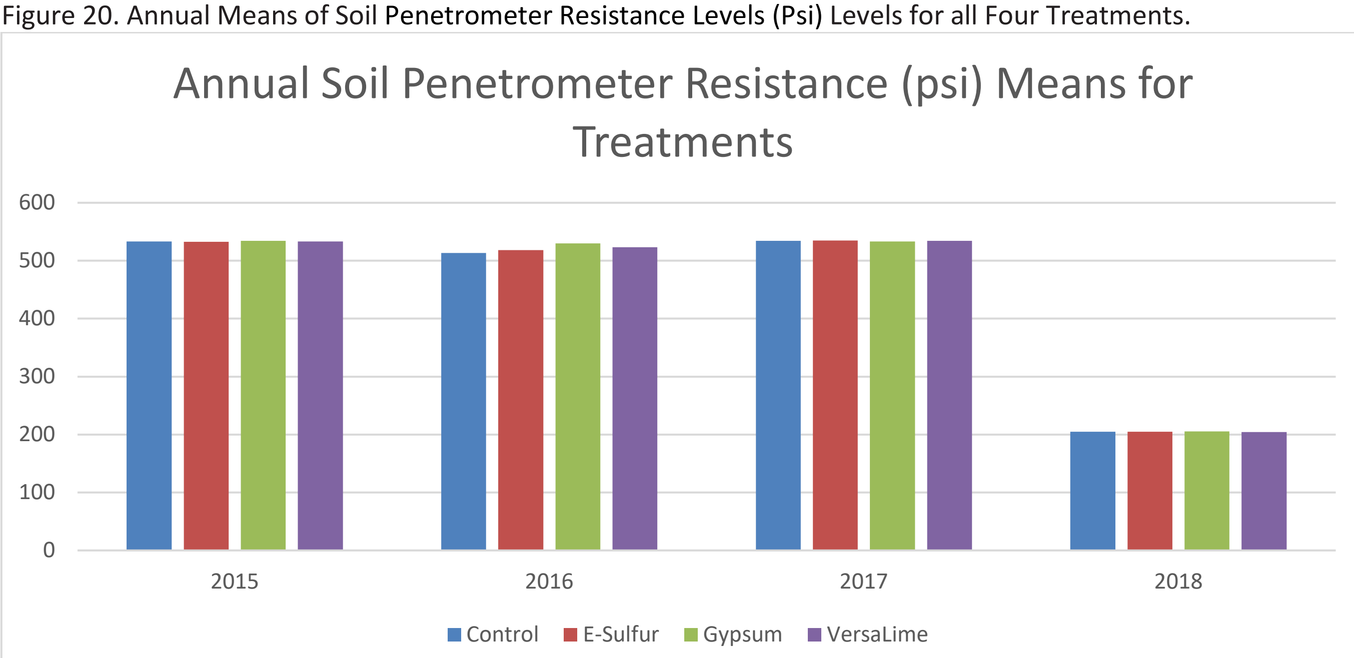
Based on the differences in the annual means of soil penetrometer resistance (psi) levels (Table 56), in 2018, resistance levels were significantly lower than the resistance levels in 2016, 2017 and 2018.

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

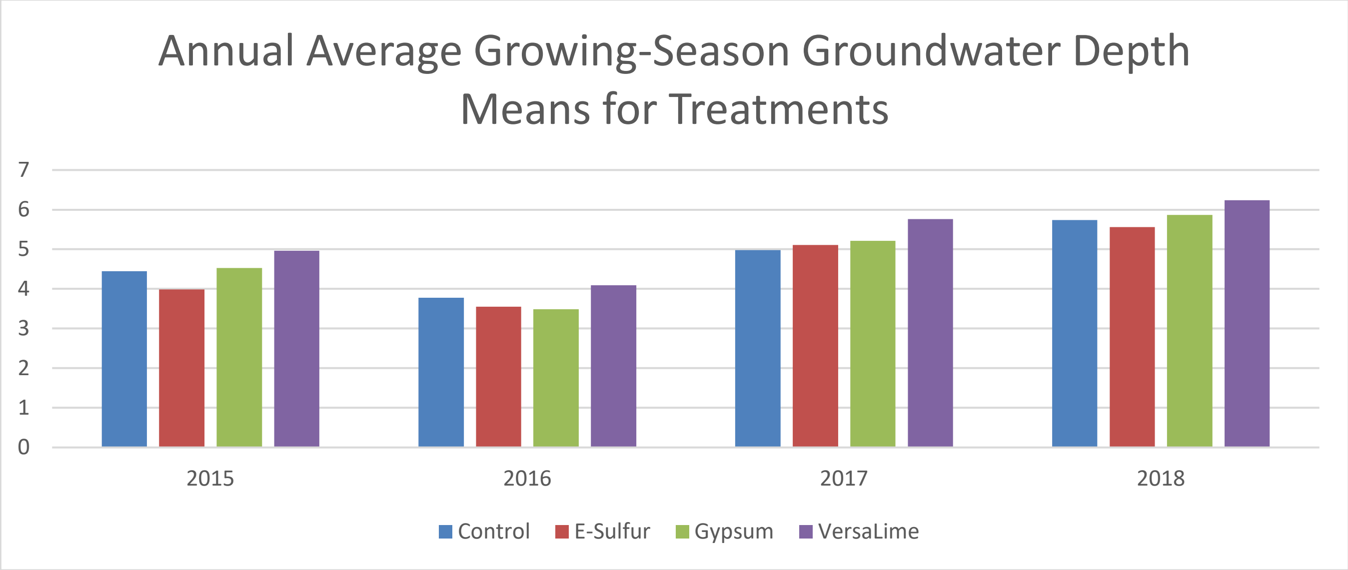
The average annual growing-season groundwater depths in 2016 were shallower than the depths in 2015, 2017 and 2018 (Table 57).

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 NO_3^--N (pounds/acre) Levels

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil NO_3^--N levels (Table 62).

Table 62. Statistical Differences in Soil NO_3^--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 HCO_3^- (mg/L) Levels

Statistically, there were significant differences in the soil HCO_3^- levels in years due to the changes in the average annual growing-season groundwater depths as 2017 HCO_3^- levels were higher than the HCO_3^- levels in 2018 (Table 68).

Table 68. Statistical Differences in Soil HCO_3^- (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 SO_4^{2-} (mg/L) Levels

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil SO_4^{2-} levels (Table 70).

Table 70. Statistical Differences in Soil SO_4^{2-} (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 Ca^{2+} (mg/L) Levels

Statistically, there were no significant effects of the average annual growing-season groundwater depths on soil Ca^{2+} levels (Table 71).

Table 71. Statistical Differences in Soil Ca^{2+} (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 Mg^{2+} (mg/L) Levels

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

Table 72. Statistical Differences in Soil Mg^{2+} (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 density levels in years due to the changes in the average annual growing-season groundwater depths (Table 75). The 2015 soil bulk density levels 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/cm^3) 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 NO_3^--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 NO_3^- -N levels will decrease if not added through commercial fertilizers, plant biomass, manure or compost.

Soil P levels: have been more stable than NO_3^- -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 HCO_3^- 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, HCO_3^- 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 SO_4^{2-} levels: have been consistent with the average annual growing-season groundwater depth and annual rainfall. The SO_4^{2-} 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 SO_4^{2-} ions back.

Soil Ca^{2+} 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 Ca^{2+} before it would displace the excess Na^+ from the cation exchange sites. Leaching the Ca^{2+} 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 Ca^{2+} levels.

Soil Mg^{2+} 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.