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 (Johnsgard, reprinted in 1974) in 1967. Another study estimated 5.8 million saline acres in North Dakota (Brennan and Ulmer, 2010). That is nearly 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 capillary rise of soil water results in 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 optimum water movement through the soil profile depending upon texture. Calcium ions are able to flocculate soil particles together as they act like a bridge between them due to being divalent. In addition, as they have smaller hydrated ionic sizes, Ca^{2+} ions hold on to the negative charges of soil particles tighter, so the bond is strong. Magnesium (Mg^{2+}) ions are also divalent so they can promote flocculation, however, due to their bigger hydrated ionic sizes, the bond between soil particles and resulting soil structure is not as strong as in case of calcium.

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 (Seelig, 2000). 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^+.
- Clayey soils will infiltrate water slower than sandy soils, however, sodicity can drastically reduce the soil water infiltration irrespective of soil texture. A clayey soil without dispersion issues will infiltrate water much faster than the same clay soil having dispersion.

OBJECTIVES

Remediation of soil sodicity requires application of amendments that add Ca^{2+} to the soil, followed by salinity remediation practices of establishing a good vegetative cover to reduce evaporation and lowering the groundwater depths to desirable levels by promptly draining the excess soil water under wet conditions. The newly added Ca^{2+} will displace 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. Once that happens, a combination of Ca^{2+} with clay/humus promotes flocculation resulting in improved soil aggregation, structure and infiltration.

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 ability of a tile drainage system to drain excess soil water in a timely manner greatly depends upon how fast water moves or infiltrates through the soil layers above the tiles. This is especially important, if soils are suspected of having dispersion. That will require sampling and analyzing potential areas for salts, Na^{+} causing sodicity (dispersion) and pH up to the deepest proposed depth of tiles in one-foot increments. Salinity and sodicity levels can be determined by sampling the areas in question and getting the samples and depths analyzed by a soil laboratory for Electrical Conductivity or EC (for salinity) and Sodium Adsorption Ratio or SAR (for sodicity) by using the "saturated paste extract" method. If sodicity is established, in order to calculate the rates of soil amendments, samples will also need to be analyzed for cation exchange capacity (CEC) by using "sodium saturation, ammonium extraction" method. In case of high Na^{+} levels causing sodicity, not adding Ca^{2+} can render tiling ineffective. 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 (revised July 2020); "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?**

Due to the growing concerns of producers and landowners about the effects and effectiveness of tiling, the Langdon Research Extension Center (LREC) tiled a field that had excessive levels of sodicity and moderately high levels of soluble salts in July 2014. Layout included 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. Remediation of the area was accomplished 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.

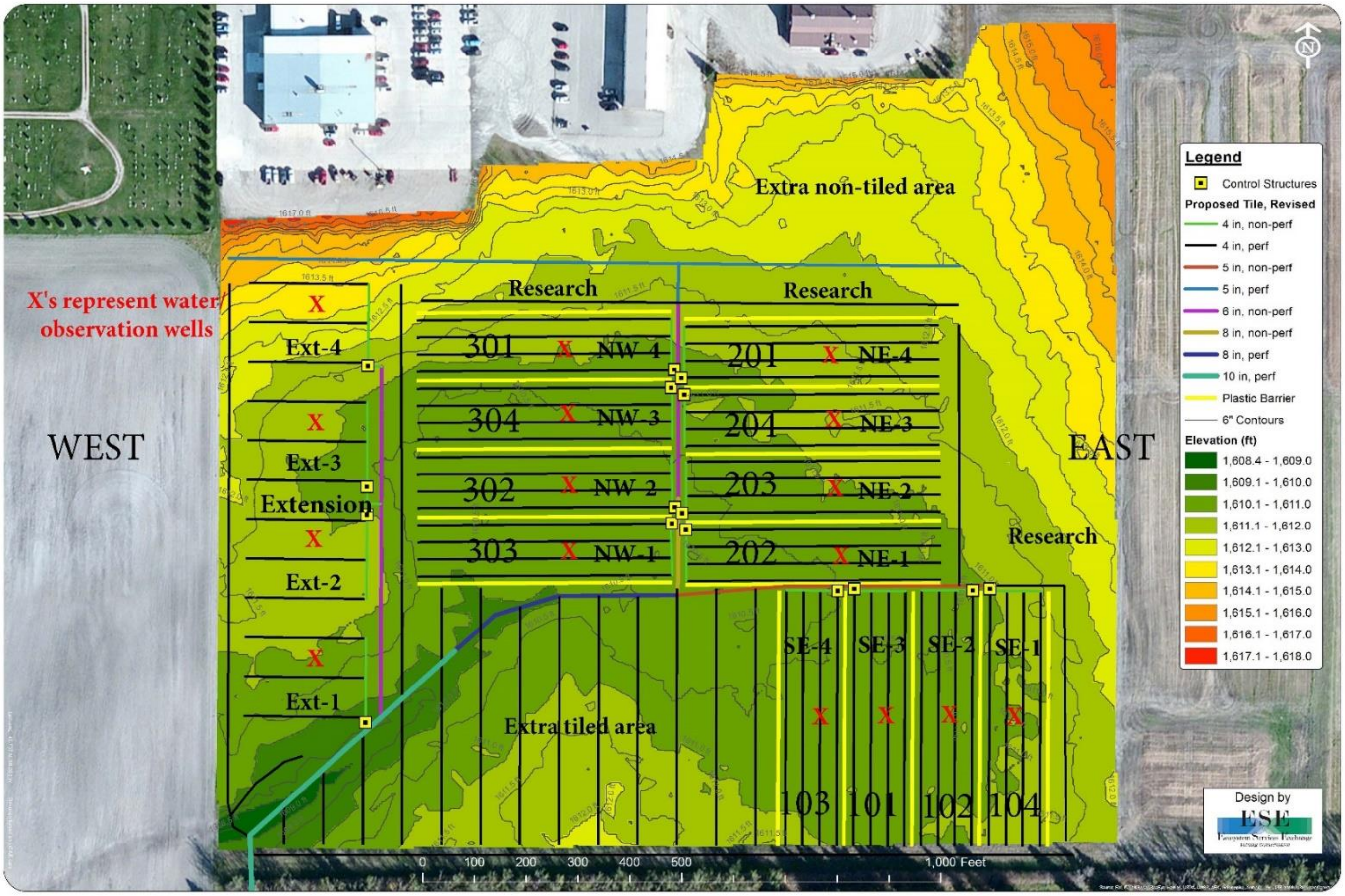


Figure 1. Final layout of the Langdon Research Extension Center Groundwater Management Research Project having twelve research plots and three replications. Replication 1 is on the southeast and includes SE-1, SE-2, SE-3 and SE-4 plots, replication 2 is on the northeast and includes NE-1, NE-2, NE-3 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 X's represent the seven and 1/2-foot deep observation wells and yellow boxes indicate the location of water control structures that are four-feet deep.

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

- Evaluate success of tiling on sodic or saline-sodic soils prior to starting salinity or sodicity remediation?
- Evaluate the relationship between varying groundwater depths and resulting soil salt and sodicity levels.
- Evaluate the quality and suitability of water samples collected at the tile drainage lift station as well as upstream and downstream of the lift station 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. Prior to tiling in 2014, site was conventionally tilled, fertilized annually and annual crops like soybean, spring-wheat and canola were planted without much success. Site is also one of the lowest areas at the Research Extension Center, which results in shallow groundwater depths, salinity and sodicity. These effects were maximized due to the poor germination and growth of the annual crops. As per the USDA Web Soil Survey, soil series is a mix of Cavour-Cresbard and Hamerly-Cresbard loams (Figure 2).

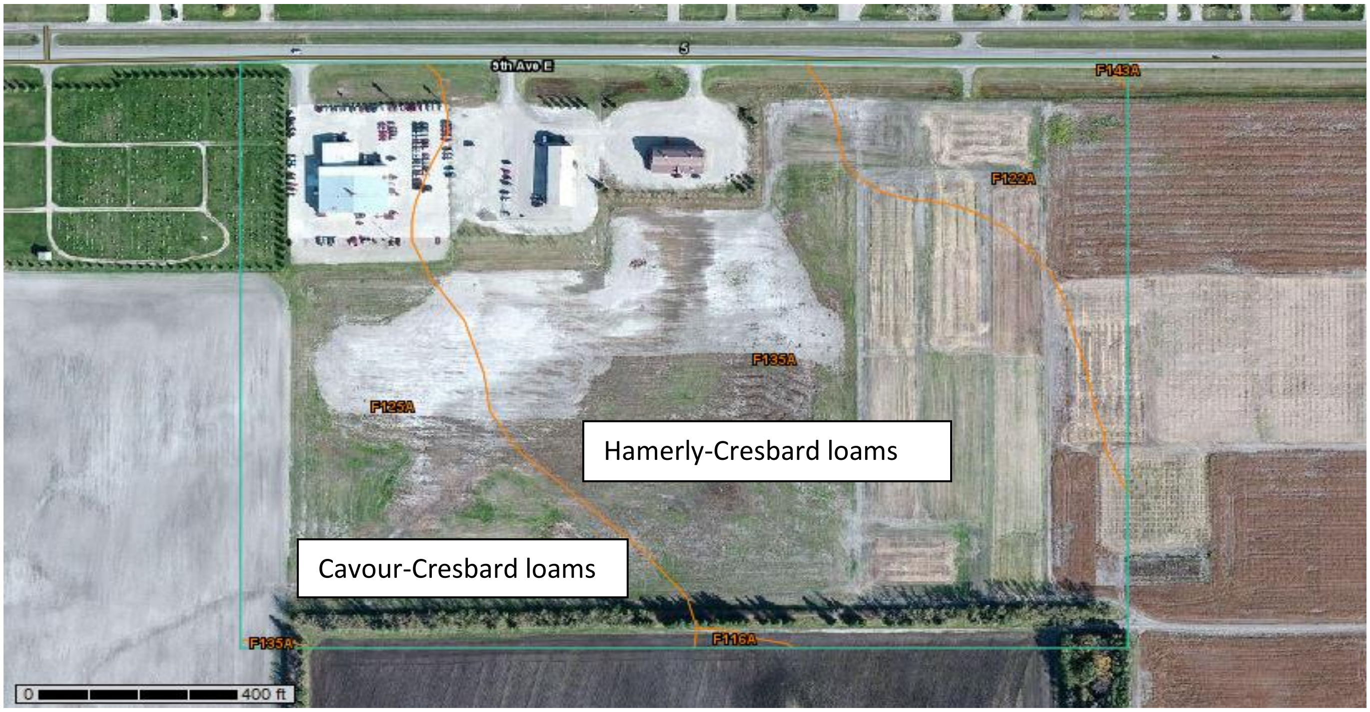


Figure 2. USDA Web Soil Survey map of the Langdon Research Extension Center Groundwater Management Research Project before tiling the site along with the soil series descriptions.

TRIAL DESIGN AND PLOT SIZE

Trial design is randomized complete block design. Each plot is 325 X 80 feet (0.6 acre).

METHODOLOGY

Soil Textural Analysis

Right after tiling in September 2014, soil textural analysis was also performed for all research plots for 0-12, 12-24, 24-36 and 36-48 inch depths by using Hydrometer method (Dar, P.R. 1956 and 1965). This analysis was not repeated in the following years like chemical and physical properties as soil texture hardly changes except some catastrophic events for example flooding, which can bring new soil sediments and deposit them over the existing soil layers.

Soil Chemical Analysis

Three random four-foot deep soil cores were collected from each plot to complete representative soil samples 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), in June of 2018 (four years after tiling and three years after applying the amendments) and in June 2019 (five years after tiling and four years after applying the amendments). Sampling depths were separated into 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 (EC), Sodium Adsorption Ratio (SAR, pH, calcium carbonate equivalent or CCE, bicarbonates (HCO_3^-), chlorides (Cl^-), sulfates (SO_4^{2-}), soil water 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. All of the soil tests were performed by the North Dakota State University Soil Testing Laboratory located in Fargo, ND by using the following methods:

- Soil EC, SAR, pH, soil water saturation percent, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, CO_3^{2-}, HCO_3, Cl^{-} and SO_4^{2-} was analyzed by using the Saturation Paste Extract method (Miller, R.O., Gavlak, R. and Horneck, D., 2013).
- Soil calcium carbonate equivalent percent by using Pressure Calcimeter Principle method (Horvath, B., Opara-Nadi, O. and Beese, F., 2005).
- Soil nitrate-nitrogen by using Transnitration of Salicyclic Acid method (Vendrell, P. and Zupancic, J., 1990).
- Soil phosphorus by using Olsen or Sodium Bicarbonate method (North Central Regional Research Publication No. 221, page-6.5. Revised August, 2015).
- Soil Organic Matter by using Loss-on-Ignition method (North Central Regional Research Publication No. 221, page-12.2 Revised August, 2015).
- Cation exchange capacity by using the Sodium Saturation, Ammonium Extraction method (Chapman, H.D., 1965).

Soil Physical Analysis:

Eighteen-inch deep soil compaction measurements were measured in one-inch increments with the Field Scout SC 900 meter penetrometer in 2015, 2016, 2017, 2018 and 2019. 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, 2018 and 2019. At the time of bulk density sampling, gravimetric water content was also measured for the 0-5 inch and 5-10 inch soil depths.

Weekly Groundwater Depth Measurements

Seven and ½-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 on a weekly basis, whereas, in 2016, 2017, 2018 and 2019 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 tile drainage lift station as well as upstream and downstream of the lift station from the surface water drainage ditch in which tile drainage water was draining, in November of 2015, May, July and September of 2016, May and August of 2017, June 2018 and August and September of 2019. 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:

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

(USDA Handbook No. 60, 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:

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

(USDA Handbook No. 60, P-49).

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 ton of 100% pure elemental sulfur was applied (O'Geen, 2015). Considering the very low solubility of Versalime (locally known as beetlime), for each ton of 100% pure gypsum, three tons of VersaLime were applied. Differences in amendment purities were compensated by using the following formula:

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

(Hanson, 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 (spent 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 the final amendment rates applied to 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, amendment treated plots were rototilled to incorporate amendments into the soil three to four inches deep. Control plots were also rototilled for uniformity purposes. Rototilling was done to uniformly mix the amendments with the soil to achieve optimum reaction between amendments and soil particles.
- Control structures of all of the treatments were fully opened right after the incorporation of the amendments in order to allow for 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 three to four times a year since 2016.

RESULTS AND DISCUSSION

Soil Textural Analysis Results

Soil textural analysis results are shown in Table 2. Based on the results in Table 2, except one sample (R1T1, 0-12 inch depth), all of the samples either had clay or clay loam texture. Details of the sand, silt, clay percent and the textural class of each plot and depth are in Table 2.

Table 2. Details of the soil textural classes of each plot from zero to four-feet depth in 12-inch increments.

Treatments and Replications	Depths (inches)	Sand (%)	Silt (%)	Clay (%)	Soil Texture
R1T1 (101)	0-12	14	40	46	Silty Clay
	12-24	12	38	56	Clay
	24-36	16	36	48	Clay
	36-48	27	39	34	Clay Loam
R1T2 (102)	0-12	18	34	48	Clay
	12-24	17	33	50	Clay
	24-36	25	31	44	Clay
	36-48	40	28	32	Clay Loam
R1T3 (103)	0-12	20	38	42	Clay
	12-24	24	30	46	Clay
	24-36	27	31	42	Clay
	36-48	32	32	36	Clay Loam
R1T4 (104)	0-12	24	32	44	Clay
	12-24	26	24	50	Clay
	24-36	32	30	38	Clay Loam
	36-48”	41	29	30	Clay Loam
R2T1 (201)	0-12	26	33	41	Clay
	12-24	20	34	46	Clay
	24-36	33	29	38	Clay Loam
	36-48	36	29	35	Clay Loam
R2T2 (202)	0-12	26	34	40	Clay Loam
	12-24	24	27	49	Clay
	24-36	23	34	43	Clay
	36-48	40	30	30	Clay Loam
R2T3 (203)	0-12	26	34	40	Clay Loam
	12-24	28	26	46	Clay
	24-36	20	36	44	Clay
	36-48	28	36	36	Clay Loam
R2T4 (204)	0-12	24	34	42	Clay
	12-24	24	31	45	Clay
	24-36	34	30	36	Clay Loam
	36-48	38	34	28	Clay Loam
R3T1 (301)	0-12	26	36	38	Clay Loam

	12-24	23	31	46	Clay
	24-36	28	32	40	Clay Loam
	36-48	45	27	28	Clay Loam
R3T2 (302)	0-12	20	36	44	Clay
	12-24	20	32	48	Clay
	24-36	24	28	48	Clay
	36-48	24	31	45	Clay
R3T3 (303)	0-12	18	38	44	Clay
	12-24	14	29	57	Clay
	24-36	21	37	42	Clay
	36-48	24	33	43	Clay
R3T4 (304)	0-12	26	38	36	Clay Loam
	12-24	20	32	48	Clay
	24-36	23	27	50	Clay
	36-48	20	39	41	Clay

Soil Chemical Analysis Results

The findings below are based on the statistical analysis of the soil chemical properties analyzed in 2014, 2016, 2017, 2018 and 2019 and soil physical properties measured in 2015, 2016, 2017, 2018 and 2019. That was done to compare the differences in soil chemical properties due to the effects of treatments (soil amendments). In addition, effects of annual growing-season rainfall, resulting average annual growing-season groundwater depths and potential evapotranspiration (Penman) measured during May to October on a weekly basis were noted for any change in the soil chemical properties. For the soil physical properties, differences were compared due to the effects of treatments (soil amendments) and the available soil moisture levels measured as the gravimetric soil water content at the time of bulk density sampling or penetrometer resistance measurements. For both comparisons, SAS package 9.4 was used at 95% confidence interval. The treatment means of EC, SAR, pH, NO_3-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.

Annual Changes in the Soil Chemical Properties

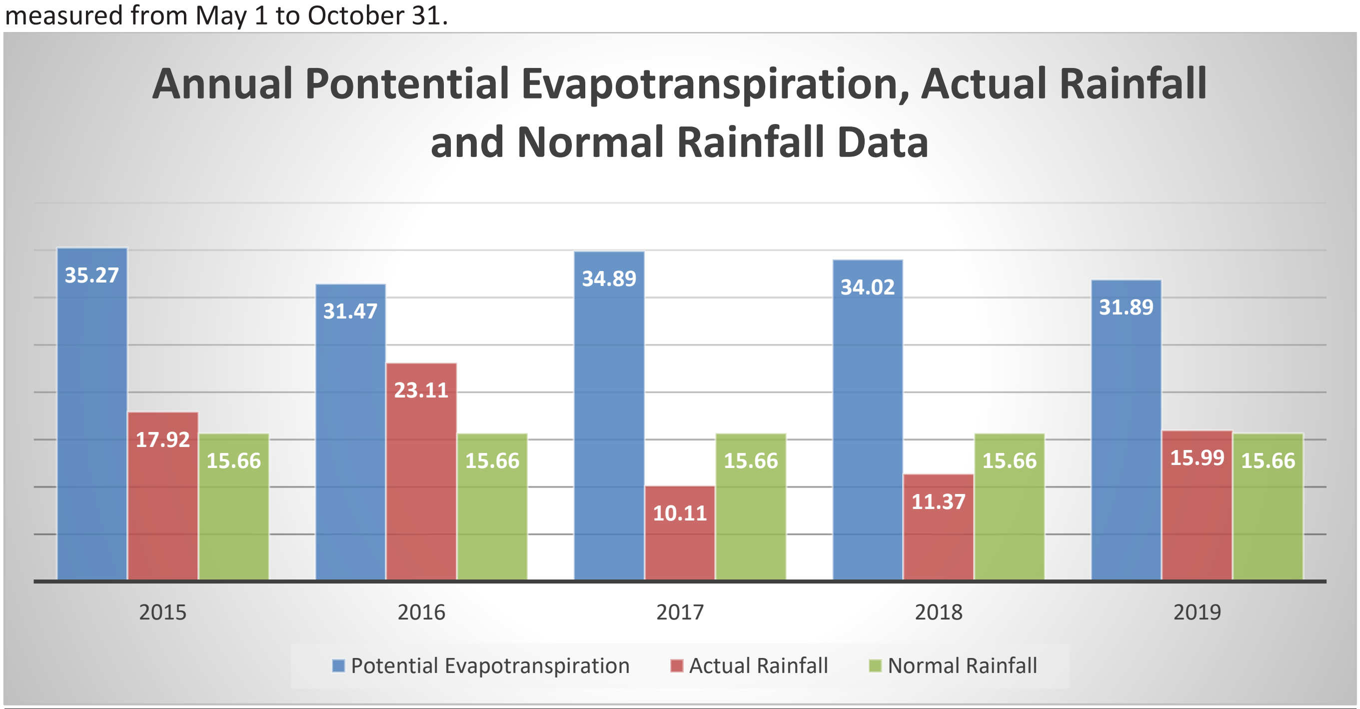
At the time of tiling in 2014, all treatments (plots) had moderately high EC levels with control treatments having the lowest levels (mean = 7.39 dS/m) and gypsum treatments having the highest levels (mean = 9.58 dS/m). The soil SAR levels in all of the treatments were high to very high with control treatments having the lowest levels (mean = 12.58) and gypsum treatments having the highest levels (mean = 18.36). Soil pH of all treatments were close to neutral. Soil NO_3^--N and P levels were medium, whereas O.M. levels were moderately high in all treatments. Soil CEC and saturation % were in the higher range in all treatments. Among 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+}, Mg^{2+} and K^+. Details are in Table 3.

Table 3. The treatment means of the soil chemical properties at the time of tiling (2014) and before the application of soil amendments.

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

Changes in soil chemical properties are also greatly influenced by the fluctuations in the weather like annual evapotranspiration and rainfall (Figure 3), and resulting groundwater depths and capillary rise of soil water.

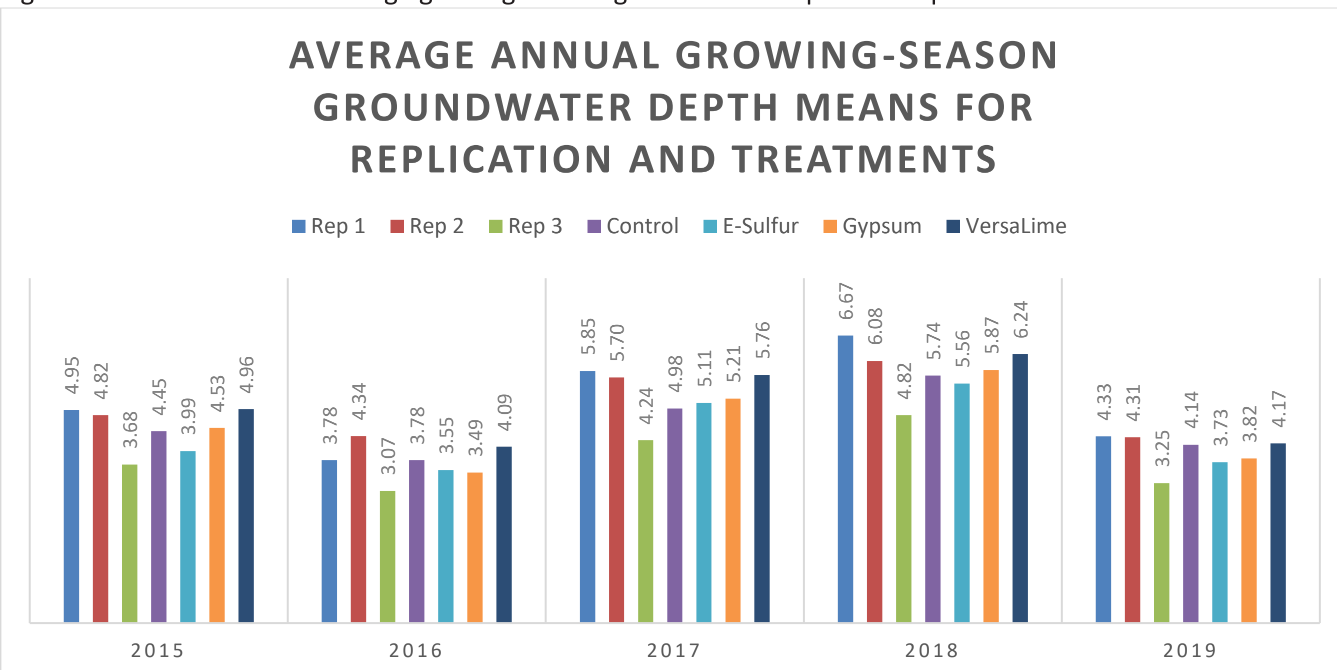
Figure 3. Annual growing-season potential evapotranspiration (Penman), actual rainfall and normal rainfall in inches measured from May 1 to October 31.



A Bigger gap between evapotranspiration and rainfall means increased capillary rise of soil water and less leaching of soluble salts. A narrower gap between these two could result in shallower groundwater depths, however, under good soil water infiltration and improved drainage, excess salts can be moved out of the fields. In addition, a narrower gap between evapotranspiration and rainfall will result in reduced capillary rise of soil water (wicking up). In 2016, the gap between evapotranspiration and rainfall was narrow, site was tiled and the infiltration was still good as higher levels of soluble salts were neutralizing the dispersion cause by sodicity. That resulted in the highest decrease in soil salt levels since the site has been tiled in 2014. In 2017, 2018 and early part of 2019, there was an increase in soil salt levels compared to 2016, which could be due to an increase the capillary rise of soil water due to the greater differences between annual evapotranspiration and rainfall.

Figure 4 below has the average annual growing-season groundwater depth means for replications and treatments for 2015, 2016, 2017, 2018 and 2019. The means of groundwater depths represent actual annual measurements of groundwater depths measured from May 1 to October 31 on a weekly basis.

Figure 4. Annual means of average growing-season groundwater depths for replications and treatments in feet.



Note: In 2015, groundwater depths were only measured from mid-June to end of October.

The 2016 groundwater depths were shallower than the depths in 2015, 2017, 2018 and 2019, whereas, the 2018 groundwater depths were the deepest versus rest of the years. Replication 3 had significantly shallower annual groundwater depths compared to replication 1 and 2 during all years.

These fluctuations in the groundwater depths are also reflective of a very wet 2016 versus drier weather in 2017 and 2018. In 2019, weather was dry until July 30th. From July 31st, it started getting wet. The NDSU Langdon Research Extension Center, NDAWN Station recorded 5.88 inches of rainfall versus a normal of 9.71 inches from May 1st to July 30th of 2019. The Total Potential Evapotranspiration (Penman) for the same period was 21.44 inches. Same station recorded 9.74 inches of rain versus a normal of 4.76 inches from July 31st to October 5th, 2019. The Total Potential Evapotranspiration (Penman) for the same period was 9.04 inches. On July 31st, 0.77 inch was recorded and in August of 2019, 2.48 inches of rain were recorded versus a normal of 2.57 inches. September 2019 was the wettest month of the year and 5.87 inches of rain were recorded versus a normal of 1.81 inches. Overall, most of the early growing-season was dry, whereas, fall was very wet, which also created a lot of harvest issues.

Differences in Soil Electrical Conductivity (EC) Levels

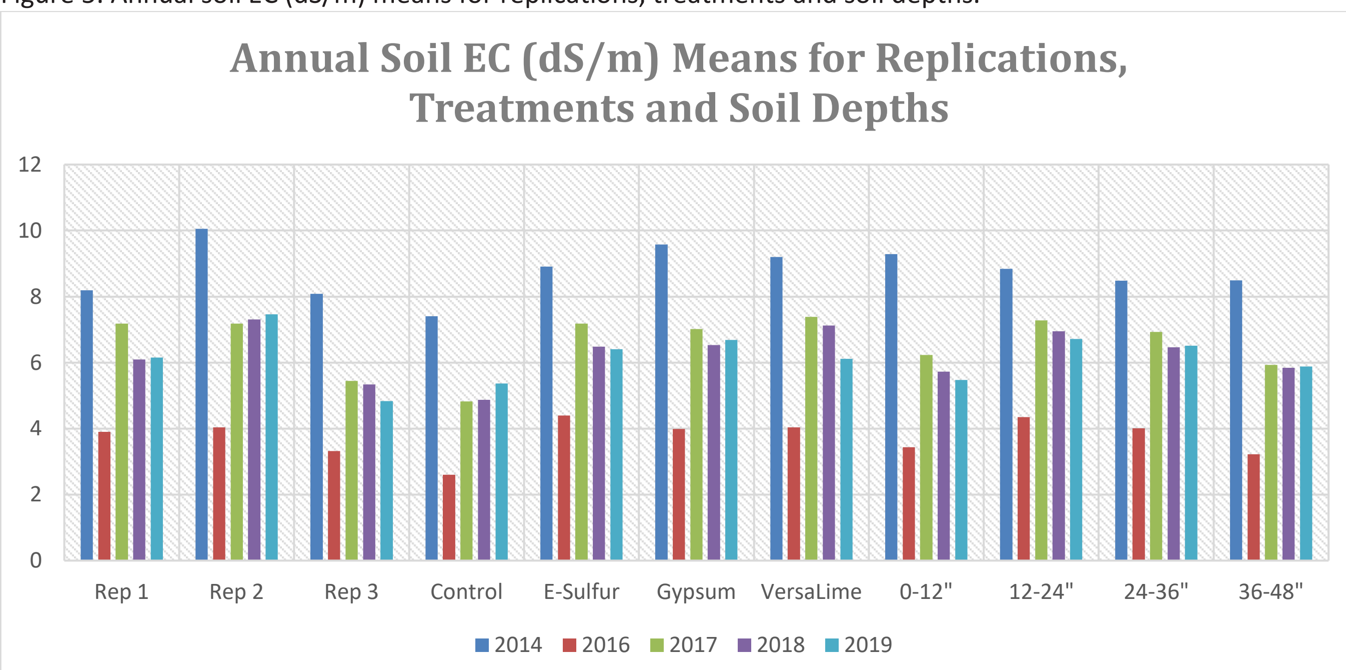
Statistically, there were significant differences in the annual soil EC (dS/m) levels in replications, treatments and soil depths (Figure 5).

At the time of tiling in 2014, replication 2 had significantly higher EC levels compared to replication 1 and 3. Overall, EC levels in all three replications remained high in 2014 versus rest of the years, whereas, 2016 EC levels were the lowest in all replications versus the EC levels during 2014, 2017, 2018 and 2019.

In 2014, Gypsum and VersaLime treatments had significantly higher EC levels compared to control, which also had numerically lower EC levels compared to E-Sulfur treatments. The EC levels in Control treatments decreased significantly in 2016 versus EC levels in rest of the treatments in 2014, 2017, 2018 and 2019. In addition, E-Sulfur, gypsum and VersaLime treatments in 2016 had significantly lower EC levels compared to rest of the annual treatments except control treatments in 2017, 2018 and 2019. Overall, EC levels in all treatments were high in 2014 and low in 2016. Despite decrease in 2016, EC levels increased back in 2017 and that trend continued in 2018 and 2019 due to drier weather and resulting capillary rise (wicking up) of soil water.

In 2014, 0-12 inch soil depths had the highest EC levels followed by 12-24, 24-36 and 36-48 inch depths. However, from 2016 to 2019, highest EC levels were observed in 12-24 inch depths followed by 24-36, 0-12 and 36-48 inch depths. Overall, like replications and treatments, EC levels in all soil depths in 2014 were higher than rest of the years, whereas, 2016 EC levels were the lowest for all soil depths.

Figure 5. Annual soil EC (dS/m) means for replications, treatments and soil depths.



Apart from the effects of different treatments on soil EC levels, there were some interesting effects of annual growing-season rainfall and resulting average annual growing-season groundwater depths and total potential evapotranspiration (Penman) and resulting capillary water movement on EC levels. (Table 3).

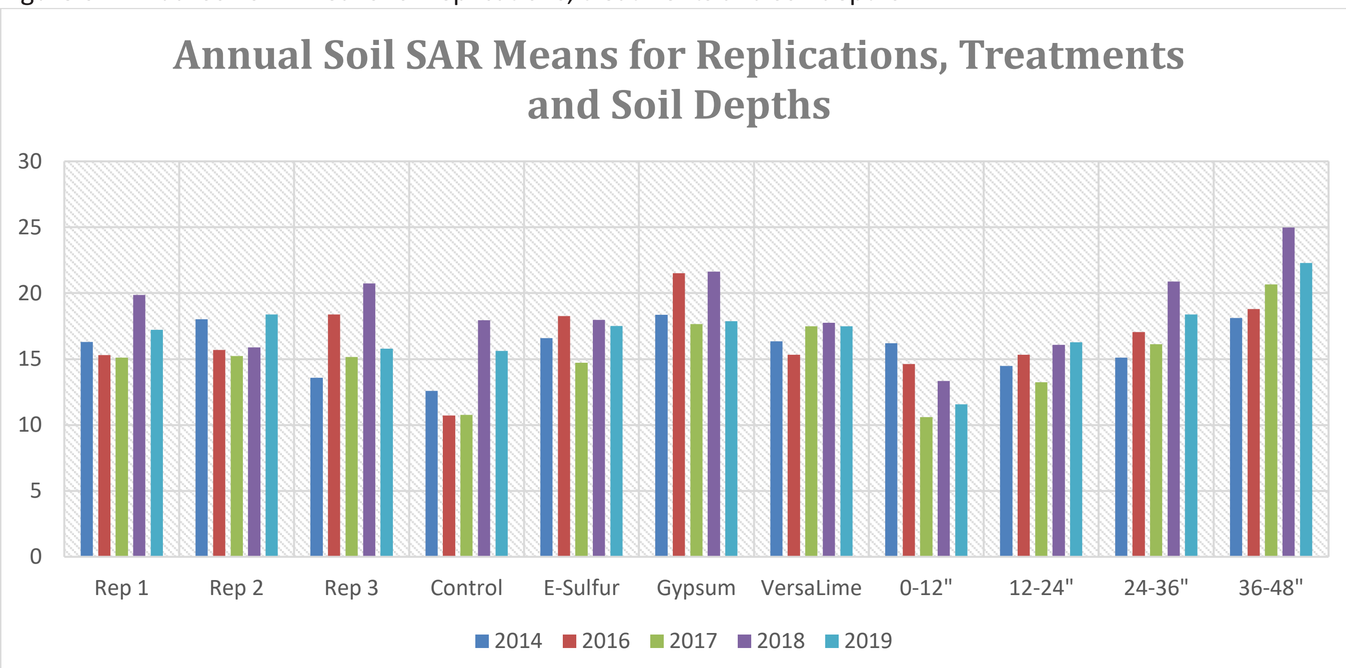
The 2016 soil EC levels were lower than the 2017, 2018 and 2019 EC levels because of the highest annual growing-season rainfall (23.11 inches) under shallowest average annual growing-season groundwater depths (Figure 2). The average annual growing-season groundwater depths lowered in 2017, 2018 due to drier weather, which also resulted in increased capillary rise and higher EC levels. The lower groundwater depth trend continued in 2019 during early part of the growing-season until late fall when 5.87 inches of rain was recorded during September versus a normal of 1.81 inches. Overall, 9.74 inches of rain was recorded during July 31st to October 5th versus a normal of 4.76 inches.

Overall, EC levels remained the highest in 2014 followed by 2017, 2018, 2019 and 2016, replication 2 had the highest EC levels followed by replication 1 and 3, VersaLime treatments had the highest levels followed by gypsum, E-sulfur and control treatments and 12-24 inch soil depths had the highest EC levels followed by 24-36 inch, 0-12 inch and 36-48 inch depths.

Differences in Soil Sodium Adsorption Ratio (SAR) Levels

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

Figure 6. Annual soil SAR means for replications, treatments and soil depths.



At the time of tiling (2014), gypsum treatments had significantly higher SAR levels versus control treatments. In 2016, E-sulfur and gypsum treatments had significantly higher SAR versus control treatments, whereas VersaLime treatments also had numerically higher SAR levels than the control treatments. That trend continued in 2017. In 2018, control treatments had significantly higher SAR levels versus the control treatments in 2014, 2016 and 2017.

In all of the years, soil SAR levels increased with soil depth with 0-12 inch depths having the lowest levels, whereas, 36-48 inch depths having the highest levels.

Unlike soil EC, there was not a noticeable effect of annual growing-season rainfall and resulting average annual growing-season groundwater depths and potential evapotranspiration (Penman) and resulting capillary water movement on SAR levels.

Overall, SAR levels remained the highest in 2018 followed by 2019, 2016, 2014 and 2017, replication 1 had the highest SAR levels followed by replication 3 and 2, gypsum treatments had the highest levels followed by E-sulfur, VersaLime and control treatments and 36-48 inch soil depths had the highest SAR levels followed by 24-36 inch, 12-24 inch and 0-12 inch depths.

Differences in Soil pH Levels

Statistically, there were significant differences in the annual soil pH levels in replications, treatments and soil depths (Figure 7).

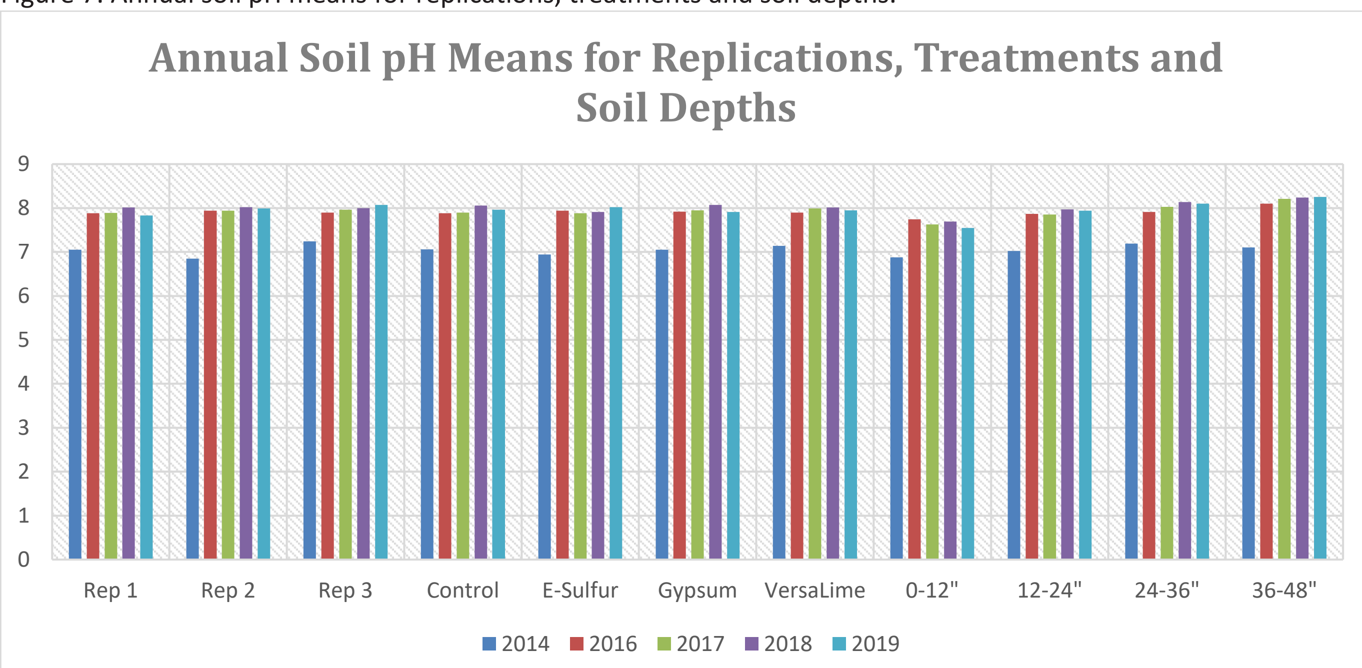
At the time of tiling (2014) all of the replications had lower pH levels versus the pH levels in 2016, 2017, 2018 and 2019. The lower soil pH levels in 2014 can be attributed to the lower soil moisture levels at the time of sampling (September 2014) compared to rest of the years when samples were taken in June.

Similarly, pH levels of all treatments in 2014 had lower levels versus rest of the years. Again, that could be attributed to the lower soil moisture levels at the time of sampling (September 2014) compared to rest of the years.

Like SAR, soil pH significantly increased with soil depth with 0-12 inch depths having the lowest pH levels and 36-48 inch depths having the highest pH levels. Increase in pH with soil depth was due to the increase in soil moisture levels. Since soil moisture levels had a prominent effect on soil pH, annual growing-season rainfall and resulting average annual growing-season groundwater depths and potential evapotranspiration (Penman) and resulting capillary water movement also had an effect on soil pH.

Overall, pH levels remained the highest in 2018 followed by 2019, 2017, 2016 and 2014 and replication 3 had the highest pH levels followed by replication 2 and 1. That is interesting as generally, replication 3 has the shallowest average annual growing-season groundwater depths followed by replication 2 and 1 every year. The VersaLime treatments had the highest levels followed by gypsum, control and E-sulfur treatments and 36-48 inch soil depths had the highest pH levels followed by 24-36 inch, 12-24 inch and 0-12 inch depths.

Figure 7. Annual soil pH means for replications, treatments and soil depths.



Differences in Soil Nitrate-Nitrogen (NO_3^-N) Levels

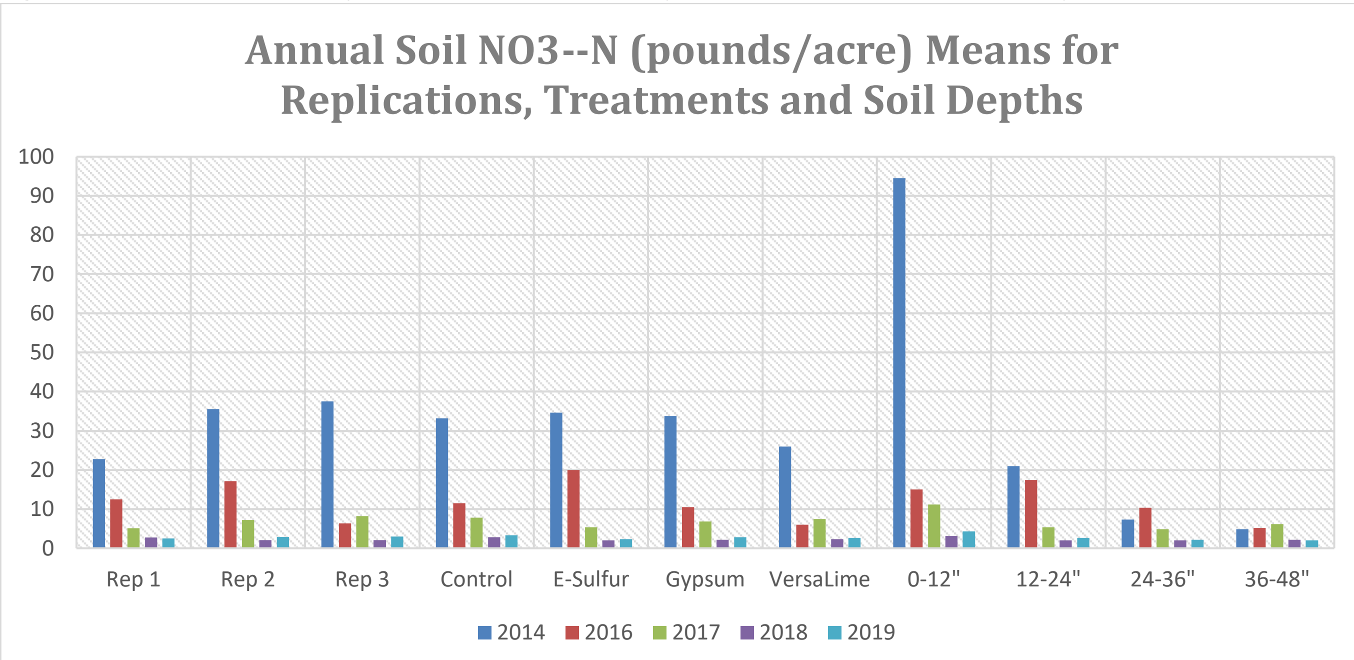
Statistically, there were significant differences in the annual soil NO_3^--N (pounds/acre) levels in replications, treatments and soil depths (Figure 8).

The soil NO_3^--N levels at the time of tiling (2014) were significantly higher than the NO_3^--N levels in 2016, 2017, 2018 and 2019. Similarly, all treatments in 2014 had significantly higher NO_3^--N levels versus rest of the years. At the time of tiling, 0-12 inch soil depth had significantly higher NO_3^--N levels versus rest of the depths, whereas, 12-24 inch depths had significantly higher levels than 24-36 and 26-48 inch depths. Higher NO_3^--N levels prior to tiling (2014), could be due to the annual fertilization this site received at the time of planting. In addition, a steady decline in soil NO_3^--N levels may also be due to leaching, removal by the perennial grass mix and no application since 2014.

Since NO_3^--N are very susceptible to leaching, annual growing-season rainfall and resulting average annual growing-season groundwater depths may have prominent effect on NO_3^--N levels.

Overall, NO_3^--N levels remained the highest in 2014 followed by 2016, 2017, 2019 and 2018, replication 2 had the highest NO_3^--N levels followed by replication 3 and 1, E-sulfur treatments had the highest levels followed by control, gypsum and VersaLime treatments and 0-12 inch soil depths had the highest NO_3^--N levels followed by 12-24 inch, 24-36 inch and 36-48 inch depths.

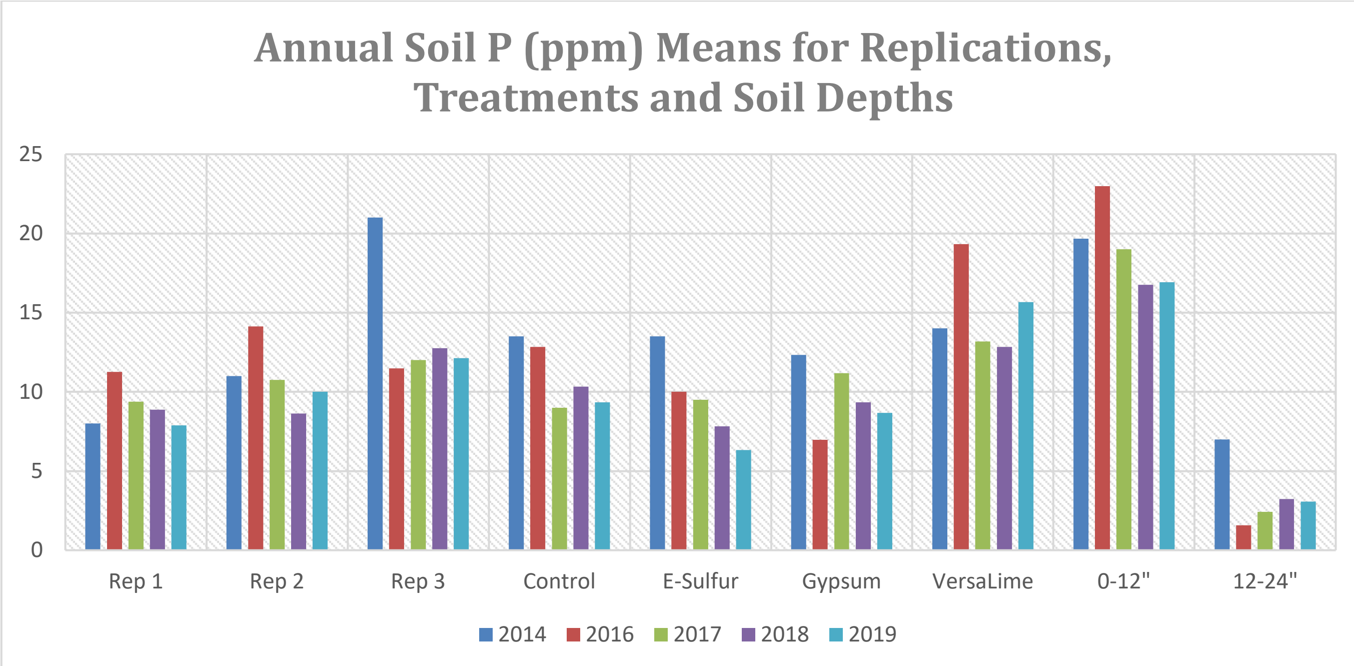
Figure 8. Annual soil NO_3^--N (pounds/acre) means for replications, treatments and soil depths.



Differences in Soil Phosphorous (P) Levels

Differences in soil P (ppm) levels are shown in Figure 9. The only statistically significant difference observed in the annual soil P levels was that the 0-12 inch soil depths had significantly higher P levels versus 12-24 inch depths.

Figure 9. Annual soil P (ppm) means for replications, treatments and soil depths.



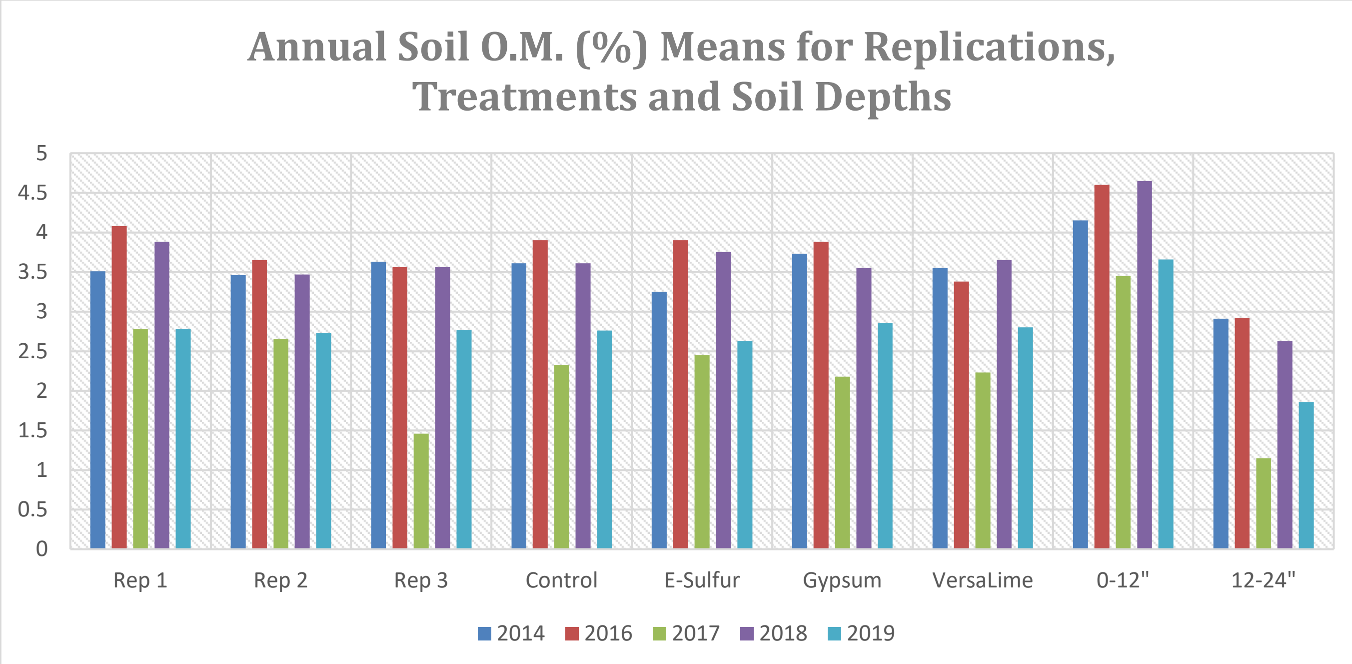
Overall, P levels remained the highest in 2014 followed by 2016, 2017, 2018 and 2019, replication 3 had the highest P levels followed by replication 2 and 1, VersaLime treatments had the highest levels followed by control, gypsum and E-sulfur treatments and 0-12 inch soil depths had the highest P levels followed by 12-24 inch depths.

It is also important to note that like nitrogen, no phosphate fertilizer has been applied to the site since 2014. Before 2014, site was planted with annual crops and commercial fertilizer was applied annually. The numerically lower P levels in 2017, 2018 and 2019 versus 2014 and 2016 could also be due to the drier weather during these years resulting in limited P solubility and mobility.

Differences in Soil Organic Matter Percent (SOM) Levels

Soil organic matter (%) levels are shown in Figure 10. Statistically, there were significant differences in the annual O.M. levels in replications, treatments and soil depths.

Figure 10. Annual soil O.M. (%) means for replications, treatments and soil depths.



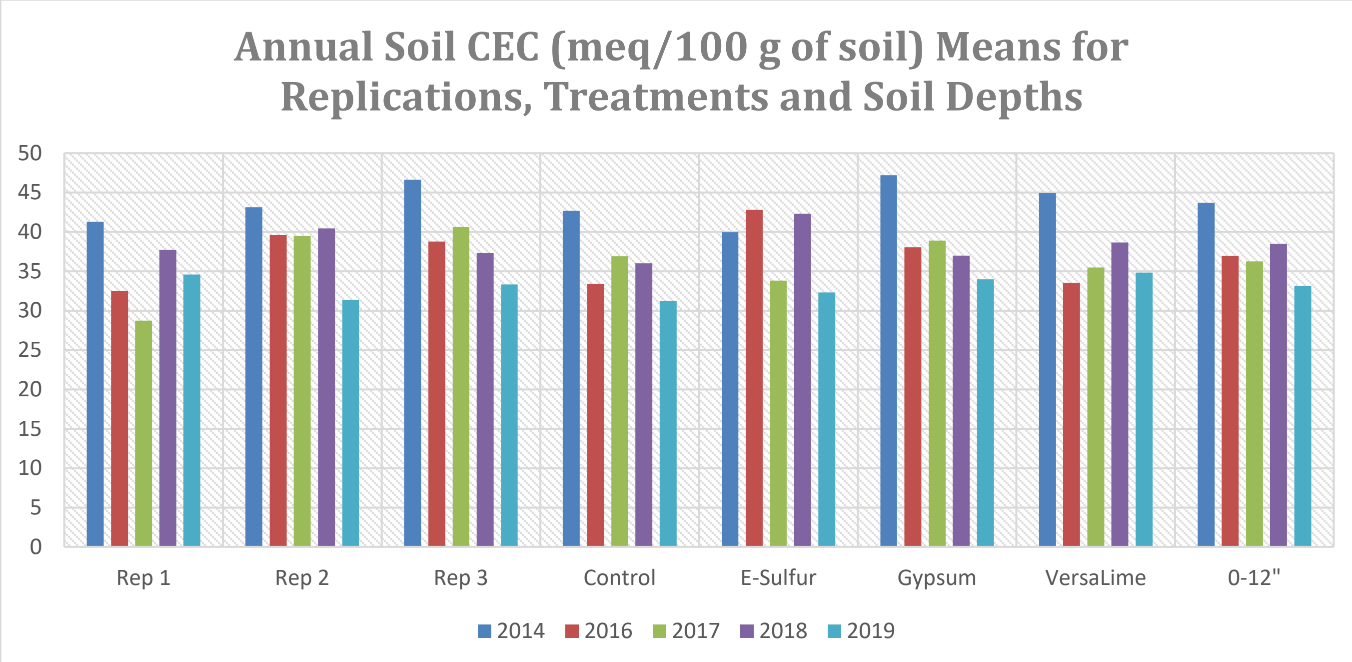
In 2016 and 2018, replication 1 had significantly higher O.M. levels versus replications 1, 2 and 3 in 2017 and 2019. All four treatments had significantly lower O.M. levels in 2017 versus control, E-sulfur and gypsum treatments in 2016 and E-sulfur treatments in 2018. In addition, numerically, the 2019 O.M. levels in all treatments remained lower compared to the levels in 2014, 2016 and 2018. Lower soil O.M. levels in 2017 and 2019 in all treatments could be due to a slightly drier weather in June of 2017 and 2019 when soil samples were collected. The 0-12 inch soil depths had significantly higher O.M. levels than the 12-24 inch depths in 2014, 2016, 2017, 2018 and 2019. There were also some significant differences in the annual O.M. levels within the 0-12 inch depths. The O.M. levels in 2016 and 2018 in 0-12 inch soil depths were significantly higher than the levels in 0-12 inch depths in 2014, 2017 and 2019. In addition, 2014 O.M. levels in 0-12 inch soil depths were significantly higher than the levels in same depths in 2017 and 2019. The 12-24 inch depths had significantly higher O.M. levels in 2014, 2016 and 2018 versus 2017 and 2019 for the same depths. In addition, 2019 O.M. levels in 12-24 inch depths were significantly higher than the levels in 12-24 inch depths in 2017.

Overall, O.M. levels remained the highest in 2014 followed by 2016, 2018, 2019 and 2017, replication 1 had the highest O.M. levels followed by replication 2 and 3, Gypsum treatments had the highest levels followed by control, E-sulfur and VersaLime treatments and 0-12 inch soil depths had the highest O.M. levels followed by 12-24 inch depths.

Differences in Soil Cation Exchange Capacity (CEC) Levels

Soil cation exchange capacity (meq/100 g of soil) levels are shown in Figure 11. Statistically, there were significant differences in the annual soil CEC levels in replications and within the 0-12 inch soil depths.

Figure 11. Annual soil CEC (meq/100 g of soil) means for replications, treatments and soil depths.



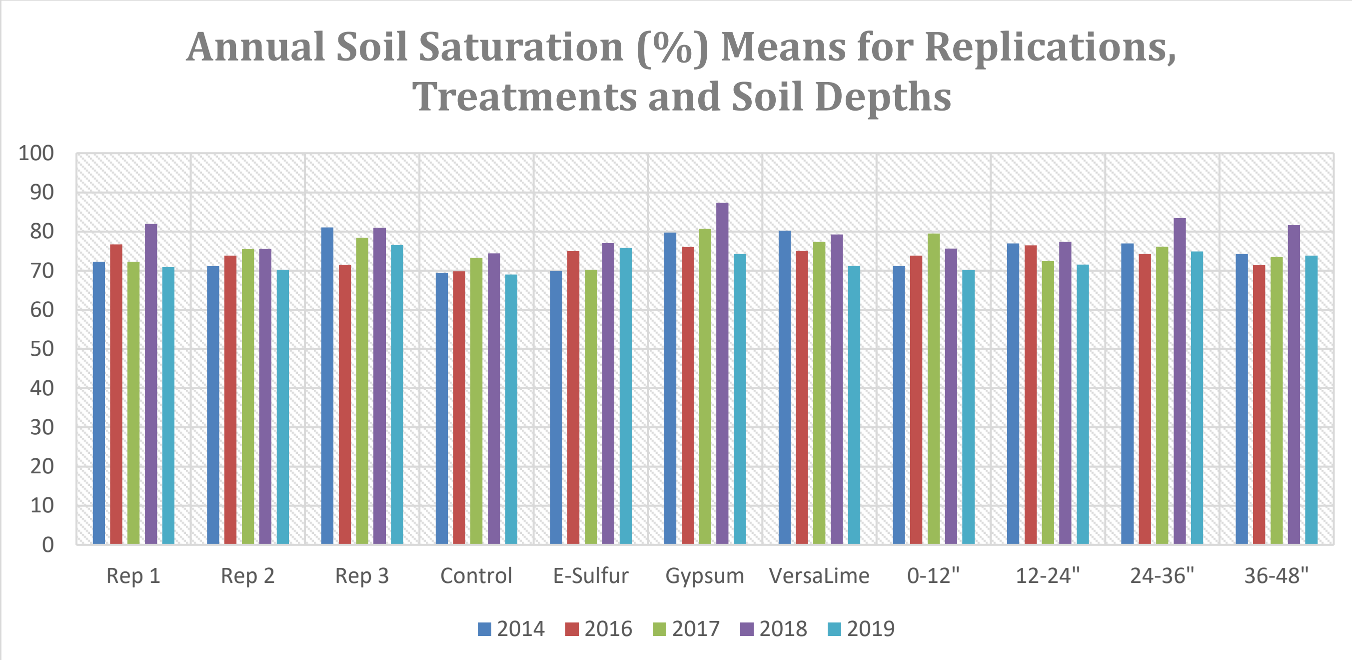
Replication 3 in 2014 had significantly higher CEC levels versus replication 1 in 2016, 2017 and 2019, replication 2 in 2019 and replications 3 in 2018 and 2019. For the 0-12 inch soil depths, CEC levels in 2014 were significantly higher than the levels in 2016, 2017 and 2019.

Overall, CEC levels remained the highest in 2014 followed by 2018, 2016, 2017 and 2019, replication 3 had the highest CEC levels followed by replication 2 and 1, Gypsum treatments had the highest levels followed by E-sulfur, VersaLime and control treatments.

Differences in Soil Water Saturation Percent Levels

Soil saturation (%) levels are shown in Figure 12. Statistically, there were significant differences in the annual soil saturation levels in replications, treatments and soil depths.

Figure 12. Annual soil saturation (%) means for replications, treatments and soil depths.



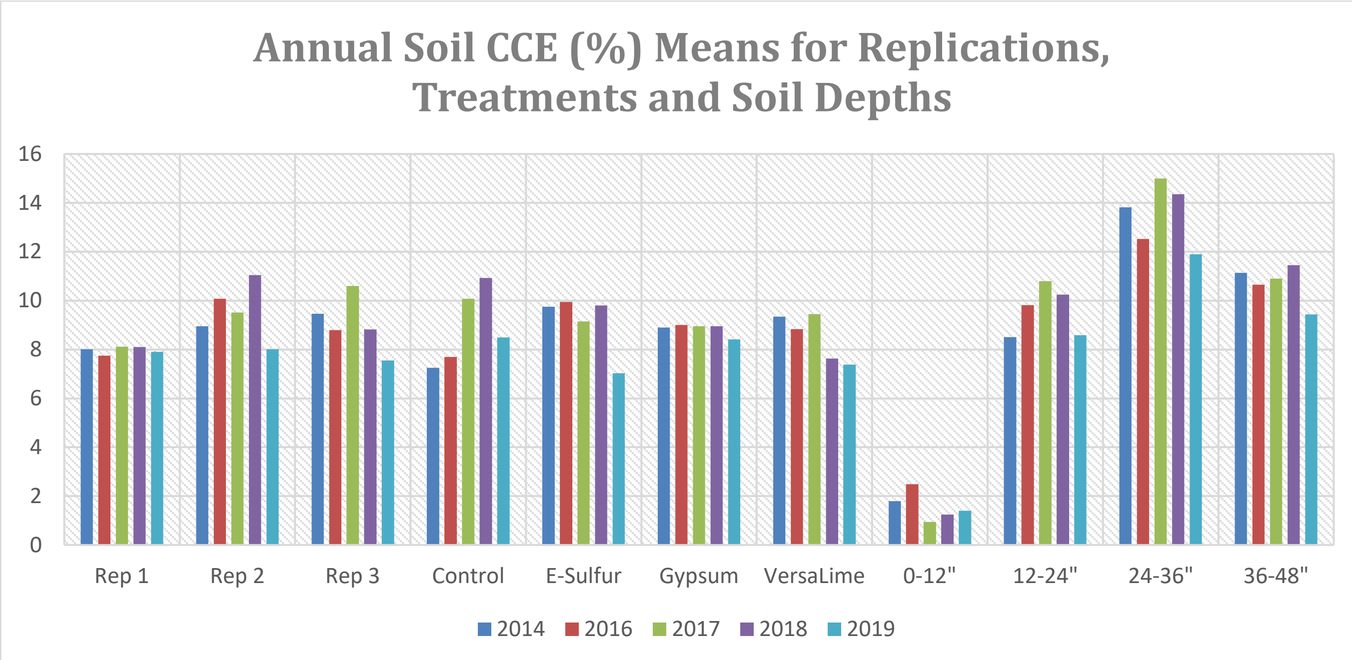
Replication 1 in 2018 had significantly higher saturation levels versus replication 1 in 2014, 2017 and 2019, replications 2 in 2014, 2016, 2017, 2018 and 2019 and replication 3 in 2016. The saturation levels in gypsum treatments in 2018 were significantly higher than the levels in control, E-sulfur, gypsum and VersaLime treatments during rest of the years. The 24-36 inch soil depths in 2018 had significantly higher saturation levels than the levels in 0-12 inch depths in 2014, 2016, 2018 and 2019, 12-24 inch depth in 2017 and 2019, 24-36 inch depths in 2017, 2016 and 2019 and 36-48 inch depths in 2014, 2016, 2017 and 2019.

Overall, saturation levels remained the highest in 2018 followed by 2014, 2017, 2016 and 2019, replication 3 had the highest saturation levels followed by replication 1 and 2, Gypsum treatments had the highest levels followed by VersaLime, E-sulfur and control treatments and 24-36 inch soil depths had the highest saturation levels followed by 12-24 inch, 36-48 inch and 0-12 inch depths.

Differences in Soil Calcium Carbonate Equivalent Percent (CCE) Levels

Soil calcium carbonate equivalent (%) levels are shown in Figure 13. Statistically, there were significant differences in the annual soil CCE levels in soil depths.

Figure 13. Annual soil CCE (%) means for replications, treatments and soil depths.



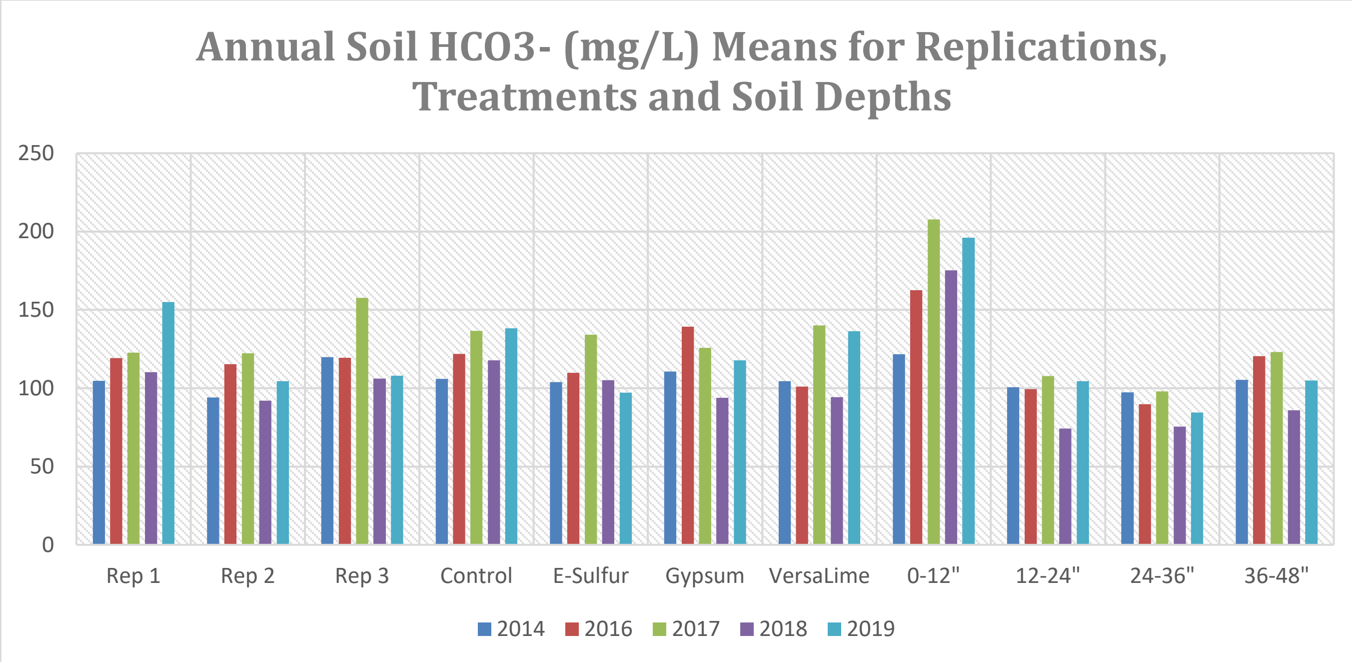
The 0-12" soil depths in all years remained significantly lower than the levels in 12-24 inch, 24-36 inch and 36-48 inch depths in all years. In addition, 24-36 inch soil depths had significantly higher CCE levels versus the levels in 0-12 inch and 12-24 inch depths in 2014, 2016, 2017, 2018 and 2019, in 24-36 inch depths in 2019 and 36-48 inch depths in 2014, 2016, 2017, 2018 and 2019.

Overall, CCE levels remained the same from 2014 to 2018, whereas, were slightly lower in 2019 compared to rest of the years, replication 2 had the highest CCE levels followed by replication 3 and 1, E-sulfur treatments had the highest levels followed by Control, gypsum and VersaLime, treatments and 24-36 inch soil depths had the highest CCE levels followed by 36-48 inch, 12-24 inch and 0-12 inch depths.

Differences in Soil Bicarbonate (HCO_3^-) Levels

Soil bicarbonate (mg/L) levels are shown in Figure 14. Statistically, there were significant differences in the annual HCO_3^- levels in replications and soil depths.

Figure 14. Annual soil HCO_3^- (mg/L) means for replications, treatments and soil depths.



Replication 3 in 2017 had significantly high soil HCO_3^- levels versus all replications except replication 1 in 2017 and 2019 and replication 2 in 2017. In addition, replication 1 in 2019 had significantly high soil HCO_3^- levels versus replication 1 in 2014 and 2018, replication 2 in 2014, 2016, 2018 and 2019 and replication 3 in 2018 and 2019.

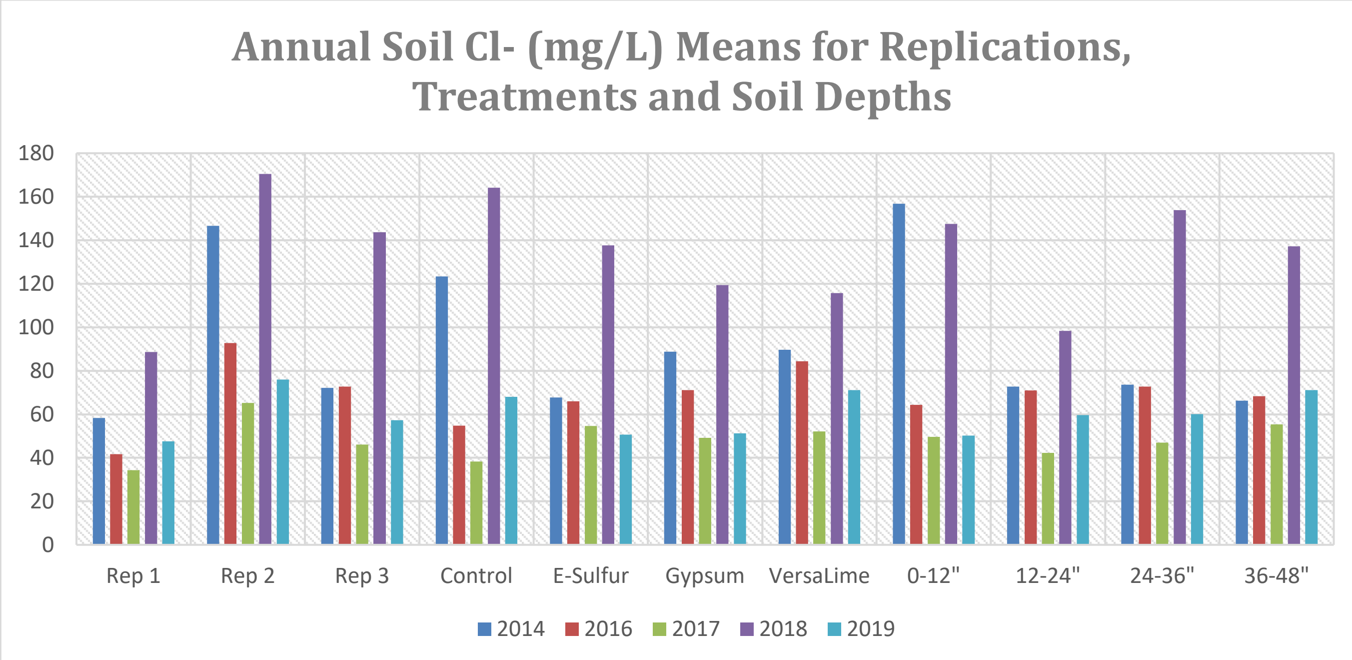
The 0-12 inch soil depths in 2017 had significantly high soil HCO_3^- levels versus rest of the depths except 0-12 inch depths in 2018 and 2019. In addition, 0-12 inch depths in 2016, 2018 and 2019 had significantly high soil HCO_3^- levels versus 0-12 inch depths in 2014, 12-24 inch depths in 2014, 2016, 2017, 2018 and 2019, 24-36 inch depths in 2014, 2016, 2017, 2018 and 2019 and 36-48 inch depths in 2014, 2016, 2017, 2018 and 2019.

Overall, HCO_3^- levels remained the highest in 2017 followed by 2019, 2016, 2014 and 2018, replication 1 had the highest HCO_3^- levels followed by replication 3 and 2, control treatments had the highest levels followed by gypsum, VersaLime and E-sulfur treatments and 0-12 inch soil depths had the highest HCO_3^- levels followed by 36-48 inch, 12-24 inch and 24-36 inch depths.

Differences in Soil Chloride (Cl^-) Levels

Soil chloride (mg/L) levels are shown in Figure 15. Statistically, there were significant differences in the annual Cl^- levels in replications, treatments and soil depths.

Figure 15. Annual soil Cl^- (mg/L) means for replications, treatments and soil depths.



Replication 2 in 2014 and 2018 and replication 3 in 2018 had significantly higher soil Cl^- levels than rest of the replications. In addition, replication 2 in 2016 had significantly higher Cl^- levels than replication 1 in 2016 and 2017, whereas, replication 1 in 2018 had significantly higher soil Cl^- levels versus replication 1 in 2017.

The control treatment in 2018 had significantly higher soil Cl^- levels versus rest of the treatments except control in 2014 and E-sulfur, gypsum and VersaLime treatments in 2018. In addition, E-sulfur treatment in 2018 had significantly higher soil Cl^- levels versus E-sulfur in 2014, control, E-sulfur, gypsum and treatments in 2016, control gypsum, E-sulfur and VersaLime treatments in 2017 and control, E-sulfur, gypsum and VersaLime treatments in 2019.

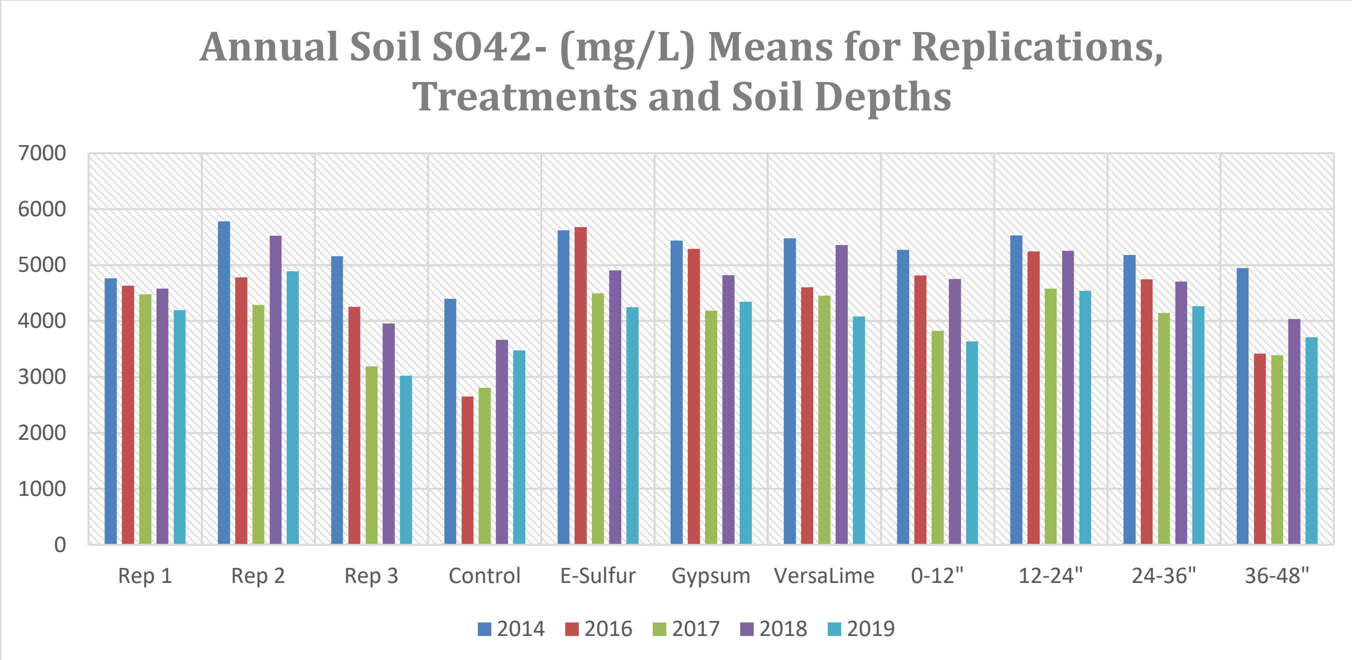
The 2014 0-12 inch soil depths had significantly higher soil Cl^- levels versus than rest of the depths except 0-12 inch, 12-24 inch and 24-36 inch depths in 2018. In addition, 2018 24-36 inch depths had significantly higher soil Cl^- levels compared to 0-12 inch depths in 2016, 2017 and 2019, 12-24 inch depth in 2014, 2016, 2017 and 2019, 24-36 inch depth in 2014, 2016, 2017 and 2019 and 36-48 inch depths in 2014, 2016, 2017 and 2019.

Overall, Cl^- levels remained the highest in 2018 followed by 2014, 2016, 2019 and 2017, replication 2 had the highest Cl^- levels followed by replication 3 and 1, control treatments had the highest levels followed by VersaLime, gypsum and E-sulfur treatments and 0-12 inch soil depths had the highest Cl^- levels followed by 24-36 inch, 36-48 inch and 12-24 inch depths.

Differences in Soil Sulfate (SO_4^{2-}) Levels

Soil sulfate (mg/L) levels are shown in Figure 16. Statistically, there were significant differences in the annual SO_4^{2-} levels in replications and treatments.

Figure 16. Annual soil SO_4^{2-} (mg/L) means for replications, treatments and soil depths.



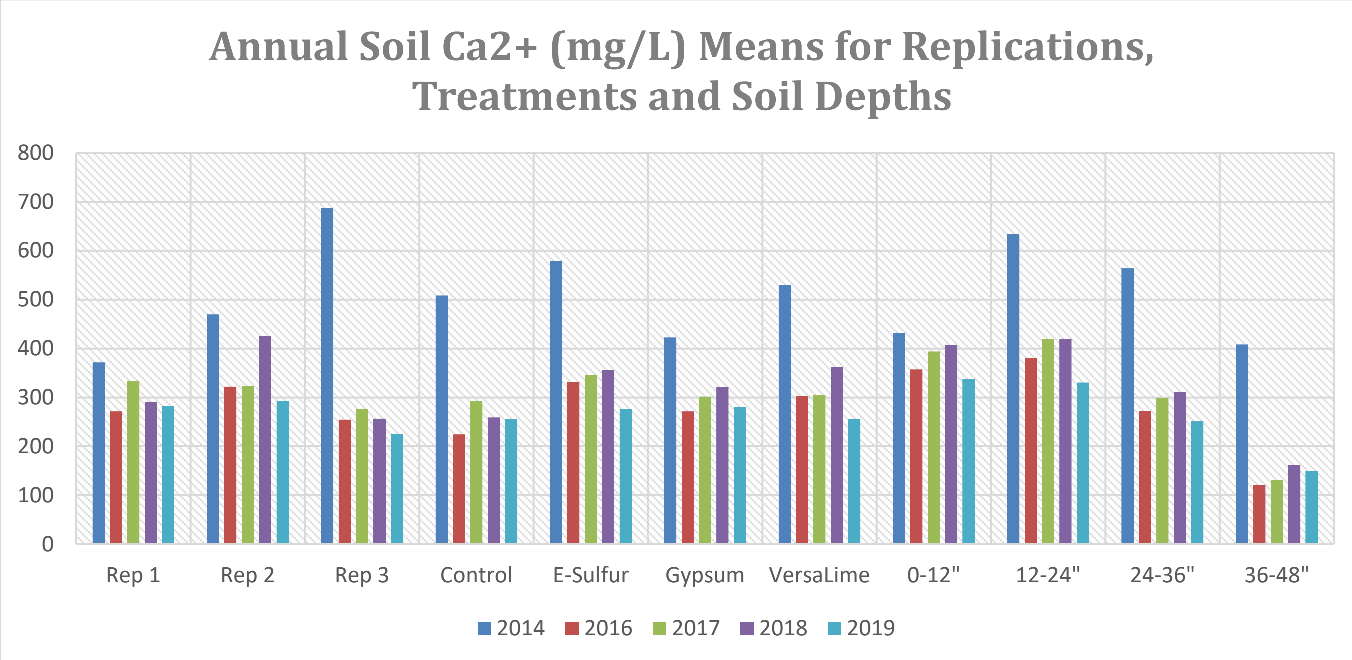
Replication 2 in 2014 had significantly higher SO_4^{2-} levels versus replication 1 in 2017 and 2019, replication 2 in 2017 and replication 3 in 2016, 2017, 2018 and 2019. In addition, replication 2 in 2018 had significantly higher SO_4^{2-} levels than replication 1 in 2019, replication 2 in 2017 and replication 3 in 2016, 2017, 2018 and 2019. The E-sulfur treatments in 2016 had significantly higher SO_4^{2-} levels versus control treatments in 2016, 2017, 2018 and 2019, E-sulfur treatments in 2019, gypsum treatments in 2017 and VersaLime treatments in 2019. In addition, E-sulfur treatments in 2014 had significantly higher SO_4^{2-} levels versus control treatments in 2016, 2017, 2018 and 2019, gypsum treatments in 2017 and VersaLime treatments in 2019.

Overall, SO_4^{2-} levels remained the highest in 2014 followed by 2018, 2016, 2019 and 2017, replication 2 had the highest SO_4^{2-} levels followed by replication 1 and 3, E-sulfur treatments had the highest levels followed by gypsum, VersaLime and control treatments and 12-24 inch soil depths had the highest SO_4^{2-} levels followed by 24-36 inch, 0-12 inch and 36-48 inch depths.

Differences in Soil Calcium (Ca^{2+}) Levels

Soil calcium (mg/L) levels are shown in Figure 17. Statistically, there were significant differences in the annual Ca^{2+} levels in replications, treatments and soil depths.

Figure 17. Annual soil Ca^{2+} (mg/L) means for replications, treatments and soil depths.



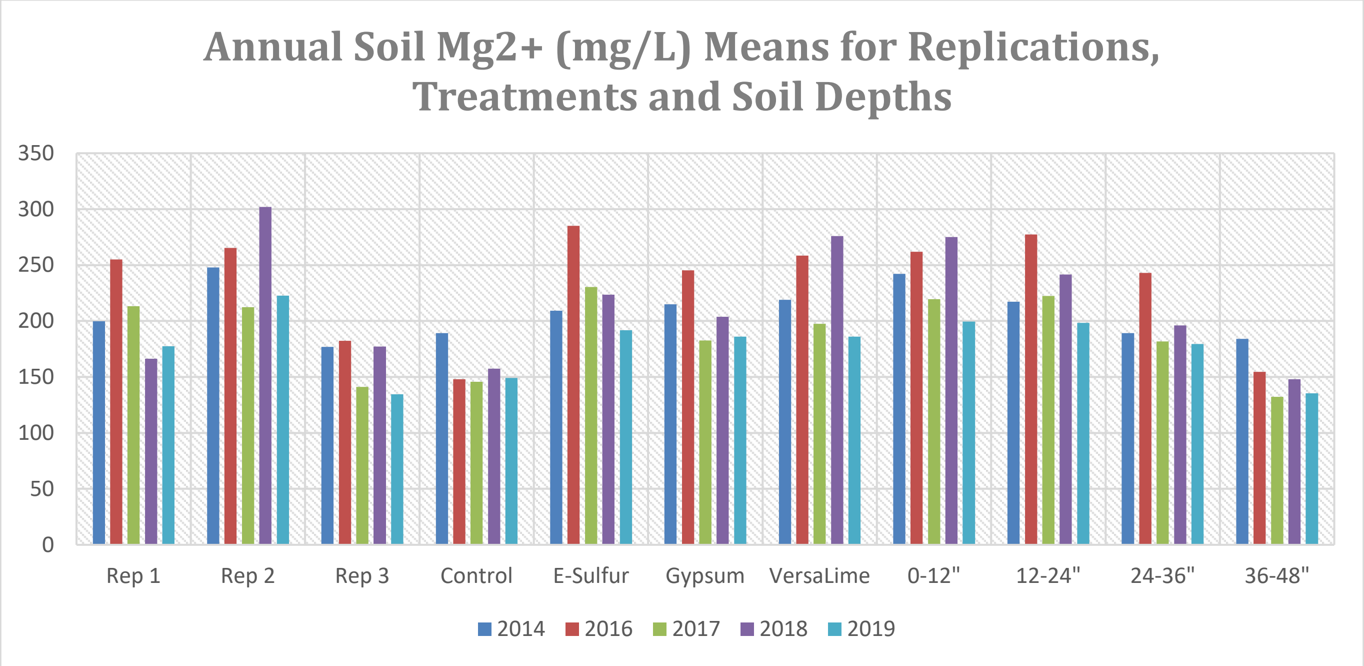
Replication 3 in 2014, had significantly higher Ca^{2+} levels versus all of the replication in 2014, 2016, 2017, 2018 and 2019. In addition, replication 2 in 2014 had significantly higher Ca^{2+} levels versus replication 1 in 2016, 2017, 2018 and 2019, replication 2 in 2016, 2017 and 2019 and replication 3 in 2016, 2017, 2018 and 2019. The E-sulfur treatments in 2014, had significantly higher Ca^{2+} levels versus all of the treatments except, control, gypsum and VersaLime treatments in 2014. In addition, VersaLime treatments in 2014, had significantly higher Ca^{2+} levels versus control treatments in 2016, 2017, 2018 and 2019, E-sulfur treatments in 2016, 2017, 2018 and 2019, gypsum treatments in 2016, 2017, 2018 and 2019 and VersaLime treatments in 2016, 2017 and 2019. The 12-24 inch soil depths in 2014, had significantly higher Ca^{2+} levels versus all depth except, 24-36 inch depths in 2014. In addition, 24-36 inch depths in 2014, significantly higher Ca^{2+} levels versus 0-12 inch depths in 2016, 2017, 2018 and 2019, 12-24 inch depths in 2016 and 2019, 24-36 inch depths in 2016, 2017, 2018 and 2019 and 36-48 inch depths in 2016, 2017, 2018 and 2019.

Overall, Ca^{2+} levels remained the highest in 2014 followed by 2018, 2017, 2016 and 2019, replication 2 had the highest Ca^{2+} levels followed by replication 3 and 1, E-sulfur treatments had the highest levels followed by VersaLime, gypsum and control treatments and 12-24 inch soil depths had the highest Ca^{2+} levels followed by 0-12 inch, 24-36 inch and 36-48 inch depths.

Differences in Soil Magnesium (Mg^{2+}) Levels

Soil magnesium (mg/L) levels are shown in Figure 18. Statistically, there were significant differences in the annual Mg^{2+} levels in replications, treatments and soil depths.

Figure 18. Annual soil Mg^{2+} (mg/L) means for replications, treatments and soil depths.



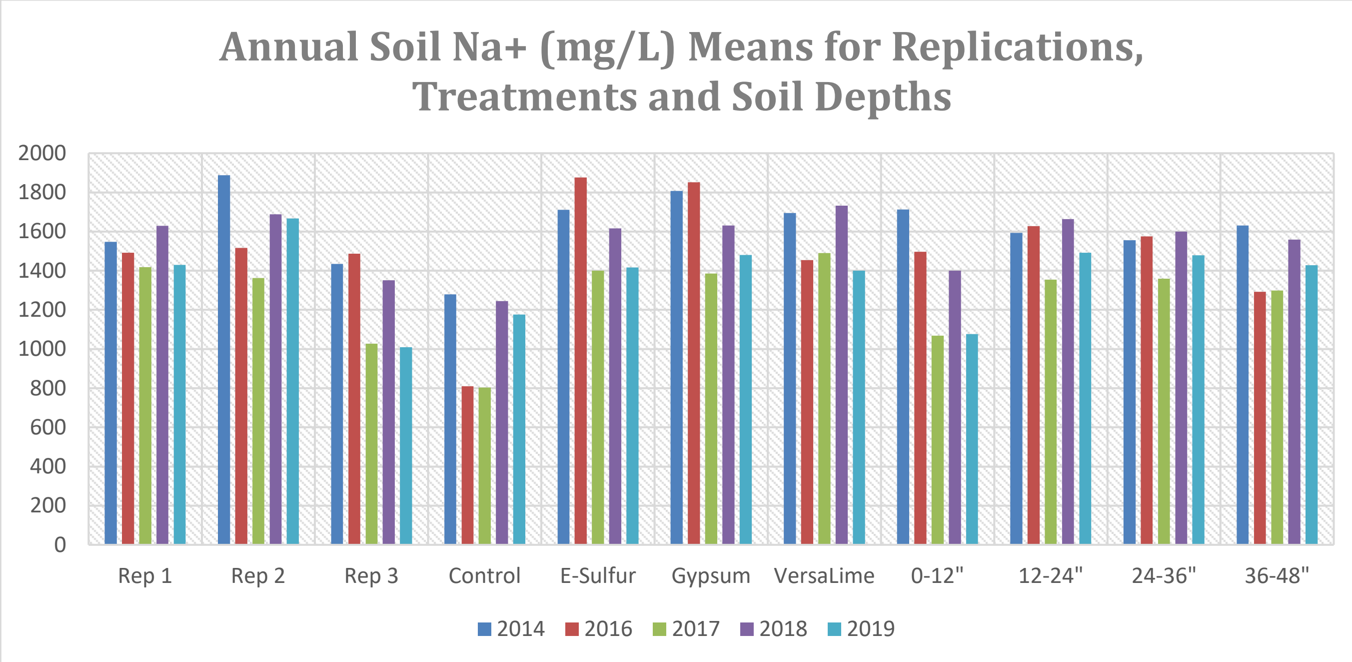
Replication 2 in 2018, had significantly higher Mg^{2+} levels versus all of the replications except replication 1 in 2016 and replication 2 in 2014 and 2016. In addition, replication 2 in 2016, had significantly higher Mg^{2+} levels versus replication 1 in 2014, 2018 and 2019 and replication 3 in 2014, 2016, 2017, 2018 and 2019. The E-sulfur treatments in 2016 had significantly higher Mg^{2+} levels versus all of the treatments except E-sulfur treatments in 2017 and 2018, gypsum treatments in 2014 and 2016 and VersaLime treatments in 2014, 2016 and 2018. In addition, VersaLime treatments in 2018 had significantly higher Mg^{2+} levels versus control treatments in 2014, 2016, 2017, 2018 and 2019, E-sulfur treatments in 2019, gypsum treatments in 2017 and 2019 and VersaLime treatments in 2017 and 2019. The 0-12 inch depths in 2018 and 12-24 inch depths in 2016 had significantly higher Mg^{2+} levels versus all of the soil depths except 0-12 inch depths in 2014, 2016 and 2017, 12-24 inch depths in 2014, 2017 and 2018 and 24-36 inch depths in 2016. In addition, the 0-12 inch depths in 2016 had significantly higher Mg^{2+} levels versus 24-36 inch depths in 2017 and 2019 and 36-48 inch depths in 2014, 2016, 2017, 2018 and 2019.

Overall, Mg^{2+} levels remained the highest in 2016 followed by 2018, 2014, 2017 and 2019, replication 2 had the highest Mg^{2+} levels followed by replication 1 and 3, E-sulfur treatments had the highest levels followed by VersaLime, gypsum and control treatments and 0-12 inch soil depths had the highest Mg^{2+} levels followed by 12-24 inch, 24-36 inch and 36-48 inch depths.

Differences in Soil Sodium (Na^{+}) Levels

Soil sodium (mg/L) levels are shown in Figure 19. Statistically, there were significant differences in the annual Na^{+} levels in replications and treatments.

Figure 19. Annual soil Na^+ (mg/L) means for replications, treatments and soil depths.



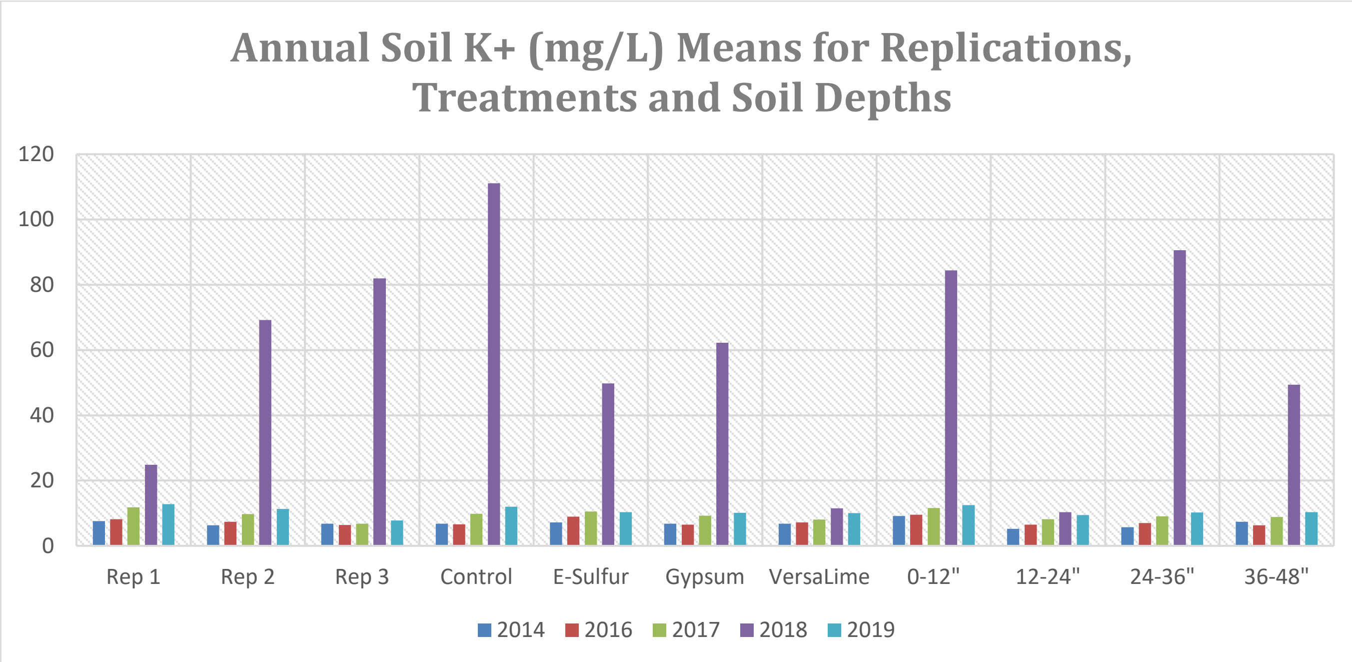
Replication 2 in 2014, had significantly higher Na^+ levels versus replication 1 in 2017 and 2019, replication 2 in 2017 and replication 3 in 2014, 2017, 2018 and 2019. In addition, replication 3 in 2017 and 2019 had significantly lower Na^+ levels compared to replication 1 in 2014, 2016 and 2018, replication 2 2016, 2018 and 2019 and replication 3 in 2016. The E-sulfur treatments in 2016, had significantly higher Na^+ levels versus control treatments in 2014, 2016, 2017, 2018 and 2019, E-sulfur treatments in 2017, gypsum treatments in 2017 and VersaLime treatments in 2019.

Overall, Na^+ levels remained the highest in 2014 followed by 2018, 2016, 2019 and 2017, replication 2 had the highest Na^+ levels followed by replication 1 and 3, gypsum treatments had the highest levels followed by E-sulfur, VersaLime and control treatments and 12-24 inch soil depths had the highest Na^+ levels followed by 24-36 inch, 36-48 inch and 0-12 inch depths.

Differences in Soil Potassium (K^+) Levels

Soil potassium (mg/L) levels are shown in Figure 20. Statistically, there were significant differences in the annual K^+ levels in replications, treatments and soil depths.

Figure 20. Annual soil K^+ (mg/L) means for replications, treatments and soil depths.



Replication 3 in 2018 had significantly higher K^+ levels versus all of the replications except, replication 2 in 2018. In addition, replication 2 in 2018, had significantly higher K^+ levels versus replication 1 in 2014, 2016, 2017, 2018 and 2019, replication 2 in 2014, 2016, 2017 and 2019 and replication 3 in in 2014, 2016, 2017 and 2019. The control treatments in 2018 had significantly higher K^+ levels versus rest of the treatments. In addition, gypsum treatment had significantly higher K^+ levels versus control, E-sulfur and gypsum treatments in 2014, 2016, 2017 and 2019 and VersaLime treatments in in 2014, 2016, 2017, 2018 and 2019. The 0-12 inch and 24-36 inch soil depths in 2018 had significantly higher K^+ levels versus rest of the depths except, 36-48 inch depths in 2018.

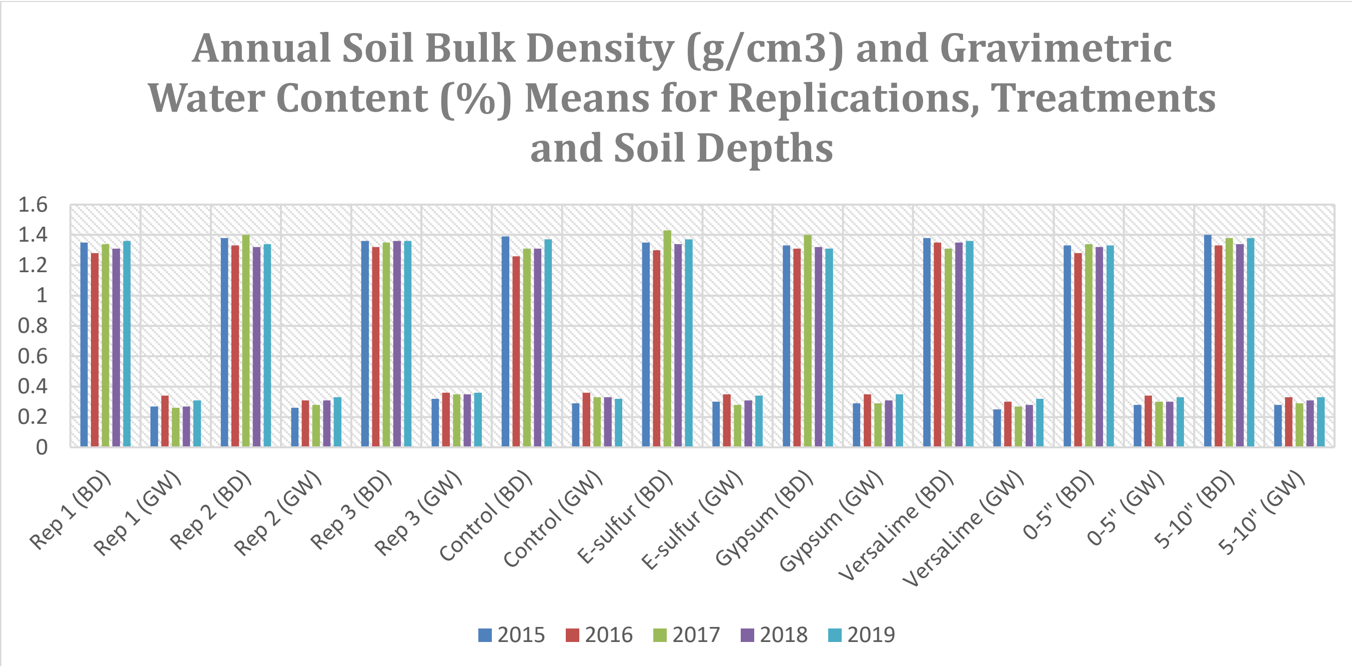
Overall, K^+ levels remained the highest in 2018 followed by 2019, 2017, 2016 and 2014, replication 3 had the highest K^+ levels followed by replication 2 and 1, control treatments had the highest levels followed by gypsum, E-sulfur and VersaLime treatments and 0-12 inch soil depths had the highest K^+ levels followed by 24-36 inch, 36-48 inch and 12-24 inch depths.

Effect of Soil Amendments on Soil Physical Properties

Differences in Soil Bulk Density (BD) Levels

Soil bulk density (g/cm^3) and corresponding gravimetric water content (%) levels are shown in Figure 21. Statistically, there were significant differences in the annual soil bulk density levels in soil depths.

Figure 21. Annual means of soil bulk density (g/cm^3) and gravimetric water (%) levels for replications, treatments and soil depths.



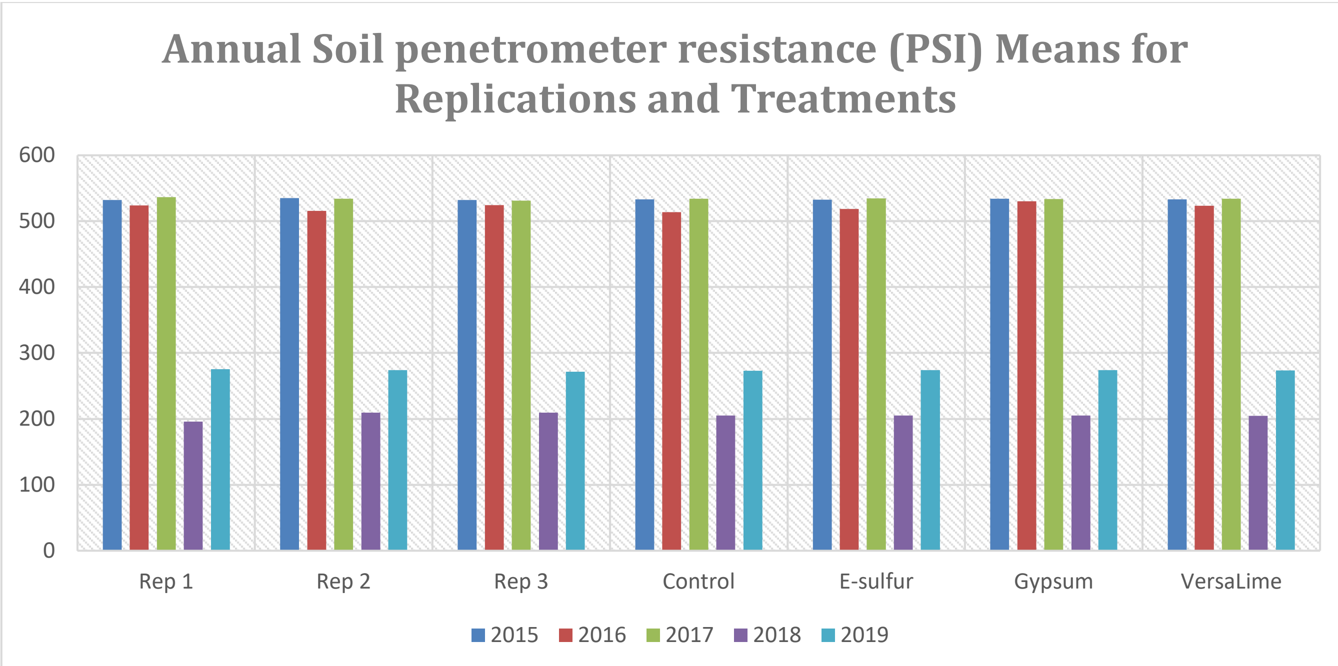
The 5-10 inch soil depths in 2015, 2016, 2017, 2018 and 2019 had significantly higher bulk density levels versus 0-5 inch soil depths.

Overall, bulk density levels remained the highest in 2015 followed by 2017, 2019, 2018 and 2016, replication 3 had the highest bulk density levels followed by replication 2 and 1, E-sulfur treatments had the highest levels followed by VersaLime, control and gypsum treatments and 0-12 inch soil depths had lower bulk density levels compared to 5-10 inch depths. Though it was not a clear trend, however, at higher gravimetric soil water contents, bulk density levels tend to be lower (Figure 19).

Differences in Soil Penetrometer Meter Resistance Levels

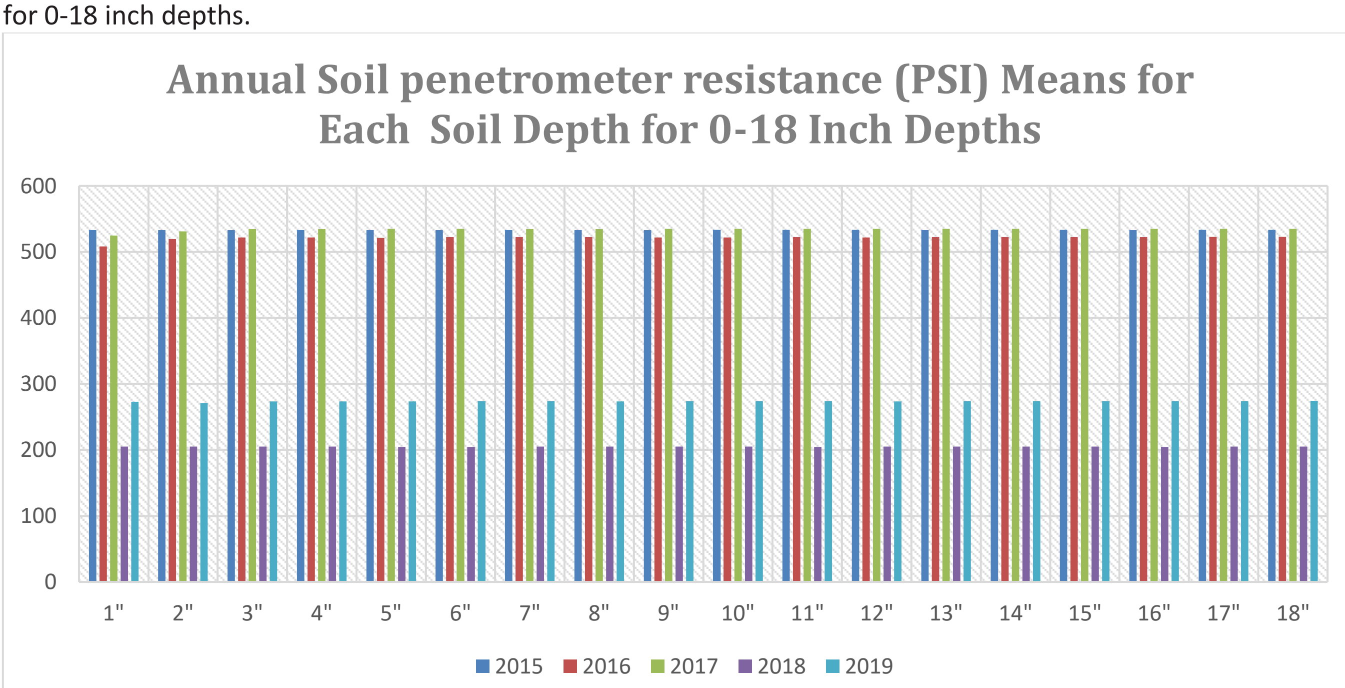
Cumulative soil penetrometer resistance measurements for the 0-18 inch depths are shown in Figure 22. Statistically, there were significant differences in the annual soil penetrometer resistance levels measured in pounds of force per square inch (psi) in replications, treatments (Figure 19) and soil depths.

Figure 22. Annual means of cumulative soil penetrometer resistance measurements for the 0-18 inch depths (pounds of force per square inch or psi) for replications and treatments.



Replication 1 in 2017 showed significantly higher penetrometer resistance versus all of the replications, except replication 2 in 2015. In addition, replication 2 in 2015 had significantly higher penetrometer resistance versus replication 1 in 2015, 2016, 2018 and 2019, replication 2 in 2016, 2018 and 2019 and replication 3 in 2015, 2016, 2017, 2018 and 2019. The control, E-sulfur, gypsum and Versalime treatments in 2015 and 2017 had significantly higher penetrometer resistance versus all four treatments in 2016, 2018 and 2019. In addition, the 2018 penetrometer resistance levels in all treatments were significantly lower versus the levels in 2015, 2016 and 2017, whereas, 2018 penetrometer resistance levels were the lowest compared to all other years.

Figure 23. Annual means of soil penetrometer resistance (pounds of force per square inch or psi) for each soil depth for 0-18 inch depths.

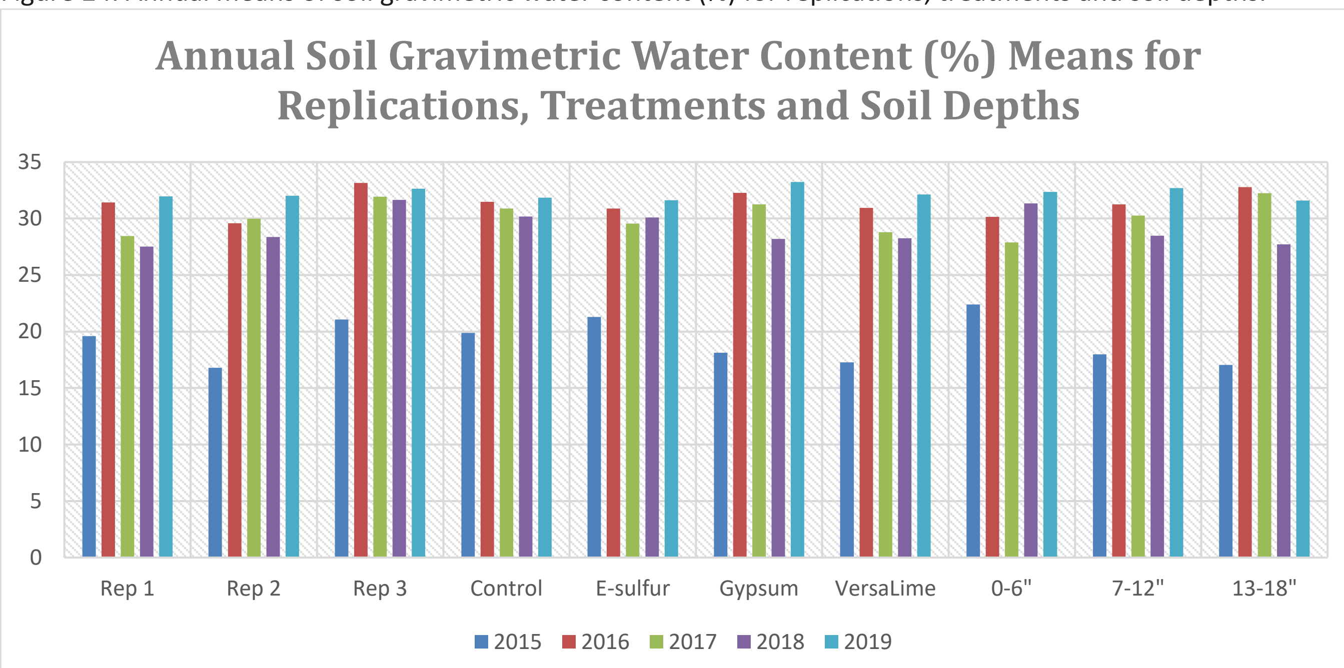


Except the 1 inch soil depths in 2017, all depths in 2015 and 2017 had significantly higher penetrometer resistance versus 1 to 18 inch soil depths in 2016, 2018 and 2019.

Overall, penetrometer resistance measurements remained the highest in 2017 followed by 2015, 2016, 2019 and 2018, replication 3 had the highest penetrometer resistance measurements followed by replication 2 and 1, gypsum treatments had the highest levels followed by VersaLime, E-sulfur and control treatments and 18 inch soil depths had the highest penetrometer resistance measurements followed by 15, 14, 17, 16, 13, 10, 12, 11, 9, 7, 6, 8, 4, 3, 5, 2 and 1 inch depths.

Since penetrometer resistance is strongly related to the soil water content at the time of recording the measurements, soil gravimetric water content was also measured for the 0-6, 7-12 and 13-18 inch soil depths. And like penetrometer resistance, , there were statistically significant differences in the annual soil gravimetric water content measured in percent (%) in replications, treatments and soil depths (Figure 24).

Figure 24. Annual means of soil gravimetric water content (%) for replications, treatments and soil depths.



Replication 1 in 2016 and 2019, replication 2 in 2019 and 3 in 2016, 2017, 2018 and 2019 had significantly higher gravimetric water content versus replication 1 in 2015, 2017 and 2018, replication 2 in 2015, 2016, 2017 and 2019 and replication 3 in 2015. In addition, all three replication in 2015 had significantly lower gravimetric water contents versus rest of the years. All four treatments in 2015, e-sulfur and VersaLime treatments in 2017 and gypsum and VersaLime treatments in 2018 had significantly lower gravimetric water contents versus rest of the annual treatment means. In addition, 2015 gravimetric water content levels were significantly lower than the other years. The 0-6 inch soil depths in 2016, 2018 and 2019, 7-12 inch depths in 2016, 2017 and 2019 and 13-18 inch depths 2016, 2017 and 2019 had significantly higher gravimetric water content versus 0-6 inch depths in 2015 and 2017, 7-12 inch depths in 2015 and 2018 and 13-18 inch depths in 2015 and 2018. In addition, the gravimetric water contents for all three depths in 2015 were significantly lower than rest of the years.

Soil Penetrometer resistance was strongly dependent upon the available soil moisture levels measured as gravimetric water content for the 0-6 inch, 7-12 inch and 13-18 inch soil depths.

Overall, soil gravimetric water content penetrometer remained the highest in 2019 followed by 2016, 2017, 2018 and 2015, replication 3 had the highest gravimetric water content followed by replication 1 and 2, control treatments had the highest gravimetric water content followed by E-sulfur, gypsum and VersaLime treatments and 0-6 inch soil depths had the highest penetrometer resistance measurements followed by 7-12 and 13-18 inch soil depths.

Considering the high penetrometer resistance measurements recorded in 2015 at the lowest gravimetric water contents, there is an inversely proportional relationship between these two.

Quality of Water Draining from the Research Project Site for Human and Livestock Health

Groundwater samples from upstream, tile drainage lift station and downstream were collected one to three times a year depending upon the weather by using North Dakota Department of Health protocols and were sent to its Chemical Lab for analysis in 2015, 2016, 2017, 2018 and 2019. Samples were collected after a decent rain event of close to an inch or more, which allowed standing water in the ditch in which tiling project water was draining for upstream and downstream samples as well as fresh flow of water from the lift station. Upstream samples were collected from the beginning of the drainage ditch 100-150 feet north of the lift station. Lift station samples represent water quality coming out of tiles, whereas, downstream samples were collected 100-150 feet south of the lift station in the direction where drainage water flows. Each sampling activity included collecting a set of samples from upstream, lift station and downstream, 10-15 minutes apart on the same day. Each set included the following:

1. 500 mL to analyze major cations, anions and bromide (procedures 200.7, 300 and 2320-B, USEPA).
2. 250 mL preserved with 2mL of Nitric Acid (HNO_3) for trace metal (procedure 200.8, USEPA).
3. 500 mL preserved with Sulfuric Acid (H_2SO_4) to analyze for nutrients that included Total Nitrogen, Kjeldahl Nitrogen, Nitrite + Nitrate Nitrogen and Phosphorous (procedures 353.2, Lachat Method No. 10-107-04-1-C, 353.2, Lachat Method No. 10-107-04-1-O, and 200.7, Lachat Method 10-115-01-1-E, USEPA).
4. 200 mL filtered and then preserved with Sulfuric Acid (H_2SO_4) to analyze dissolved Phosphorous (procedure 365.1, Lachat Method 10-115-01-1-E, USEPA).
5. Each set of samples then was sent to Chemical Lab of ND Department of Health in a cooler with icepacks through overnight delivery.

Below is the breakdown of the annual water quality analysis of the samples collected from upstream, lift Station and downstream locations. Please note that CO_3^{2-}, OH^-, silica, beryllium, chromium, silver, cadmium, antimony, thallium and lead are not discussed in the results below as analysis results were below the detectable levels at almost all of the sampling times. In addition, “ND” in the result tables mean “Not Detectable”.

Differences in Salts, Dissolved Solids, Total Hardness as CaCO3 and Total Alkalinity as CaCO3 Levels

Based on the results of each sampling activity, conductivity (mmhos/cm) levels in the lift station were higher than the upstream and downstream samples, except samples taken on May 11, 2016, May 10, 2017 and June 12, 2018. Differences between upstream and downstream samples fluctuated and there was no consistent trend. Concentration of dissolved solids (mg/L) of the lift station samples were higher than the upstream and downstream samples, except the samples taken on May 10, 2017 and June 12, 2018. Total hardness as $CaCO_3$ (grams/gallon) concentrations were also higher in the lift station samples versus upstream and downstream samples, except the samples taken on May 10, 2017. Total alkalinity as $CaCO_3$ levels were higher in the lift station samples versus all of the upstream and downstream samples. Details are in Table 4.

Table 4. Results of conductivity (mmhos/cm), dissolved Solids (mg/L), total hardness as $CaCO_3$ (g/G) and total alkalinity as $CaCO_3$ for each sampling activity.

Date	Site	Conductivity (mmhos/cm)	Total Dissolved Solids (mg/L)	Total Hardness as $CaCO_3$ (g/G)	Total Alkalinity as $CaCO_3$ (mg/L)
November 9, 2015	Upstream	5650	4510	1110	326
	Lift Station	10200	8840	2160	564
	Downstream	6800	5700	1460	370
May 11, 2016	Upstream	7220	6060	1500	230
	Lift Station	7200	7170	1720	501
	Downstream	7560	6390	1500	202
July 11, 2016	Upstream	999	647	243	127
	Lift Station	8140	6820	1610	507
	Downstream	966	627	251	105
September 8, 2016	Upstream	3440	2570	787	467
	Lift Station	7220	5960	1500	630
	Downstream	3200	2340	771	338
May 10, 2017	Upstream	6920	5840	1680	387
	Lift Station	5980	4950	1360	543
	Downstream	6070	5200	1370	504
August 17, 2017	Upstream	3360	2590	774	158
	Lift Station	6590	6010	1220	615
	Downstream	2100	1430	381	173
June 12, 2018	Upstream	5130	3910	887	288
	Lift Station	4470	3420	926	517
	Downstream	4840	3680	816	369
August 26, 2019	Upstream	3710	2860	757	337
	Lift Station	5430	4290	1000	700
	Downstream	5070	4080	903	635
September 30, 2019	Upstream	754	488	200	142
	Lift Station	6460	5620	1390	530
	Downstream	1350	891	285	174

Based on the cumulative means of all sampling activities, conductivity (mmhos/cm), dissolved Solids (mg/L), total hardness as $CaCO_3$ (g/G) and total alkalinity as $CaCO_3$ concentrations of the lift station samples were higher than the upstream and downstream samples.

Since it was important to assess the total dissolved solids (TDS) coming out of the tiled area represented by the lift station samples compared to upstream and downstream samples, results are presented in a line chart below (Figure 25). We can see that except the samples taken on May 10, 2017 and June 12, 2018, the TDS levels of the lift station samples were noticeably higher than the upstream and downstream samples.

Figure 25. Results of total dissolved Solids (mg/L) for each sampling activity.

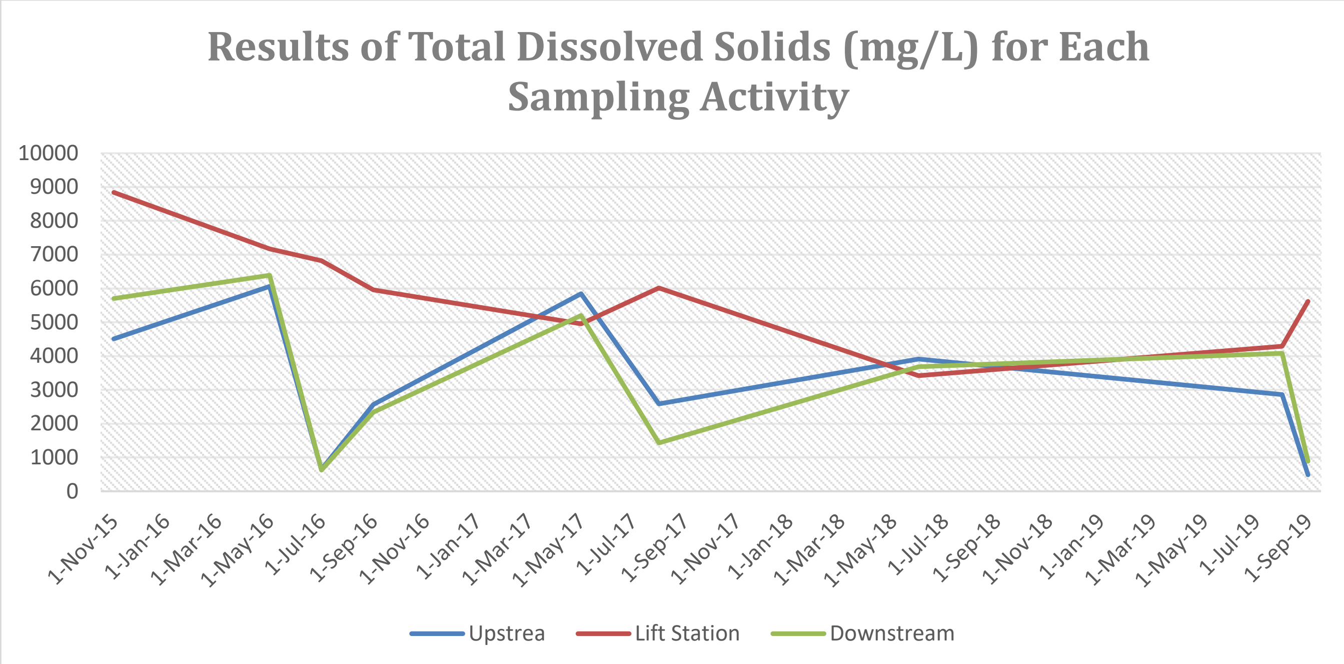
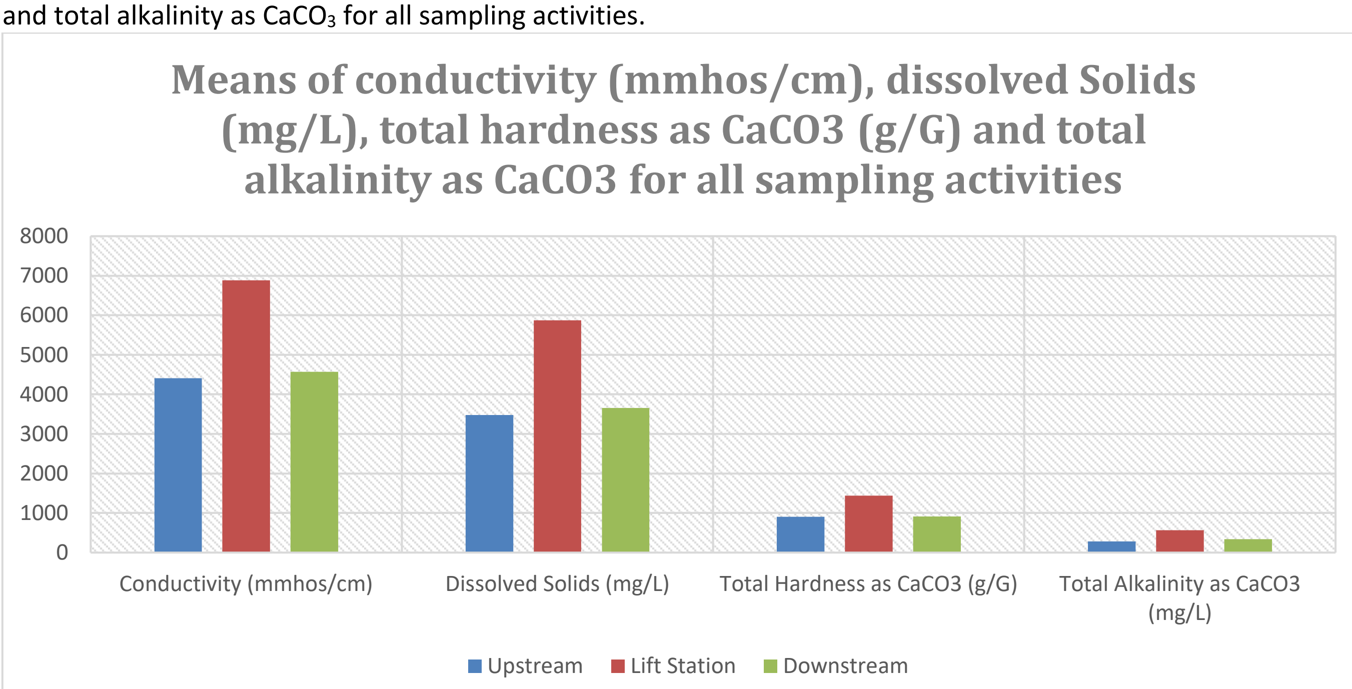


Figure 26. Cumulative means of conductivity (mmhos/cm), dissolved Solids (mg/L), total hardness as $CaCO_3$ (g/G) and total alkalinity as $CaCO_3$ for all sampling activities.



<u>Differences in Sodium Adsorption Ratio (SAR) and pH Levels</u>

Based on the results of each sampling activity, SAR levels of the lift station samples were higher than the upstream and downstream samples, except in the samples that were taken on May 11, 2016, May 10, 2017 and June 12, 2018.

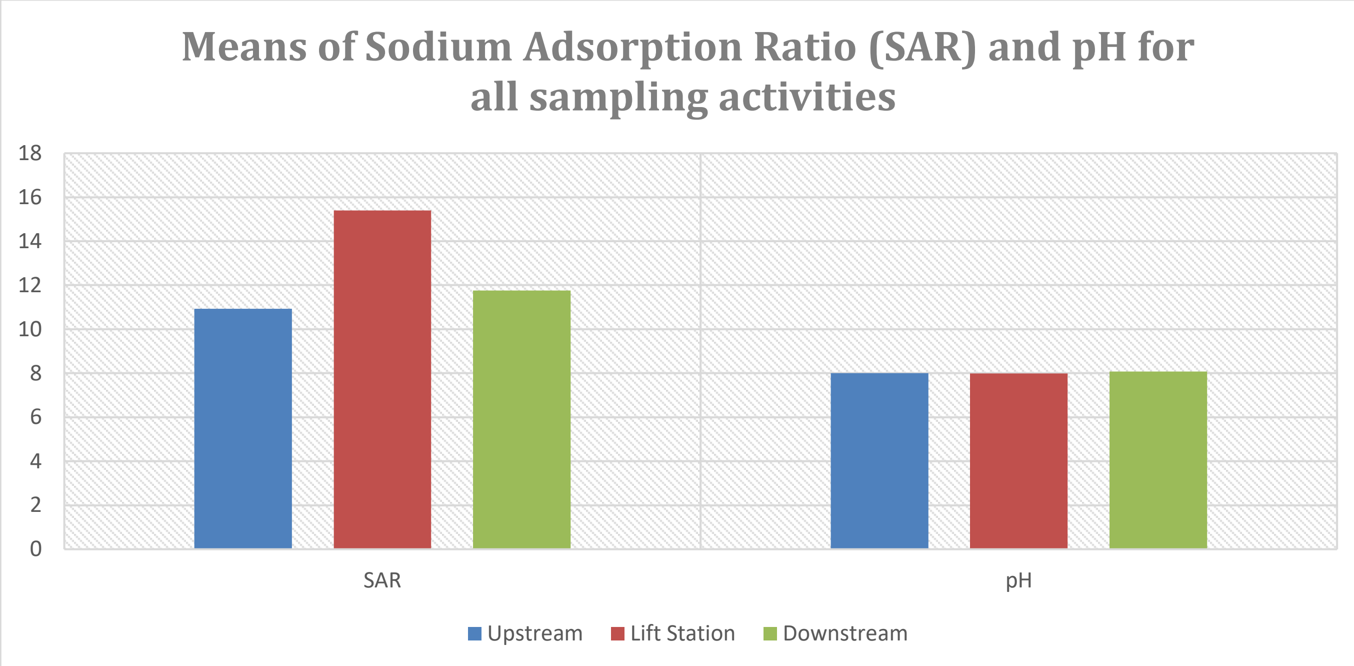
The differences between the soil pH levels of upstream, lift station and downstream samples were negligible. Details are in Table 5.

Table 5. Results of Sodium Adsorption Ratio (SAR) and pH for each sampling activity.

Date	Site	Sodium Adsorption Ratio (SAR)	pH
November 9, 2015	Upstream	13.10	8.27
	Lift Station	17.40	7.91
	Downstream	16.30	8.37
May 11, 2016	Upstream	16.60	8.92
	Lift Station	14.90	7.96
	Downstream	17.60	9.23
July 11, 2016	Upstream	3.54	7.60
	Lift Station	16.20	8.32
	Downstream	3.07	7.56
September 8, 2016	Upstream	8.55	8.31
	Lift Station	15.60	8.10
	Downstream	6.87	7.92
May 10, 2017	Upstream	14.20	8.27
	Lift Station	13.50	8.08
	Downstream	14.00	8.28
August 17, 2017	Upstream	8.36	7.60
	Lift Station	22.60	7.99
	Downstream	6.52	7.67
June 12, 2018	Upstream	13.80	7.70
	Lift Station	11.00	8.00
	Downstream	13.50	7.92
August 26, 2019	Upstream	10.70	7.92
	Lift Station	14.70	8.03
	Downstream	14.60	8.11
September 30, 2019	Upstream	3.11	7.77
	Lift Station	15.20	7.78
	Downstream	4.55	7.71

Based on the cumulative means of all sampling activities, SAR levels in the lift station samples remained higher than the upstream and downstream samples, whereas, differences in the pH levels were negligible.

Figure 27. Cumulative means of Sodium Adsorption Ratio (SAR) and pH for all sampling activities.



Differences in the Major Cations and Anions levels

Based on the results of each sampling activity, Ca^{2+} (mg/L) levels of the lift station samples were higher than the upstream and downstream samples, except in the samples taken on May 10, 2017. Mg^{2+} (mg/L), Na^{+} (mg/L) and SO_4^{2-} (mg/L) levels of the lift station samples were higher than the samples taken from upstream and downstream samples except the samples that were taken on May 11, 2016, May 10, 2017 and June 12, 2018. K^{+} (mg/L) levels of the lift station samples were lower or equal versus the levels in the upstream and downstream samples at all sampling times. Cl^{-} (mg/L) levels of the lift station samples were higher than the samples taken from upstream and downstream samples except the samples that were taken on May 11, 2016, May 10, 2017, June 12, 2018 and August 26, 2019. HCO_3^{-} (mg/L) levels of the lift station samples remained higher than the upstream and downstream samples at all sampling times. Details are in Table 6.

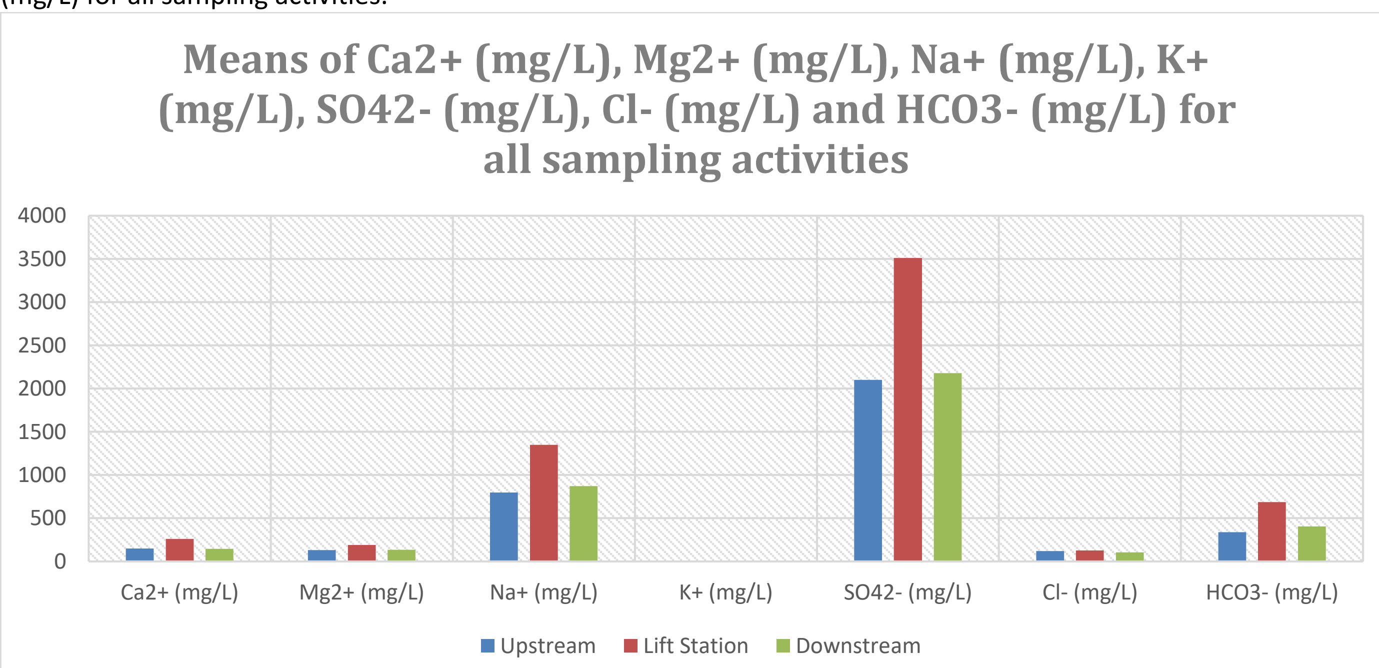
Table 6. Results of Ca^{2+} (mg/L), Mg^{2+} (mg/L), Na^{+} (mg/L), K^{+} (mg/L), SO_4^{2-} (mg/L), Cl^{-} (mg/L) and HCO_3^{-} (mg/L) for each sampling activity.

Date	Site	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	SO_4^{2-} (mg/L)	Cl^{-} (mg/L)	HCO_3^{-} (mg/L)
November 9, 2015	Upstream	187	156	1000	NA	2790	148	397
	Lift Station	398	284	1860	NA	5710	208	688
	Downstream	223	220	1430	11	3420	157	436
May 11, 2016	Upstream	173	260	1480	9.9	3790	203	220
	Lift Station	271	253	1420	5.9	3700	178	611
	Downstream	161	266	1570	10.6	4050	206	149
July 11, 2016	Upstream	55.2	25.6	127	7.9	320	29.6	155
	Lift Station	251	239	1500	6.3	4330	148	609
	Downstream	59.1	25.1	112	7.1	329	25.3	128
September 8, 2016	Upstream	147	102	552	8.6	1390	92.9	565
	Lift Station	271	199	1390	7.6	3560	128	769
	Downstream	157	92	439	16.1	1320	107	412

May 10, 2017	Upstream	263	249	1340	12.4	3490	255	472
	Lift Station	223	196	1150	5.2	2900	131	662
	Downstream	200	212	1190	6.7	3090	162	615
August 17, 2017	Upstream	160	91	535	9.7	1580	117	192
	Lift Station	221	163	1820	6.8	3290	126	751
	Downstream	72.6	48.6	293	6.5	818	81.1	212
June 12, 2018	Upstream	121	142	944	3.3	2420	101	351
	Lift Station	191	109	770	3.9	1950	72.7	631
	Downstream	129	120	889	5.2	2230	80.6	450
August 26, 2019	Upstream	149	93.5	679	9.1	1650	72.7	411
	Lift Station	202	121	1070	5.2	2400	72.4	854
	Downstream	182	109	1010	4.8	2320	67.2	775
September 30, 2019	Upstream	45.9	20.7	101	5.8	201	25.7	173
	Lift Station	245	188	1300	5.4	3470	88.4	647
	Downstream	60.4	32.7	177	7.3	462	36.4	213

Based on the cumulative means of all sampling activities, Ca^{2+} (mg/L), Mg^{2+} (mg/L), Na^{+} (mg/L), SO_4^{2-} (mg/L), Cl^{-} (mg/L) and HCO_3^{-} (mg/L) levels of the lift station samples remained higher than the upstream and downstream samples, whereas, K^{+} (mg/L) levels of the lift station samples were lower than the upstream and downstream samples.

Figure 28. Cumulative means of Ca^{2+} (mg/L), Mg^{2+} (mg/L), Na^{+} (mg/L), K^{+} (mg/L), SO_4^{2-} (mg/L), Cl^{-} (mg/L) and HCO_3^{-} (mg/L) for all sampling activities.



Differences in the Nitrogen and Phosphorous levels

Based on the results of each sampling activity, nitrate + nitrite nitrogen (mg/L) levels of the lift station remained higher than the upstream and downstream samples at all sampling times, except one downstream sample that was taken on September 30, 2019. Opposite trend was observed for the Kjeldahl nitrogen (mg/L) levels, which remained lower than the upstream and downstream samples taken at all times, except one upstream sample taken on September 30, 2019. The total nitrogen (mg/L) levels, which were a sum of Kjeldahl nitrogen (mg/L) and nitrate + nitrite nitrogen (mg/L) levels were higher in the lift station samples versus upstream and downstream samples, except the samples that were collected on November 9, 2015, May 10, 2017, August 26, 2019 and September 30, 2019. The total phosphorous (mg/L) levels of the lift station samples were equal or lower than the upstream and downstream samples. In addition, dissolved phosphorous (mg/L) levels of the lift station samples remained lower than the levels in the upstream and downstream samples except, the samples that were collected on November 9, 2015, May 11, 2016 and June 12, 2018. Details are in Table 7.

Table 7. Results of total nitrogen (mg/L), Kjeldahl nitrogen (mg/L), nitrate + nitrite nitrogen (mg/L), total phosphorous (mg/L) and dissolved phosphorous (mg/L) for each sampling activity.

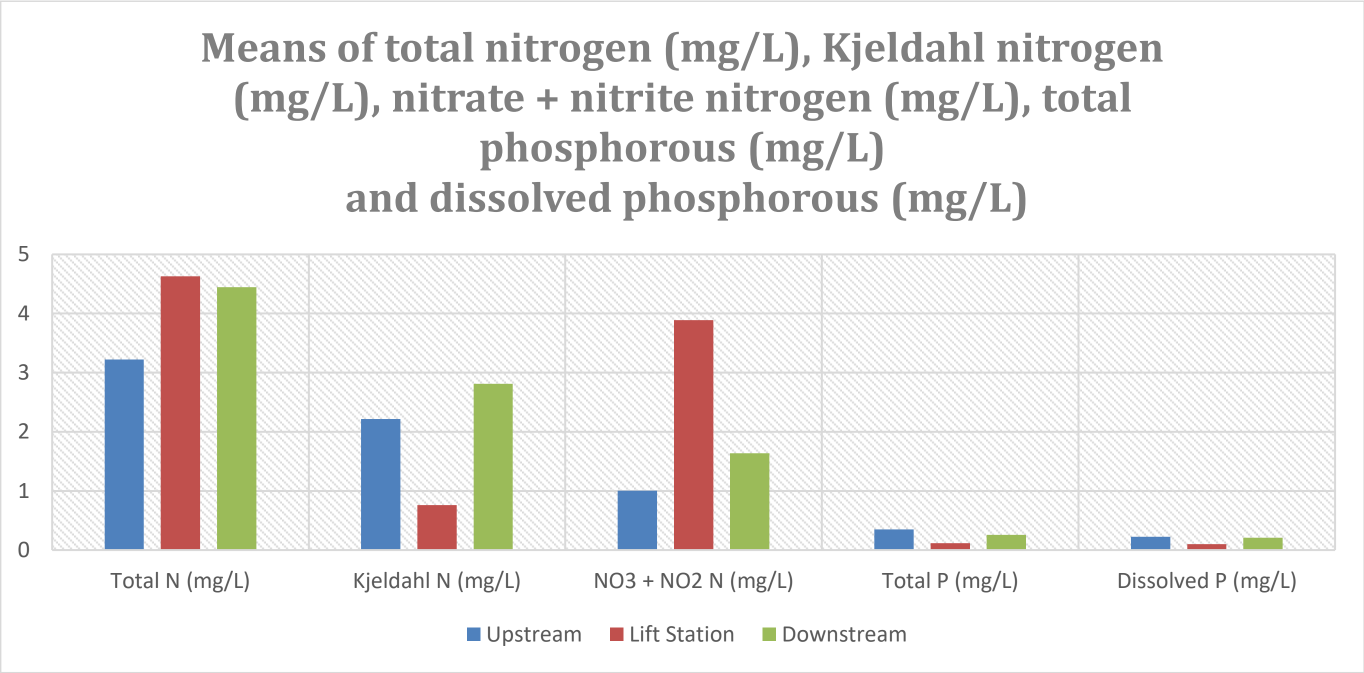
Date	Site	Total N (mg/L)	Kjeldahl N (mg/L)	$NO_3 + NO_2$ N (mg/L)	Total P (mg/L)	Dissolved P (mg/L)
November 9, 2015	Upstream	7.51	3.17	4.34	0.16	0.02
	Lift Station	7.30	0.64	6.66	0.06	0.08
	Downstream	11.70	8.40	3.30	0.03	ND
May 11, 2016	Upstream	3.65	2.67	0.98	0.09	0.02
	Lift Station	10.10	1.42	8.68	0.06	0.06
	Downstream	2.59	2.56	0.03	0.22	0.08
July 11, 2016	Upstream	2.37	1.71	0.66	0.92	0.88
	Lift Station	9.08	0.90	8.18	0.21	0.21
	Downstream	2.46	1.54	0.92	0.79	0.75
September 8, 2016	Upstream	2.11	2.08	0.03	0.93	0.69
	Lift Station	5.53	0.41	5.12	0.02	0.05
	Downstream	3.03	2.28	0.75	0.61	0.50
May 10, 2017	Upstream	3.02	2.99	0.03	0.51	0.19
	Lift Station	4.49	0.08	4.57	0.20	0.04
	Downstream	7.47	0.83	6.64	0.20	0.03
August 17, 2017	Upstream	1.80	1.77	0.03	0.18	0.12
	Lift Station	3.16	0.93	2.23	0.08	0.07
	Downstream	1.38	1.35	0.03	0.20	0.06
June 12, 2018	Upstream	2.02	1.99	0.03	0.14	0.03
	Lift Station	2.23	0.84	1.39	0.14	0.14
	Downstream	1.29	1.26	0.03	0.14	0.02
August 26, 2019	Upstream	2.13	2.07	0.05	0.39	0.29
	Lift Station	1.13	0.87	0.26	0.13	0.13
	Downstream	1.04	0.93	0.11	0.20	0.18
September 30, 2019	Upstream	0.78	0.69	0.09	0.54	0.50
	Lift Station	1.99	0.93	1.06	0.14	0.14
	Downstream	3.22	1.41	1.81	0.55	0.49

Note:

- Total Nitrogen is a sum of the Kjeldahl N and $NO_3 + NO_2$ N.
- Kjeldahl N is a sum of free ammonium and organic nitrogen.

Based on the cumulative means of all sampling activities, total nitrogen (mg/L) and nitrate + nitrite nitrogen (mg/L) levels of the lift station samples were higher than the levels in the upstream and downstream samples. Whereas, Kjeldahl nitrogen (mg/L) levels of the lift station samples remained lower than the levels in upstream and downstream samples. Both total phosphorous (mg/L) and dissolved phosphorous (mg/L) levels of the lift station samples also remained lower than the levels in upstream and downstream samples.

Figure 29. Cumulative means of total nitrogen (mg/L), Kjeldahl nitrogen (mg/L), nitrate + nitrite nitrogen (mg/L), total phosphorous (mg/L) and dissolved phosphorous (mg/L) for all sampling activities.



Differences in the Boron, Aluminum, Nickel, Copper and Zinc levels

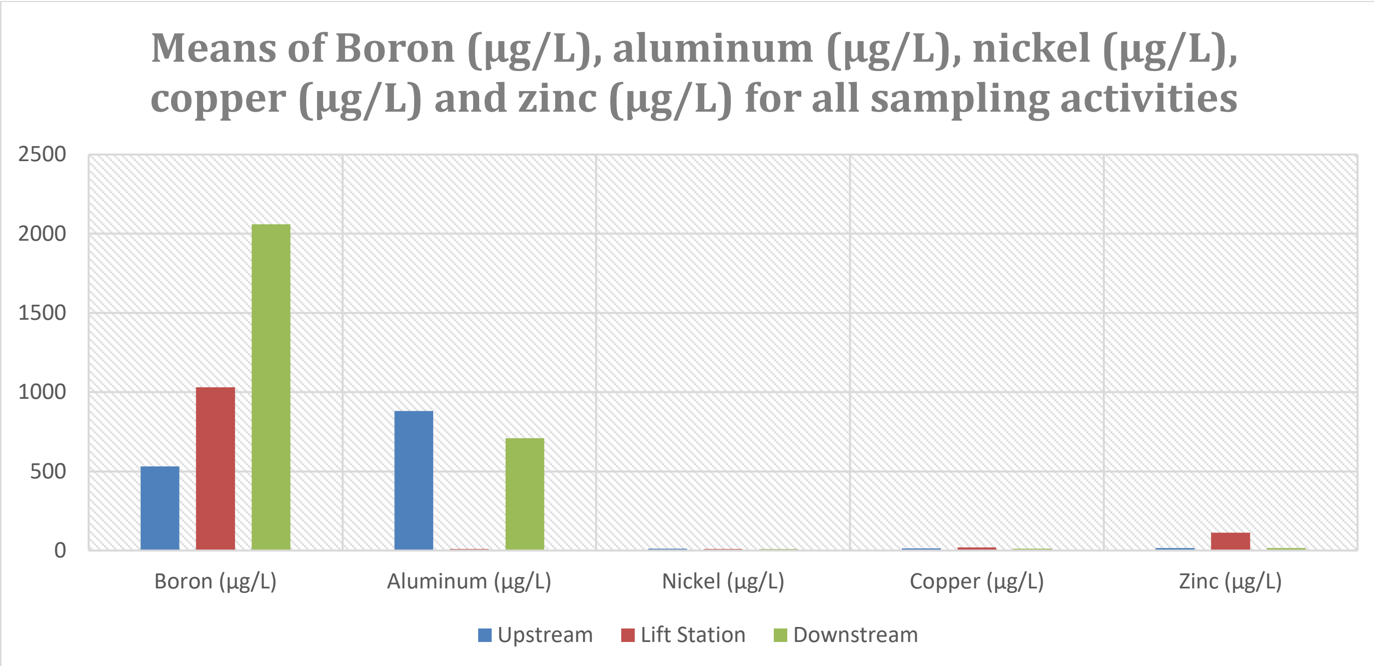
Based on the results of each sampling activity, boron (µg/L) levels were higher than the levels in the upstream samples except, the samples taken on July 11, 2016 and June 12, 2018, whereas, downstream boron (µg/L) levels were higher than the levels of lift station samples collected on November 9, 2015, July 11, 2016, May 10, 2017 and June 12, 2018. Aluminum (µg/L) levels of the lift station remained below the detection levels of 50.00 (µg/L) versus upstream and downstream levels except, the samples taken on September 8, 2016, which was still lower than the levels in upstream and downstream samples. Nickel (µg/L) levels of the lift station samples were mostly lower than the upstream and downstream samples except, in the samples taken on July 11, 2016 and September 30, 2019. Copper (µg/L) levels of the lift station samples were noticeably higher that the levels in upstream and downstream samples collected on November 9, 2015, July 11, 2016, August 17, 2017 and September 30, 2019. Zinc (µg/L) levels of the lift station samples were higher than the upstream and downstream samples at all sampling times except, one set of sample that was collected on May 10, 2017. Details are in Table 8.

Table 8. Results of Boron (µg/L), aluminum (µg/L), nickel (µg/L), copper (µg/L) and zinc (µg/L) for each sampling activity.

Date	Site	Boron (µg/L)	Aluminum (µ/L)	Nickel (µg/L)	Copper (µg/L)	Zinc (µg/L)
November 9, 2015	Upstream	580.00	887.00	9.10	9.96	17.20
	Lift Station	1260.00	ND	ND	18.80	25.40
	Downstream	7880.00	560.00	9.31	12.50	22.10
May 11, 2016	Upstream	685.00	134.00	8.87	14.20	9.98
	Lift Station	741.00	ND	6.99	14.00	15.00
	Downstream	635.00	82.00	9.36	13.7	8.66
July 11, 2016	Upstream	185.00	994.00	6.22	6.67	12.70
	Lift Station	87.00	ND	23.50	50.40	83.50
	Downstream	186.00	945.00	5.83	6.16	11.20
September 8, 2016	Upstream	318.00	250.00	13.30	42.20	7.060
	Lift Station	1700.00	52.00	9.48	34.60	10.80
	Downstream	355.00	98.00	12.50	12.10	ND
May 10, 2017	Upstream	471.00	1980.00	23.90	20.70	22.70
	Lift Station	821.00	ND	7.67	17.40	10.50
	Downstream	855.00	358.00	9.79	22.60	22.60
August 17, 2017	Upstream	445.00	333.00	12.10	10.30	ND
	Lift Station	1620.00	ND	11.70	25.80	598
	Downstream	276.00	775.00	10.20	6.40	10.40
June 12, 2018	Upstream	783.00	541.00	12.30	9.03	17.60
	Lift Station	724.00	ND	6.43	7.26	182.00
	Downstream	777.00	369.00	10.30	7.22	17.90
August 26, 2019	Upstream	754.00	ND	8.04	12.10	7.15
	Lift Station	1300.00	ND	5.36	16.20	18.90
	Downstream	1170.00	ND	5.35	16.00	10.40
September 30, 2019	Upstream	135.00	1360.00	ND	ND	8.26
	Lift Station	911.00	ND	6.66	18.60	9.60
	Downstream	187.00	1680.00	ND	ND	9.23

Based on the cumulative means of all sampling activities, boron (µg/L) levels of the lift station samples were noticeably higher than the upstream samples and lower than the downstream samples. Aluminum (µg/L) means were lower than upstream and downstream samples, whereas, nickel (µg/L) means were lower than upstream samples and slightly higher than downstream samples. Copper (µg/L) and zinc (µg/L) means of the lift station samples were higher than the upstream and downstream samples.

Figure 30. Cumulative means of Boron (µg/L), aluminum (µg/L), nickel (µg/L), copper (µg/L) and zinc (µg/L) for all sampling activities.



Differences in the Arsenic, Selenium, Molybdenum and Barium levels

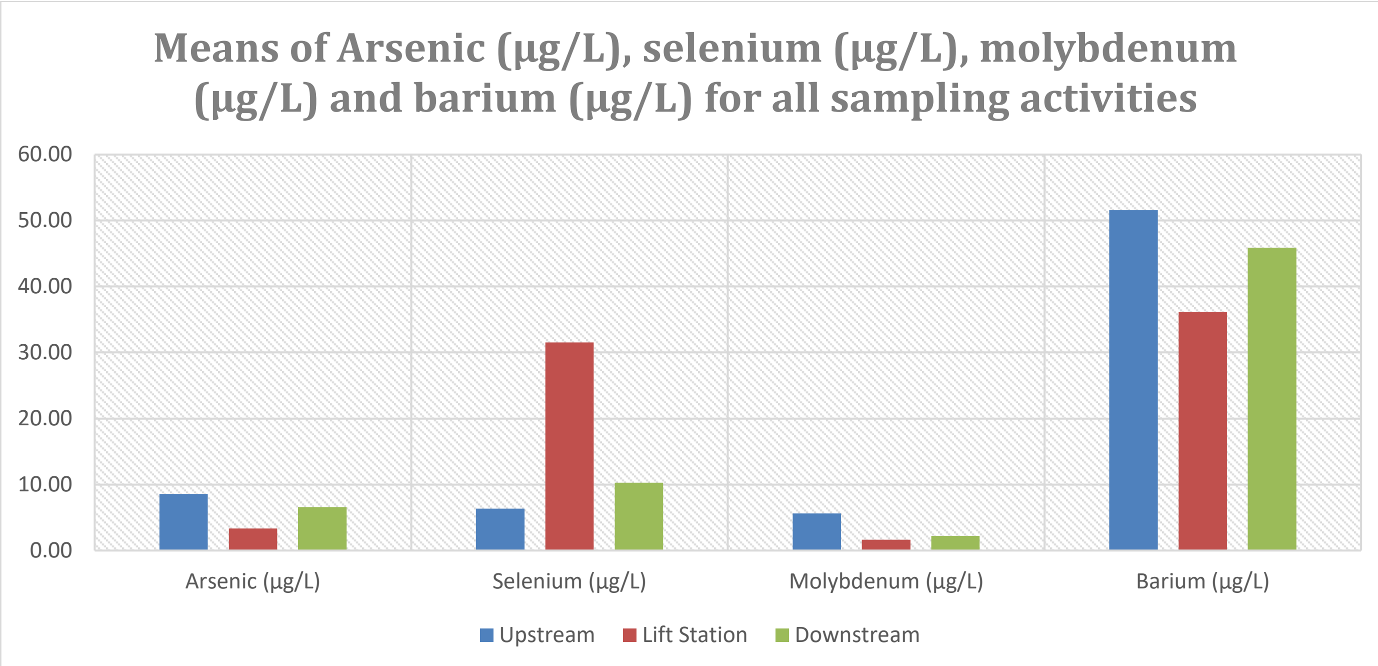
Based on the results of each sampling activity, arsenic (µg/L) levels of the lift station samples were mostly lower than the upstream and downstream samples except, for the samples taken on July 11, 2016 and September 30, 2019. Selenium (µg/L) levels were higher in the lift station samples at all sampling times compared to the upstream and downstream samples. Molybdenum (µg/L) levels in the lift station samples were mostly lower than the detectable levels (5.00 µg/L) compared to the upstream and downstream samples except, in the samples that were collected July 11, 2016 and September 30, 2019. Details are in Table 9.

Table 9. Results of Arsenic (µg/L), selenium (µg/L), molybdenum (µg/L) and barium (µg/L) for each sampling activity.

Date	Site	Arsenic (µg/L)	Selenium (µ/L)	Molybdenum (µg/L)	Barium (µg/L)
November 9, 2015	Upstream	8.19	16.10	ND	58.80
	Lift Station	ND	57.10	ND	24.80
	Downstream	5.65	28.50	6.60	47.40
May 11, 2016	Upstream	11.60	26.10	6.25	30.00
	Lift Station	11.00	31.20	ND	32.00
	Downstream	11.30	23.50	7.71	32.60
July 11, 2016	Upstream	ND	ND	ND	57.40
	Lift Station	23.70	110.00	16.60	86.80
	Downstream	ND	ND	ND	58.60
September 8, 2016	Upstream	9.34	ND	6.14	52.90
	Lift Station	ND	26.80	ND	25.30
	Downstream	5.94	ND	5.63	51.10
May 10, 2017	Upstream	10.50	7.83	9.45	118.00
	Lift Station	ND	21.70	ND	29.10
	Downstream	ND	20.30	ND	34.10
August 17, 2017	Upstream	ND	ND	5.87	33.10
	Lift Station	ND	13.90	ND	26.90
	Downstream	5.96	ND	ND	51.30
June 12, 2018	Upstream	5.15	ND	6.57	43.10
	Lift Station	ND	10.30	ND	41.30
	Downstream	6.71	ND	ND	53.20
August 26, 2019	Upstream	8.59	6.26	19.40	30.40
	Lift Station	5.03	11.70	ND	33.10
	Downstream	5.97	10.00	ND	39.70
September 30, 2019	Upstream	ND	ND	ND	36.70
	Lift Station	5.36	21.20	5.23	43.80
	Downstream	ND	ND	ND	37.90

Based on the cumulative means of all sampling activities, arsenic (µg/L), molybdenum (µg/L) and barium (µg/L) levels of lift station samples were lower than the upstream and downstream samples, whereas, molybdenum (µg/L) levels of lift station samples were higher than the upstream and downstream samples.

Figure 31. Cumulative means of Arsenic (μg/L), selenium (μg/L), molybdenum (μg/L) and barium (μg/L) for all sampling activities.



Differences in the Ammonia, Manganese, Bromide and Iron levels

Based on the results of each sampling activity, ammonia (mg/L) levels were mostly lower or equal than the levels in the upstream and downstream samples except, the samples that were collected on June 12, 2018. The manganese (mg/L) levels of the lift station samples were lower than the levels in upstream and downstream samples at all times. Bromide (mg/L) levels of the lift station samples were mostly higher than the upstream and downstream samples, except samples that were collected on May 11, 2016, May 10, 2017, and June 12, 2018. Iron (mg/L) levels of the lift station samples were either non-detectable (0.50 mg/L) or were lower than the upstream and downstream samples except, one set of sample that was collected on August 17, 2017. Details are in Table 10.

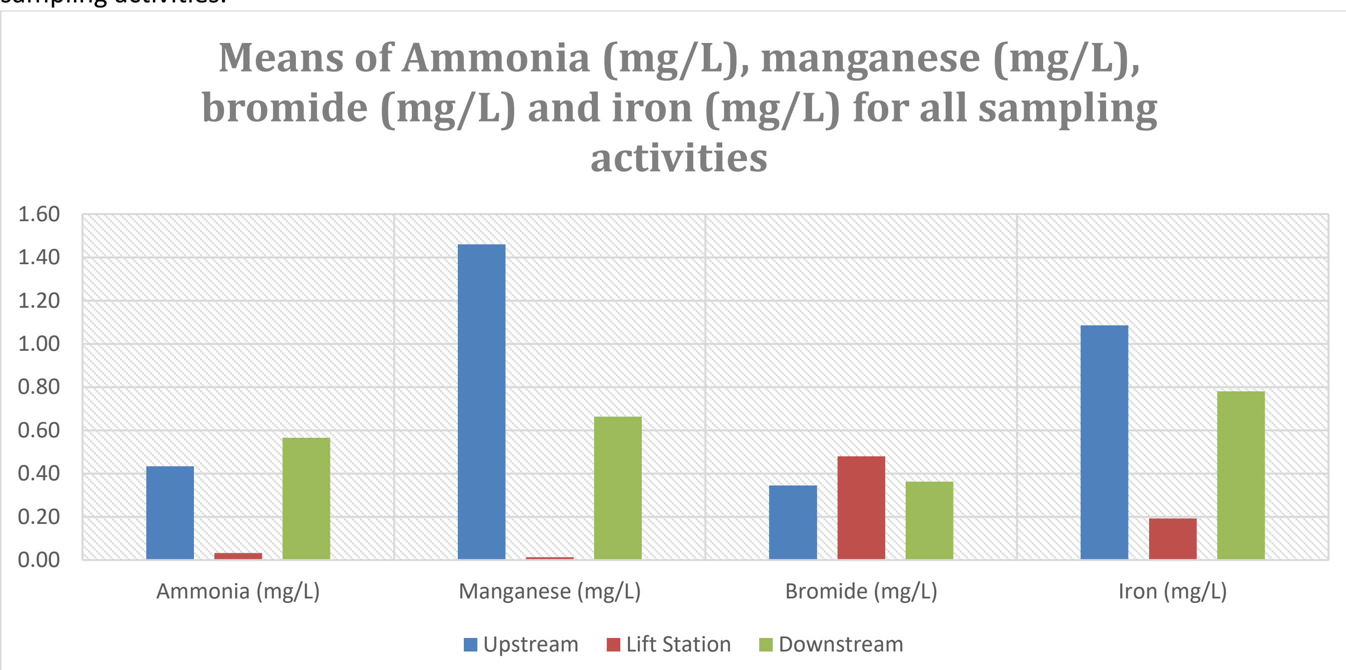
Table 10. Results of Ammonia (mg/L), manganese (mg/L), bromide (g/L) and iron (mg/L) for each sampling activity.

Date	Site	Ammonia (mg/L)	Manganese (mg/L)	Bromide (mg/L)	Iron (mg/L)
November 9, 2015	Upstream	1.77	0.26	NA	1.30
	Lift Station	ND	ND	NA	ND
	Downstream	2.10	0.23	NA	0.93
May 11, 2016	Upstream	0.05	0.59	0.87	0.24
	Lift Station	ND	0.01	0.71	ND
	Downstream	0.08	0.94	0.85	0.18
July 11, 2016	Upstream	0.29	0.11	0.05	1.14
	Lift Station	0.03	0.01	0.64	0.35
	Downstream	0.06	0.07	0.05	0.99
September 8, 2016	Upstream	0.06	2.54	0.43	0.58
	Lift Station	ND	0.02	0.64	0.08
	Downstream	0.13	0.77	0.33	0.24
May 10, 2017	Upstream	0.25	6.29	0.64	2.89
	Lift Station	0.03	0.01	0.53	0.05

	Downstream	0.13	0.62	0.68	0.44
August 17, 2017	Upstream	0.09	0.61	0.29	0.62
	Lift Station	0.03	0.02	0.51	1.28
	Downstream	0.03	0.80	0.32	1.11
June 12, 2018	Upstream	0.04	1.81	0.35	0.83
	Lift Station	0.05	0.04	0.33	ND
	Downstream	0.04	1.65	0.36	0.72
August 26, 2019	Upstream	0.08	1.32	0.23	0.12
	Lift Station	ND	ND	0.42	ND
	Downstream	ND	0.16	0.32	0.12
September 30, 2019	Upstream	0.04	0.06	ND	1.64
	Lift Station	0.14	ND	0.40	0.31
	Downstream	0.52	0.08	0.05	1.86

Based on the cumulative means of all sampling activities, ammonia (mg/L), manganese (mg/L) and iron (mg/L) levels of the lift station samples were lower than the upstream and downstream samples, whereas, bromide (mg/L) levels of the lift station samples were higher than the upstream and downstream samples.

Figure 32. Cumulative means of Ammonia (mg/L), manganese (mg/L), bromide (mg/L) and iron (mg/L) for all sampling activities.



SUMMARY

Below is the summary for soil chemical and physical properties based on data four-years after applying the soil amendments and five-years after tiling the saline-sodic site.

Soil EC levels: have been directly related to the annual growing-season rainfall and moisture levels in the topsoil. Narrower gap between annual total potential evapotranspiration and rain means more leaching of salts and less capillary rise of soil water, whereas a wider gap will indicate less leaching and increased capillary rise. 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 that trend continued in 2018 and 2019 (until July 30, 2019) despite average annual growing-season groundwater depths being deeper than the depth of tiles (four-feet) and land being tiled. 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 and good soil water infiltration to push the salts into deeper depths. Importance of good soil water infiltration is also evident from the fact that the highest EC levels were observed in 12-24 and 24-36 inch soil depths. That could be indication of decent infiltration through the first foot, however, a much slower water movement through the second and third feet of soil resulting in higher levels of salts. 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 four-years after application), weather conditions, resulting average annual growing-season groundwater depths and tiling. It could be due to the drier weather in 2017, 2018 and early part of 2019 resulting in insufficient soil water to dissolve the amendments and create the desired chemical reaction for sodicity remediation. However, this could also be a good insight that lowering SAR levels is more complex than lowering EC, which will take longer time and equal or higher than normal annual rainfall. In addition, soil SAR levels increased with soil depth with 0-12 inch depths having the lowest SAR levels and 36-48 inch depths having the highest SAR levels.

Soil pH levels: were consistent with the annual growing-season rainfall and soil moisture levels and have had no impact so far related to the application of soil amendments. Like SAR, soil pH significantly increased with soil depth with 0-12 inch depths having the lowest pH levels and 36-48 inch depths having the highest pH levels. Increase in pH with soil depth was due to the increase in soil moisture levels.

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 annually. A steady decline in soil NO_3^--N levels was observed that could be due to leaching, removal by the perennial grass mix and no application since 2014. In addition, soil NO_3^- -N levels decreased with increasing soil depth.

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. Drier weather in 2017, 2018 and 2019 probably also contributed to the limited P availability. However, VersaLime treatments had significantly higher soil P levels than rest of the treatments and that could be due to fact that it contained 42.5 ppm of available P. In addition, 0-12 inch soil depths had significantly higher P levels versus 12-24 inch depths.

Soil O.M. levels: also decreased with time under no or poor vegetation before 2016. 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. However, creating favorable growth environment for soil microbes and conversion of organic material into organic matter will take time. Soil organic matter levels continued decreasing especially in 2017 and 2019, which could be due to a slightly drier weather in June 2017 and 2019 when soil samples were collected. In addition, 0-12 inch soil depths had significantly higher O.M. levels than 12-24 inch depths.

Soil CEC levels: decreased in 2016, 2017, 2018 and 2019 compared to 2014. That could be due to a steady decline in soil organic matter. However, future biomass decomposition of the perennial salt-tolerant grasses could reverse this trend.

Soil Saturation levels: showed some trends where soil amendments were applied, how soluble each amendment was and average annual growing-season groundwater depths. Saturation levels increased in all of the treatments, which received soil amendments compared to control and in treatments that were applied with more soluble amendments for example gypsum. Gypsum treatments had the highest increase followed by VersaLime and E-sulfur treatments. In addition, replication 3 had the shallowest groundwater depths in all years and had higher saturation levels versus replication 1 and 2.

Soil CCE levels: generally, increased with the increase in soil depth. That could be due to increase in soil moisture with depth due to the close proximity of average annual growing-season groundwater depths. In addition, as lime ($CaCO_3$) is one of the least soluble salts, capillary rise did not had a profound effect on its movement. In terms of VersaLime being the spent lime, so far no increase in soil CCE levels have been observed due to the application of VesaLime.

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, HCO_3^- levels were the highest in the 0-12 inch depths. Levels remained lower in the 12-24 and 24-36 inch depths, however, spiked up again in the 36-48 inch depths.

Soil Cl^- levels: have not shown a consistent trend due to the application of soil amendments or average annual growing-season groundwater depths. However, the significant increase in Cl^- levels in 2018 under deepest average annual growing-season groundwater depths may be an indication of high levels of Cl^- ions in groundwater and its upward movement with capillary water.

Soil SO_4^{2-} levels: have not shown a consistent trend due application of soil amendments or changes in the average annual growing-season groundwater depth. Being an anion like Cl^-, SO_4^{2-} levels also fluctuate considerably due the fluctuations in the rain, depth of the groundwater and levels in the groundwater. If SO_4^{2-} levels are high in the deeper soil depths or groundwater, SO_4^{2-} ion levels can increase again due to the capillary rise of soil water under drier weather.

Soil Ca^{2+} levels: were significantly higher in 2014 at the time of tiling than rest of the years. Soil Ca^{2+} levels in 2016, decreased significantly in all treatments under higher rainfall, shallow average annual groundwater depths and tile drainage. Levels remained low in 2017, 2018 and 2019. 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 resulted in an increase in the soil Ca^{2+} levels.

Soil Mg^{2+} levels: had some annual differences, however, have had no major impact due to the application of soil amendments or average annual growing-season groundwater depths despite some changes annually. Though Mg^{2+} levels did increased with soil depth.

Soil Na^+ levels: have been inconsistent like SAR levels despite some annual changes. There was an increase in Na^+ levels in 2018 under deepest average annual groundwater depths and resulting capillary rise, 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 versus rest of the years. That could be an outlier, however, it needs to be verified in the future.

Soil Bulk Density levels: increased with soil depths. In addition, despite not being a clear trend, bulk density increased with at lower gravimetric soil water levels.

Soil Penetrometer Resistance levels: were strongly correlated with the gravimetric soil water content. Lower the gravimetric water content, higher were the penetrometer resistance measurements. An example could be 2015 when one of the highest penetrometer resistance measurements were recorded, whereas gravimetric water content was the lowest compared to rest of the years.

Quality of Water Draining from the Research Project Site for Human and Livestock Health: Based on cumulative means of all sampling times, conductivity, dissolved solids, total hardness as $CaCO_3$, total alkalinity as $CaCO_3$, SAR, Ca^{2+}, Mg^{2+}, Na^{+}, SO_4^{2-}, HCO_3^{-}, Cl^{-}, total nitrogen, nitrate + nitrite nitrogen, boron, copper, zinc, selenium and bromide levels of the lift station samples were higher than the upstream samples. The pH means of upstream, lift station and downstream samples were roughly equal. The K+, Kjeldahl nitrogen, total phosphorous, dissolved phosphorous, aluminum, nickel, arsenic, molybdenum, barium, ammonia, manganese and iron means of the lift station samples were lower than the upstream and downstream samples. These trends point out that over time depending upon the site specific soil chemistry, tile drainage water can add salts, alkalinity, sodicity, soluble nitrogen and some trace elements to the surface water resources.

CONCLUSIONS

Though the data and the observations so far are not conclusive, however, producers and landowners, who have unproductive areas with potential dispersion issues due to sodicity (and/or higher Mg^{2+} versus Ca^{2+} ratios) 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".**
- If the potential fields have unproductive or marginal areas, **"they may want to sample these areas three to four-feet deep and analyze the samples for EC (salinity), SAR (sodicity) and pH levels by using the saturated paste extract method."** 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 tiles will help drain the excess water along with leaching the excess salts.
- Tiling sodic or saline-sodic fields alone **"will not remediate sodicity and will require application of amendments at some point in time."**
- Note: calculating the rates of soil amendments will also require analyzing the first-foot samples for **"Cation Exchange Capacity (CEC) by using sodium saturation and ammonium extraction method".**
- 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), SAR (sodicity) and pH levels by using the saturated paste extract method."** 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.
- Tiling sodic or saline-sodic fields alone **"will not remediate sodicity and will require application of amendments at some point in time."**
- Note: calculating the rates of soil amendments will require analyzing the first-foot samples for **"Cation Exchange Capacity (CEC) by using sodium saturation and ammonium extraction method".**
- Under drier weather, despite applying amendments, conversion of sodicity into salinity **"will take longer time and may take several years."**
- 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.

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