FERTILIZER MANAGEMENT STRATEGIES OF SOYBEAN (*GLYCINE MAX L. MERRILL*) IN NORTHCENTRAL AND NORTHWESTERN NORTH DAKOTA

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Fertilizer Management Strategies of Soybean (*Glycine Max L.*) in Northcentral and Northwestern North Dakota

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Soybean (*Glycine max* L. Merrill) is a new cash crop for north central and northwestern North Dakota producers. Soils and climate in these new soybean areas differ from those regions where the current fertilizer recommendations were based. Northcentral and northwestern North Dakota is more undulating, drier, cooler, and has differencing soils than eastern North Dakota and Minnesota. A three-year study to evaluate soybean best management practices was conducted during the 2016 to 2018 growing seasons. Each year, the study consisted of two sites and 12 treatments. By design, one site was on acidic (pH < 6) soil while the other was on alkaline (pH > 7.3) soil. Both site treatments were: untreated check, inoculated with rhizobia (*B. japonicum* L.), broadcast urea (55 kg ha^{-1}), broadcast MAP (monoammonium phosphate, 11-52-0) (110 kg ha^{-1}), in-furrow 10-34-0 (28 L ha^{-1}), in-furrow 6-24-6 (28 L ha^{-1}), foliar 3-18-18 (28 L ha^{-1}) at V5 and R2 growth stages, and foliar 3-18-18 (28 L ha^{-1}) with sulfate (1.1 kg ha^{-1}) at V5 and R2. The acidic sites alone included two treatments of sugar beet (*Beta vulgaris* L.) waste lime (4.4 Mg ha^{-1} and 8.8 Mg ha^{-1}). The alkaline sites alone received treatments of iron ortho-ortho-EDDHA (1.8% Fe) (7.1 L ha^{-1}), and sodium (naked- without Fe) ortho-ortho-EDDHA (7.1 L ha^{-1}). Treatments did not impact soybean yield, protein content or oil content at the 95% significance level. Sugar beet waste lime surface applied at planting at rates of 4.4 Mg ha^{-1} and 8.8 Mg ha^{-1} increased soil pH to a depth of 10 cm over the course of the growing season.

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DEDICATION

To my dearest twinion sons Claymaker and Jordini. Catching 28 inch walleyes is a joy. However, there is no truer joy than coming home from work to your hugs, smiles, and excitement! The Lord has blessed me. Daddy loves you very much.

To the memory of my dear friend Mary Schuh whom is greatly missed by many.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3-18-18	Anhydrous ammonia-phosphoric acid-potassium hydroxide liquid fertilizer
6-24-6	Orthophosphate-polyphosphate liquid fertilizer
10-34-0	Ammonium polyphosphate liquid fertilizer
11-52-0	Monoammonium phosphate granular fertilizer
46-0-0	Urea granular fertilizer
ADP	Adenosine diphosphate
AEM	Adams and Evans method (Adams and Evans, 1962)
ANOVA	Analysis of variance
Al	Aluminum
Al^{3+}	Aluminum cation
AMS	Ammonium sulfate
ATP	Adenosine triphosphate
B	Boron
BP	Before present
C	Carbon
$C_{63}H_{88}CoN_{14}P$	B_{12} vitamin
Ca	Calcium
Ca^{2+}	Calcium ion
$Ca(OH)_2$	Calcium hydroxide
$CaCl_2$	Calcium chloride
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CCE	Calcium carbonate equivalence

CEC.....Cation Exchange Capacity

cm.....Centimeter

$cmol_c$ .....Centimole of charge

Co.....Cobalt

Co^{2+}.....Cobalt cation

$Co(OH)_2$.....Cobalt hydroxide

CO_2.....Carbon dioxide

CO_3^{2-} .....Carbonate

Cu.....Copper

D0.....Abnormally dry (Hoell, 2017)

D1.....Moderate drought (Hoell, 2017)

D2.....Severe drought (Hoell, 2017)

dS .....Decisiemens

E.C. .....Electrical conductivity

EDTA.....Ethylene diamine di-hydroxyl phenyl acetic acid

EPA.....Environmental Protection Agency

Fe.....Iron

Fe^{2+}.....Ferrous

Fe^{3+}.....Ferric

Fe-o-o-EDDHA.....Ortho-ortho-ethylene diamine-N,N`-bis(hydroxyl phenyl acetic acid

Fe-o-p-EDDHA.....Ortho-para-ethylene diamine-N,N`-bis(hydroxyl phenyl acetic acid

g.....gram

H.....Hydrogen

H^+ .....Hydrogen cation

H_2O .....Water

$H_2PO_4^-$.....Dihydrogen phosphate

H_3PO_4.....Phosphoric acid

ha.....Hectare

HCO_3^-.....Bicarbonate

HPO_4^{2-}.....Hydrogen phosphate

IDC.....Iron deficiency chlorosis

IPNI.....International Plant Nutrition Institute

K.....Potassium

K_2O .....Potassium oxide

KCl.....Potassium chloride (halite)

kg.....Kilogram

L .....Liter

LSD.....Least significant difference

m .....Meter

mol .....Molar

MES .....2-(N-morpholino)ethanesulfonic acid monohydrate

mg .....Milligram

Mg.....Mega gram

mm .....Millimeter

Mn.....Manganese

Mo.....Molybdenum

N.....Nitrogen

N_2 .....Dinitrogen gas

Na.....Sodium

NASS .....National Agricultural Statistics Service

NDAWN .....North Dakota Agricultural Weather Network

NH_4^+ .....Ammonium

NH_4OAC .....Ammonium acetate

NO_3^-.....Nitrate

NS .....Not significant

O_2 .....Dioxygen gas

^oC.....Degrees celsius

OH^- .....Hydroxide

P .....Phosphorus

P_2O_5.....Phosphorus pentoxide

pKa.....Acid dissociation constant

ppb.....Parts per billion

ppm .....Parts per million

PROC GLM .....General linear model statistics procedure

r .....Relationship of Pearson correlation coefficient

R1.....Beginning bloom reproductive growth stage (Fehr and Caviness, 1977)

R2.....Full boom reproductive growth stage (Fehr and Caviness, 1977)

R3.....Beginning pod reproductive growth stage (Fehr and Caviness, 1977)

R4.....Full pod reproductive growth stage (Fehr and Caviness, 1977)

R5.....Beginning seed reproductive growth stage (Fehr and Caviness, 1977)

R6.....Full seed reproductive growth stage (Fehr and Caviness, 1977)

R7.....Beginning maturity reproductive growth stage (Fehr and Caviness, 1977)

R8.....Full maturity reproductive growth stage (Fehr and Caviness, 1977)

S .....Sulfur

$S_2O_3^{2-}$.....Thiosulfate

SMP.....Shoemaker, Mclean, and Pratt soil buffer method (Shoemaker et al., 1961)

USDA-NASS .....United States Department of Agriculture-National Agricultural Statistics Service

USDA-NRCS.....United States Department of Agriculture-Natural Resources Conservation Service

V1.....Vegetative growth stage one node (Fehr and Caviness, 1977)

V2.....Vegetative growth stage two nodes (Fehr and Caviness, 1977)

V3.....Vegetative growth stage three nodes (Fehr and Caviness, 1977)

V4.....Vegetative growth stage four nodes (Fehr and Caviness, 1977)

V5.....Vegetative growth stage five nodes (Fehr and Caviness, 1977)

V6.....Vegetative growth stage six nodes (Fehr and Caviness, 1977)

WWL.....Waste water lime

Zn .....Zinc

LIST OF SYMBOLS

@.....Fertilizer applied at

%.....Percent

LIST OF APPENDIX TABLES

ORGANIZATION OF DISSERTATION

This dissertation has a literature review section, a materials and methods section, results and discussion section, and a chapter on liming North Dakota soils. The literature review covers selected past works on soybean fertility management, with emphasis on the immediate region. The materials and methods sections explains the procedures used to generate data to support the results. The results and discussion section consist of the results and narrative for the soybean fertility research. The liming North Dakota soils chapter covers the theory and past work of liming soils. This chapter includes a one-year study that examined soil pH changes due to surface applied sugar beet waste lime. The reference section is placed following the chapter on amelioration of acidic soils in North Dakota Finally, there are three appendices with ANOVA tables of the soybean fertility experiments, soil descriptions, and raw data from the soybean fertility and soil liming experiments.

1. LITERATURE REVIEW

1.1. Introduction

North Dakota has historically been a leading United States spring wheat (*Triticum aestivum* L.) producing state (NASS, 2018a). Spring wheat acres have decreased from 3.37 million ha in 1997 to 2.17 million ha in 2017 (Jantzi et al., 2018). Many former wheat acres are now planted to soybean (*Glycine max* L., Merrill), as the area now seeded to soybean in North Dakota soybean hectares has increased from 28 hundred ha in 1942 to 463 thousand ha in 1997 to 2.88 million ha grown in 2017 (Jantzi et al., 2018). The change in planted area since 1997 is largely west of the Red River Valley of North Dakota, including northcentral and northwestern North Dakota.

Limited fertility research had been conducted in northwest and north central North Dakota until the experiments described herein were initiated in 2016. Current North Dakota soybean fertility recommendations have been developed from data collected in the eastern third of North Dakota, western Minnesota and the northern tier of counties in South Dakota (Franzen, 2018c). Eastern North Dakota receives more rainfall than western North Dakota. The annual normal total precipitation in Fargo is 57.4 cm (46.897^{o}N, 96.812^{o}W) while Crosby (48.807^{o}N, 103.312^{o}W) receives 38.6 cm (NDAWN, 2019b). Southern North Dakota is warmer than northern North Dakota. The average annual air temperature in Crosby is 3.9 ^{o}C whereas Fargo is 5.6 ^{o}C (NDAWN, 2019a). Due to climatic factors, soybean seed breeders and agronomists recommend growers use Group 0 maturity soybeans in Fargo, whereas 00 and 000 maturity group soybeans are recommended in Crosby (Kandel, 2010).

Soil parent materials north and east of the Missouri river in North Dakota are of glacial origin. Outside of a few outwash areas comprised of alluvium; the Red River Valley consists of

mostly lacustrine sediments from thousands of years of sedimentation from ancient glacial Lake Agassiz. Landscapes have greater soil variability in western North Dakota compared to eastern North Dakota (Bluemle, 2000).

Different soil types, climate, and lack of soil fertility data demonstrate the need for research in the new soybean growing areas in northwestern and northcentral North Dakota. The data generated will help improve grain quality and yield, and to maximize soybean farmer economic return on investment in this region.

1.2. A Brief History of Soybean Cultivation

Soybean was first domesticated in China about 3,000 years BP. Over the following centuries, soybean was disseminated throughout Asia. European traders brought soybean to Europe during the period from 1500 to 1700 (Hymowitz, 2009). Soybean was first planted in the United States in 1765 near Thunderbolt in what is now the state of Georgia (Hymowitz and Shurtleff, 2005). Soybean was first cultivated in Illinois in 1851. Over the next few decades, soybean cultivation spread throughout the states in the present U.S. Corn Belt. The first Land Grant University study on soybean was conducted during 1879 in New Jersey by Dr. George H. Cook (Hymowitz, 2009).

The earliest soybean research conducted by the North Dakota Agricultural Experiment Station evaluated soybean maturity in Fargo and Park River, North Dakota in 1945 (North Dakota Agricultural Experiment Station, 1946). North Dakota soybean has an export advantage to markets in the Far East due to the rail system that links North Dakota grain handling facilities to ports in the Pacific Northwest. This makes transportation of soybean from North Dakota to China, Japan and Korea more efficient than shipment from US Corn Belt states and South America (Denicoff et al., 2014). However, North Dakota soybean protein levels tend to be less

than that of US Corn Belt states and South America, which puts North Dakota soybeans at a quality disadvantage (Henson, 2004).

1.3. Nitrogen

Nitrogen (N) is an essential plant nutrient that is required for all metabolic processes related to plant growth and reproduction. Nitrogen is a component of all amino acids which are used to build proteins that comprise enzymes and structural components in plants (Crawford et al., 2000). Soybean plants obtain N mineralized from the soil, synthetic fertilizers, and N fixed by symbiotic bacteria (Ohyama et al., 2009).

Soybean is a legume that has the ability to form a symbiotic relationship with the rhizobia bacteria (*Bradyrhizobium japonicum* L.) for the purpose of transforming atmospheric N_2 to ammonium-N. A large portion of the total N required for soybean is generally produced as a result of the activity of the symbiotic N-fixing rhizobium bacteria. The symbiotic N-fixation process is complex and interactive, with continuous feedback between the soybean and the *B. japnicum* bacteria. Soil inorganic N in adequate supply may delay in the short- or long-term, the initiation of root nodule development (Gage, 2004). In order for nodules to form, the host plant signals rhizobia by secreting particular flavonoids that attract the bacteria (Stacey et al., 2006). Once the bacteria physically contacts the soybean root hair it releases a growth regulator-like substance that causes the root hair to curl and crack. The bacteria can then infect the root cortical cell through the root hair crack using an infection thread root-like organelle to enter the root hair cell. Once inside the cell, the bacteria then produce the nodule, which houses structures similar to cell vacuoles. These structures then differentiate into bacteroids, consisting of thousands of N-fixing bacteria (Stacey et al., 2006). The bacteroids are where the N fixation takes place. The bacteria take N_2 from the soil air, and with the enzyme nitrogenase and an iron-molybdenum

(FeMo) cofactor, convert the N_2 to ammonium-N in the form of ureides, which allow distribution of the otherwise toxic ammonia throughout the plant. The ureide produced may act as part of the feedback mechanism that increases or decreases N-fixation rate. Nodules are considered a plant organ since the cells function to produce plant-usable N (Stacey et al., 2006).

Nitrogen fixation through the activity of symbiotic N-fixing bacteria is an energy intensive process, with the energy supplied by the host plant (Tjepkema and Winship, 1980). The rhizobia infect soybean roots, form nodules, and fix atmospheric dinitrogen (N_2) gas. Dinitrogen is reduced to ammonium (NH_4^+) by nitrogenase. In exchange for the N_2, rhizobia receive carbohydrates in the form of sugars (Strodtman and Emerich, 2009). The sugar contents of nodules is predominately sucrose with low amounts of fructose and glucose (Strodtman and Emerich, 2009).

The enzyme nitrogenase requires energy to function in the form of carbohydrates. In order to fix 1 g of N, the rhizobia require 12.2 g carbohydrates. Sixty percent of the carbohydrates sent to root nodules is used to produce plant usable N through nitrogenase, 24% for nodule maintenance, and 16% is used for N transport and assimilation (Serraj et al., 1999). Nitrogen from the nodules is transported through the plant by the ureide compounds allantoin and allanotoic acid. Ureides are formed from the NH_4^+ in the nodule (Goos et al., 2015, Goos et al., 2019).

External soil and environmental factors influence symbiotic N-fixation in soybean. When soil pH is less than 5.5, nodulation of soybean is greatly reduced (Kopittke and Menzies, 2007). The N-fixation process is also dependent on soil moisture conditions. Nodules are more massive and abundant when moisture conditions are adequate. When soils approach the wilting point, nodule numbers and size decrease (Serraj et al., 1999). Dry soil conditions hinder nodule

initiation, through reduction in the movement of rhizobia to soybean roots. Dry conditions decrease phloem flow and likely reduce a plant's ability to sustain rhizobia. The frequency of reported positive N fertilizer responses due to lack of adequate nodulation in soybean tends to increase under droughty conditions (Serraj et al., 1999). Inversely, too much soil water can impact nodule growth (Nathanson et al., 1984).

Saturated soils can impede nodule and root growth (Nathanson et al., 1984). Saturated soils are have limited gas exchange, are nearly void of O_2, and can have less pore space, and are more prone to compaction (Hillel, 1998). Soybean prior to podset (before and after flowering) can adapt to shallow ground water by initiating new root growth above the saturated root zone (Stanley et al., 1980). A greenhouse study observed a decrease of N-fixation activity in faba bean (*Vica faba* L.). Water stress can directly impact nodule activity, but is exacerbated from decreased photosynthetic activity from wilting leaves (Sprent, 1972).

The benefits of soybean providing N for subsequent crops was realized over a century ago, as George Washington Carver suggested in 1904 to plant soybean or peanuts (*Arachis hypogaea* L.) for two years, then rotate with cotton as the legumes can replenish the soil with N (North Carolina Soybean Producers Association, 2019). However, this story appears to be a myth as Hymowitz and Shurtleff (2005) argue that a public relations firm confused the legume peanut for soybean.

North Dakota fertility guidelines recommend providing a 44 kg N ha^{-1} credit against the N recommended for the crop immediately following soybean. Growers can subtract the N credit from the N fertilizer recommendation (Franzen, 2018b). A common misconception is that the N credit source is the result of soybean adding N to the soil from N fixation and residue mineralization providing N to the following crop. However, when the N in the harvested grain is

accounted for, there is a net removal of soil N. The smaller amount of residue remaining following soybean harvest compared to the residue following wheat or corn leads to less N immobilization from residue breakdown following soybean than wheat or corn (Green and Blackmer, 1995). Residue and soil microorganism activity seem to be the main factors of the N credit. There is evidence that soybean stimulates soil microbes that increase N mineralization rates under soybean and into the subsequent year, increasing N availability to the subsequent crop (Vanotti and Bundy, 1995). Soybean is commonly harvested before corn and has less residue than corn. Less residue allows soil to warm earlier in spring which encourages more N mineralization (Klinger and Budeja, 2018). Growing soybean can reduce soil organic matter levels since it is a low residue crop (Blackmer, 1996). Soybean residues immobilize faster than corn, but corn has more residue than soybean. The greater amount of decomposing residue requires more plant-available N. The differences of immobilized N between corn and soybean residues is part of the N credit following soybean (Blackmer, 1996).

1.4. Importance of Rhizobium to Soybean Production

W.P. Brooks conducted a soybean experiment in 1893 that showed that soybean growth and yield is improved when the soybean seed is inoculated with *B. japonicum* bacteria (Hymowitz, 2009). Potted soil that had no history of soybean was treated with dust collected from a soybean harvest threshing room. The dust-treated soybean growth and yield was greater than that of the untreated check. Nodules were observed on the roots of the treated plants and were not present on the untreated check. Samples from this study were sent to New Jersey and Kansas where the study was repeated and the findings of Brooks were confirmed. In 1905 inoculum was made available to producers (Hymowitz, 2009).

Inoculation is the method of introducing *B. japonicum* to soybean fields. There are three formulations of soybean inoculant currently available to farmers; granular, peat-based, and liquid (Franzen, 2018c). Studies have shown yield and quality improvement of soybean from the use of proper inoculants (Buetow, 2016; Christmas, 2008; Hesterman and Isleib, 2013; Hymowitz, 2009; Ruiz Diaz et al., 2009). Inoculation products serve to enable attachment to the seed, or placement in very close proximity to the soybean seed or root, resulting in effective rhizobia infection of soybean roots if environmental conditions allow (Strodtman and Emerich, 2009).

Granular and peat-based inoculum is usually applied in the furrow with the seed at planting. Liquid products are typically sprayed on soybean seeds prior to planting; either physically mixed with small batches of seed in a planter box, or sprayed onto the seed as it is being conveyed from seed storage to the planter box. Virgin soybean fields lack the rhizobia for symbiotic N fixation to occur. Without supplemental N or rhizobia, soybean yields are reduced (Kandel, 2010). However, the yield response to inoculation is not always significant (Eriksmoen, 2015; Henson, 2004; and Lee et al., 2007) or economic (Lamb et al., 1990; Hesterman and Isleib, 2013).

When soybean is grown in a field for the first time, a popular inoculation strategy is to use two different inoculum formulations to better ensure successful inoculation. (Fleury, 2017; Forster, 2015; Manitoba Pulse Soybean Growers, 2019). Double inoculation is a strategy where two different formulations (not twice the rate) of inoculum are used in a single seeding. An example of double inoculation would be treating seed with liquid inoculum and also applying a granular product in-furrow at planting (Endres et al., 2018b).

Rhizobia inoculum are living organisms so special care is required to ensure that the rhizobia are viable at planting. Inoculum should be stored in an area where the temperature is

consistent within a range from 4-27 ^{o}C (Voight, 2018). Soybean seldom responds positively to inoculation if the field had been previously seeded to successfully inoculated soybean. Endres et al. (2018b), Henson (2003), and Lamb et al. (1990) conducted soybean inoculation experiments on fields with a soybean history and did not observe a yield increase due to inoculation at these sites. Lamb et al. (1990) observed the effects of rhizobia applied on virgin soybean ground in Minnesota, where 11 of 12 sites did not have a soybean history. Even with twice the normal amount of rhizobia numbers applied with the seed, no yield response was observed. In order to positively impact soybean yield on land previously planted to properly inoculated soybean, Ham and Smith (1975) stated that rates of rhizobia inoculum may need to be 1,000 times the recommended rate. Therefore, inoculation may not always be an economical practice. Soybean yields rarely benefit from inoculation if the field has previously grown soybeans with good nodulation (Endres, 2018b; Endres et al., 2015; Franzen, 2018c; and Kandel, 2010). It has been suggested that fields that have not had soybeans for more than five years should be inoculated (Voight, 2018).

1.5. Nitrogen Fertilizer

Supplemental N application can increase yield of non-nodulating or poorly-nodulated soybeans. Weber (1966) evaluated the effects of N applied at 55, 110, and 165 kg N ha^{-1} to nodulating and non-nodulating soybean cultivars. Under favorable growing conditions, nodulating soybean produced greater grain yields than fertilized non-nodulating soybean. Yields were similar when soybean was moisture stressed. This research suggests that N obtained from rhizobia may be “more biologically suitable” than N received from a synthetic N fertilizer for soybean grain production (Weber, 1966).

Two Manitoba studies evaluated N applications on poorly nodulated soybean (Heard et al., 2014) and on soybeans that exhibited no nodules (Heard et al., 2011). The mean nodule count of poorly nodulated soybean was 1.5 to 13.4 nodules plant^{-1} (Heard et al., 2014). A rescue N application was not as effective as soybean that had nodulation (Heard et al., 2011). In both experiments, there was a positive yield response from the use of in-season N to poorly nodulated and non-nodulated soybean. Heard et al. (2011) recorded a soybean yield response with application of 110 kg N ha^{-1} urea treated with Agrotain™ (Koch Agronomic Services, 2019) at R4 growth stage (Fehr and Caviness, 1977) (2,441 kg grain ha^{-1}) or R1 growth stage (Fehr and Caviness, 1977) (2,415 kg grain ha^{-1}) compared to the untreated check yield of 2,077 kg grain ha^{-1}. Heard et al. (2014) did not observe a yield advantage with a N rescue application when compared to well-nodulated soybean. The nodulated soybean had a 29% greater yield than the poorly nodulated N rescue treatment.

According to Neales and Incoll (1968), the source-sink principle was first hypothesized by Boussingault in 1868. The “source” is a part of the plant that produces the “assimilates”. This would be (leaves) or takes up nutrients (roots). The “sink” is the portion of the plant where the “assimilates” energy and nutrients are utilized for growth or for storage (Neales and Incoll, 1968). In crop production for grain, the sink of most concern is the grain produced from photosynthesis. As a plant grows the stems, leaves, and roots are considered sinks (Egli, 1998). Soybean nodules have been referred to a sink and leaves/stem/pods as a source early in the soybean growing season. Once the pods begin to develop, less carbohydrates move to the root and more move to the pods for seed development (Franzen, 2016).

During the reproductive stages, nodule activity decreases and the flowering parts of the plant become sinks. Soybean nitrogen demand increases greatly between the R1 and R5 growth

stages (Harper and Hageman, 1972). Fehr and Caviness (1977) describe the R1 and R5 growth stages as “beginning bloom” to “beginning seed” respectively. Many have theorized (Afza et al., 1987; Barker and Sawyer, 2005; Garcia and Hanway, 1976; Schmitt et al., 2001; Wesley et al., 1998) that an in-season N application might improve soybean yield and/or quality by increasing availability of N that is available to the ‘sink’. However, dryland research indicates that there is little response from an in-season N application made during the soybean reproductive stage in healthy soybean crops (Barker and Sawyer, 2005, Prochaska, 2019).

However, a high yielding environment such as a properly irrigated soybean crop may provide an opportunity for a yield response to supplemental N. A yield response from N applied at the reproductive stage might be more likely, but the response may not include an increase in soybean grain protein content. Care needs to be practiced if foliar fertilizer is applied to soybean during the reproductive phase to minimize leaf burn (Wesley et al., 1998). Wesley et al. (1998) observed an 11% grain yield increase at six of eight sites from the application of 22 and 44 kg of N ha^{-1} at the R3 growth stage (Fehr and Caviness, 1977). There was no difference in yield between N rates and N fertilizer source. However, when accounting for the cost of N and its application, the practice of late season N applications are usually not economically profitable (Schmitt et al., 2001).

1.6. Cobalt

Cobalt (Co) is a Group VIII element in the periodic table with an atomic number of 27. The properties of Co are similar to iron and nickel as it lies between the two elements on the periodic table (IPNI, 2018). Cobalt is present in soil due to its release into the environment through volcanic eruptions, burning fossil fuels, emissions from smelting facilities, forest fires, marine emissions, and as a contaminant in phosphate fertilizers (EPA, 2005). Soil Co

concentrations typically range from 1-40 ppm with a mean of eight ppm (Lindsay, 2001). Soils containing the minerals olivine and pyroxene tend to have high levels of Co (IPNI, 2018). Cobalt soil concentrations are usually higher in clayey soils (Beeson et al., 1965; IPNI, 2018) and are more plant available in saturated soils (Adams and Honeysett, 1964) and under acidic conditions. As a solution changes from acidic to alkaline, Co will bind to hydroxyl groups ($Co(OH)_2$), which tend to precipitate (Alrehaily, 2013). Cobalt toxicity in plants is rare and is most likely to occur in acidic soils (Zheng et al., 1999). However, it is common for toxic levels of arsenic and nickel to exist with toxic Co levels. Under these conditions, arsenic and nickel are of greater concern than Co (Ministry of the Environment, 2001).

Some areas of the United States have been prone to Co deficiency (Ensminger et al., 1990). Livestock raised around Lake Michigan, central New England, Florida, and the coastal Carolinas have dealt with Co deficiency. Though many of these soils are acidic, these areas do not have sufficient levels of Co contained in locally grown forage, which is then fed to livestock which results in their Co deficiency (Ensminger et al., 1990).

Rhizobia require anO_2 free environment to reduce N_2 gas into NH_4^+. Leg-hemoglobin contain Co and is used by rhizobia to void the environment of O_2. Healthy and active nodules have a pinkish appearance that is caused by leg-hemoglobin. Leg-hemoglobin is required for N-fixation and governs the number and size of root nodules (Yadav and Khanna, 1988). Many factors are possible that reduce nodule activity, including temperature, adequate to excessive soil NO_3^-, pH < 5.5, and saturated soil conditions that limit soil oxygen/nitrogen (Kandel, 2010). Another possible reason for poor nodule performance is through inadequate uptake and availability of soil Co.

Cobalt was determined to be a required nutrient for N-fixation and healthy rhizobia almost sixty years ago (Ahmed and Evans, 1959; Ahmed and Evans, 1960; Lowe et al., 1969). The role of Co with the rhizobial life-cycle is not fully understood. However, Co is needed to form leg-hemoglobin by synthesizing cobalamin, or more commonly known as vitamin B_{12} ($C_{63}H_{88}CoN_{14}P$). Ahmed and Evans (1959) increased soybean growth with a soil application of B_{12}.

Soybean N content has been found to increase in rhizobia as a result of Co applications (Lowe et al., 1960). Ahmed and Evans (1959) recorded that Co applied as cobalt-chloride at 1 ppb and 50 ppb increased the biomass of soybean. Markova and Chanova (1984) observed that soybean nodule doubled in size and nodule mass increased by a factor of 1.5 from an application of 3 mg Co kg^{-1} of soil as cobalt-sulfate**.** A greenhouse study, Jayakumar et al., (2008) applied 0, 50, 100, 150, 200, and 250 mg Co kg^{-1} to soil as a cobalt chloride solution at planting. Nodule counts were performed at 15, 30, 45, 50, and 75 days after sowing. The 50 mg Co kg^{-1} soil treatment had a significantly higher nodule count at each sampling interval; however, the Co treatments greater than 100 mg kg^{-1} had a lower nodule count than the untreated check, illustrating a fine line between Co nodule deficiency and toxicity. Significant differences of root and shoot growth was observed 90 days after sowing (50 > Control > 100 > 150 > 200 > 250 mg Co kg^{-1} soil) (Jayakumar et al., 2008). In a related study, Co soybean yield increased most with 50 mg Co kg^{-1} soil treatment compared to the untreated check. Cobalt rates > 50 mg Co kg^{-1} resulted in lower soybean yield compared to the check (Jayakumar and Jaleel, 2009). Cobalt applications greater than 100 mg Co kg^{-1} soil might be toxic to soybean or rhizobia.

Cobalt is taken up by plant roots as Co^{+2}. This form is plant immobile. However, Co is plant mobile when associated with organic compounds, where it is cannibalized in older plant

parts and translocated to new growth (IPNI, 2018). Cobalt plays a role in the formation of chlorophyll b. Cobalt toxicity reduces photosynthesis by inhibiting the Hill reaction (Palit and Sharma, 1994). Currently, Co is not considered an essential plant nutrient (IPNI, 2018).

Due to insufficient nodulation and associated N-fixing activity, legumes that grow in Co deficient soils develop N deficiency symptoms (IPNI, 2018). Young leaves appear healthy, whereas old growth become chlorotic. Nitrogen deficiency symptoms from lack of Co can be alleviated with a timely N rescue treatment. (IPNI, 2018).

There are currently no scientifically accepted Co soil thresholds for rhizobial health (Sims, 1996a). Various extraction methods have been developed, including a calcium-chloride extraction (Kubota and Cary, 1982) and an acetic acid extraction (Mitchell et al., 1957). The calcium-chloride extractable Co is very sensitive to soil pH. If pH levels are too high, the 0.02M ethylenediaminetetraacetic acid (EDTA) extraction over-estimates soil available Co (Jarvis, 1984). The difficulty of measuring and correlating Co soil levels with crop production is believed to be due to the prevalence of Co associated with manganese oxides (Jarvis, 1984). Soil testing for manganese may be an indirect way to determine if Co applications are needed, as Zheng et al. (1999) observed that soil manganese (Mn) concentration is highly correlated with soil Co levels.

1.7. Phosphorus and Potassium

Phosphorus (P) is a key component of adenosine diphosphate (ADP) and adenosine triphosphate (ATP), which are the primary chemical energy compounds used in plants to fuel metabolic processes. Phosphorus is also an important component in lipids used in cell membranes, as well as DNA/RNA for cell and plant reproduction, and for controlling protein synthesis (Kochian, 2000). The solubility and plant availability of P is highly dependent on soil

pH. The plant preferred form of P for nutrient uptake are $H_2PO_4^-$ when the soil is acidic and HPO_4^{-2} when the soil is alkaline (Lindsay, 2001). When soil pH is greater than 7.5, P tends to precipitate with Ca compounds by forming octocalcium phosphate, dicalcium phosphate dehydrate, and hydroxyapatite (Lombi et al., 2004). At pH less than 6.8, the dominant P precipitates are Fe-P compounds. Aluminum (Al) becomes soluble when soil pH is less than 5.5 (Lindsay, 2001) and produces a toxic effect that stunts root growth and reduces nodulation (Kochian, 2000). Insoluble Al-P compounds form when aluminum is solubilized at a soil pH less than 5.5 (Lindsay, 2001). Insoluble Al-P compounds are not plant available. At first the plant may express P-deficiency symptoms, but as the pool of Al increases, root growth is hindered from the Al toxicity (Kochian, 2000). A majority of fertilizer P applied is not utilized by crops during that growing season. Soil pH-controlled precipitation of P compounds with Fe, Al, and Ca result in poor efficiency of crop P uptake applied the year of application (Lombi et al., 2004).

Soybean takes up P throughout the growing season; however, the greatest P demand by the plant occurs during the reproductive stage (Scott and Aldrich, 1983). Soybean grain removes about 14.5 kg P for each 1,000 kg grain yield (Franzen and Gerwing, 1997). Since that time, breeding has increased soybean P content (Kovács and Casteel, 2014).

Despite the soybean yield gain of 0.5% per year (Kumudini et al., 2001) and increase of soybean P content, responses of soybean due to P fertilizer application have been inconsistent from year to year and/or where yield increases are insignificant (Bardella, 2016; Blackmer et al., 1992; Cihacek et al., 1991; Lauzon and Miller, 1997; Mallarino and Borges, 2000; Mallarino and Haq, 2005; Slaton et al., 2010). The mixed results could be from newer soybean cultivars becoming more efficient at acquiring soil P compared to other crops such as rape (*Brassica napis* L) or oat (*Avena sativa* L) (Kalra and Soper, 1968).

Banding P is a fertilizer practice that improves the efficiency of P fertilizer in some crops. Banding is defined as placing a high concentration of fertilizer (band) in a specific place in the soil. Banding fertilizer at planting places the fertilizer with or near (within 5 cm) of the seed, which is then easily intercepted by young roots after germination (Sanchez et al., 1990). Fertilizer applied with or at the seed placement is called a 'starter fertilizer', or 'row starter' fertilizer. The starter fertilizer band at planting may be placed to the side, below, or within the seed furrow. Banding sometimes allows producers to obtain similar yield to that achieved using larger amounts of broadcast fertilizer P (Sanchez et al., 1990). In small grains, banding P can be beneficial, regardless of the soil test (Alessi and Power, 1980). Results are mixed as to whether greater soybean yields can be obtained by broadcasting or banding P fertilizer, although the greatest proportion of P experiments in soybean indicate that broadcast P tends to result in greater soybean yield compared to banded P (Buah et al., 2000; Edwards, 2017; Rehm. 1986).

Some previous experiments have recorded delayed soybean emergence and stand loss from the application of P fertilizer in-furrow; however, the uneven emergence and stand loss in these experiments resulted in no yield losses (Bardella, 2016; Rehm and Lamb, 2010; Schatz, 2005). Other studies have indicated soybean stand losses that resulted in yield loss due to in-furrow P fertilizer application (Endres and Hendrickson, 2008). Bullen et al. (1983) observed greater soybean yield with banded compared to broadcast P. Others have reported no yield differences between broadcast or banded P (Bardella, 2016; Borges and Mallarino, 2000; Buah et al., 2000; Ham and Caldwell, 1978).

Phosphorus fertilizer band placement can impact soybean yield. Bullen et al. (1983) observed a band placed 2.5 cm directly below and 2.5 cm to the side of the seed resulted in a 39% and 40% greater yield than fertilizer broadcasted or placed 5cm to the side and 5 cm

directly below the seed. Width of the fertilizer band was also evaluated, but the rate of fertilizer and location impacted yield more than P band width (Bullen et al., 1983). Mid-row banding or a 5x5 band (5 cm to the side of the seed and 5 cm below the soil surface) provided a yield advantage compared with the same rate as in-furrow fertilizer. Bly and Woodard (1997) observed that corn with banded P can increase the subsequent soybean yield when the residual P fertilizer bands are less than 9 cm from the current soybean row when row spacing was 75 cm and soybean was sown into the corn rows (Bly and Woodard, 1997).

The rate of in-furrow P and the soil texture can greatly impact soybean stand. Soil P availability in the fertilizer band can be detected through soil sampling and crop response two or more years after application (Bly and Woodard, 1997). Soybean emergence with in-furrow fertilizer P bands are much more susceptible to uneven emergence and stand loss compared with soil textures with higher clay content (Ham et al., 1973). A similar study (Endres and Hendrickson, 2007) on loam soils did not observe in-furrow fertilizer adversely affecting soybean stand or yield. However, a similar study the subsequent year (Endres and Hendrickson, 2008) using in-furrow 10-34-0 applied at 37.4 and 74.8 L ha^{-1}, negatively impacted soybean emergence date and yield. The difference in soybean response was probably the result of a excess soil moisture at planting in 2007, and a drier soil in 2008.

Potassium (K) is an essential element for soybean required for the activation of several enzymes, to improve plant water uptake, and in controlling leaf/plant cell turgor pressure (Kochian, 2000). Soybean takes up K as K^+. Soybean has a high K demand and a crop of harvested soybean grain removes more than twice the amount of K that corn grain removes, despite corn grain yields that are greater than soybean by a factor of four (Scott and Aldrich, 1983). Over time a soil can be depleted of K as result of soybean production. One Mg of soybean

grain removes about 22 kg of K_2O and removes more K_2O than corn > wheat = oat > barley (*Hordeum vulgare* L) comparing average yields of the crops. Potato *(Solanum tuberosum* L.) removes more K_2O (276 kg K_2O ha^{-1}) than all other row crops grown in North Dakota, while alfalfa generally removes about 23 kg K_2O Mg^{-1} of hay (Franzen and Gerwing, 1997).

Available soil K in North Dakota is analyzed using the 1-N ammonium acetate method (Warncke and Brown, 1998). When the K soil test indicates a high probability of soybean yield response soil test guidelines are used to determine fertilizer rates (Guertal et al., 1991; Kopittke and Menzies, 2007). Some have observed that the 1-N ammonium acetate method has not predicted K response of soybeans consistently (Beegle and Oravec, 1990; Mallarino and Blackmer, 1994; Randall et al., 1997). Soybean may be more effective than other crops at mining soil K (Bourns et al., 2019). The lack of reliability from soil K analysis alone may be caused by differences in pH, clay mineralogy, soil moisture, redox potential, degree of soil mineral weathering, and the presence and relative importance and equilibrium between different K pools. Potassium in the soil is generally regarded as unavailable and is comprised in North Dakota soils as a primary mineral (Helmke and Sparks, 1996). Breker (2017) evaluated various K soil testing methods and found the 1-N NH_4OAc method to be most predictive of crop response, although it only correctly predicted corn yield response approximately half the time. However, when the clay mineralogy is accounted for, the K soil testing critical values can be shifted to better reflect a fertilizer response based off of the 1-N NH_4OAc K soil test (Franzen and Bu, 2018d).

Soil solution K is readily available to microbes and plants, and regardless of where the K originated, soybean plants take up K from the soil solution in greatest proportion, with much smaller amounts taken up as a result of direct contact and diffusion. In descending order of most

available are exchangeable K, fixed K, and structural K (Sparks, 1987); however, these forms of K are in constant equilibrium with soil solution K, and substantial quantities of K can be taken up by crops in a growing season from all three origins (Sparks and Huang, 1985). Weathering of minerals is much greater in the rhizosphere than the bulk soil. Bacteria, fungi, and decaying plants release acids and C compounds break chemical bonds that release rhizosphere K. However, the bulk soil content of K is much greater than the rhizosphere (Murrell, 2018). Exchangeable K is bound to colloid surfaces as part of the CEC potential for the soil (Helmke and Sparks, 1996).

Nonexchangeable K is held between tetrahedral, trioctahedral, and octahedral interlayers of soil clays (Helmke and Sparks, 1996). Potassium is nonexchangeable when colloid binding forces are greater than hydration forces, and in smectites, particulary in beidelites, K becomes more nonexchangeable when soils are dry. This K is termed ‘fixed’, although this is probably a poor term since the ‘fixed’ K can become more available when the soil is again moist. Structural K is found as primary minerals that contain K. The K is mainly found in feldspars, muscovite, and biotite (Helmke and Sparks, 1996), with K-feldspars being particularly prevalent in North Dakota soils east and north of the Missouri River. Structural K release is dependent on the solution K concentration, climate, mineral weathering, pH, and biological activity; however, the contribution of K from structural sources during a growing season can be substantial, and sometimes the dominant source (Sparks, 1987).

1.8. Nutrient Uptake and Foliar Feeding

Roots are the main procurer of water and nutrients in plants. Nutrients dissolved in the soil solution are most readily taken up by the roots through mass flow caused by the moisture deficit around the roots of a transpiring plant and the movement of soil water to the zone of

lower water potential (Kochian, 2000). Some nutrient acquisition is improved by roots releasing acidifying compounds and chelating compounds to solubilize nutrients and keep nutrients in a stable form (Fe, P, Zn), or by secreting electrons that exchange for other cations on the soil CEC complex. The uptake of mineral nutrients from the soil is enhanced through the development of root hairs and root hair length, which results in increasing the overall root surface area. This strategy is also enhanced in some angiosperm plant families through the formation and promotion of symbiotic endo-mycorrhizal associations (Kochian, 2000).

Plant leaves can absorb nutrients through the epidermis or stomata, although leaf cuticles and waxes tend to inhibit this process and reduce the efficiency of any foliar fertilizer application (Havlin et al., 1999). The ability of leaves to absorb mineral nutrients and the profitability of commercial products that could be utilized for this purpose has resulted in great interest by the fertilizer industry into foliar fertilization. However, the success of foliar fertilization of soybean has been mixed at best (Garcia and Hanway, 1976; Haq and Mallarino, 1998, 2005; Mallarino et al., 2001).

Foliar feeding offers practical benefits to farmers who might add a fertilizer to a post-emergence herbicide or other pest management treatment to save trips over a field (Mallarino et al., 2001). A foliar fertilizer application may also help to overcome nutrient tie-up in the soil. A foliar fertilizer application may result in rapid nutrient use (Havlin et al., 1999), and help to overcome leaf nutrient depletion at the reproductive stage (Garcia and Hanway, 1976). However, foliar fertilization may also result in leaf injury which may reduce yield and offset any yield advantage. To minimize leaf damage, foliar feedings should be applied in the morning when temperatures are relatively cool and the plant is turgid and most resistant to rapid absorption (Mallarino et al., 2001). Soybean yield improvement due to foliar fertilizer application tend to be

infrequent and small (Haq and Mallarino, 2005; Mallarino et al., 2000). Increases in oil or protein content are unlikely or insignificant (Haq and Mallarino, 2005). Garcia and Hanway (1976) reported a large soybean yield increase from foliar fertilization, but failed to mention in their news release the sites where no yield increase was recorded. Most of their sites had no yield increase associated with their program of four applications of a liquid N:P:K:S formula of 24:2.4:7.3:1.2 kg ha^{-1} respectively. The total application was 96 N: 9.6 P: 29 K: 4.8 S kg ha^{-1} (Garcia and Hanway, 1976).

In some experiments, foliar fertilizer application timing was important. Garcia and Hanway (1976) reported that the most consistent soybean yield increase to foliar fertilizer occurred at the R5 and R6 growth stages (Fehr and Caviness, 1977). The news releases associated with Garcia and Hanway (1976) stated that the applications (3 separate applications) should occur from early to later pod-fill when, theoretically, the soybean nutrient uptake from the soil or symbiotic N-fixation may not meet plant nutrient demands. The yield increases reported in these two studies came from a greater number of seeds, but smaller seeds, suggesting that the yield increases may have come from a smaller number of aborted pods. Haq and Mallarino (2005), Mallarino et al. (2000), and Mallarino et al. (2001) performed their foliar applications during the vegetative growth stages. They theorized that foliar fertilizer applications made during the early vegetative growth stages might supply nutrients when soybean root growth is limited (Haq and Mallarino, 2000). However, they also concluded that a foliar fertilizer response is less likely when the initial soil test nutrient value is high (Haq and Mallarino, 2000).

1.9. Climate

North Dakota is located in a frigid soil climate zone. The western third of North Dakota is predominately in an ustic soil moisture regime (USDA-NRCS, 2019b). A frigid soil is one that

has an annual mean temperature of 0 to 8 ^{o}C and the difference of summer and winter soil temperature at the 50 cm depth is greater than 6 ^{o}C. A frigid ustic soil moisture regime is where a soil in a normal year at the 50 cm depth is dry for 90 or more cumulative days. However, the 25 to 100 cm depth may not be dry for more than half the cumulative days when the soil temperature at the 50 cm depth is greater than 5 ^{o}C (USDA-NRCS, 2014). The short, semi-arid growing season have been cited as factors limiting soybean yield potential in the northcentral and northwest regions of North Dakota. North Dakota soybeans typically require 406 mm water growing season^{-1} or 3.3 mm day^{-1} (Bauder and Ennen, 1981). During most years, precipitation in northwest North Dakota is less than the soybean water requirement, although there is a potential for rainfall supplementation from residual soil water following the spring thaw from winter ice and snowmelt. The northcentral growing season precipitation is greater and more favorable for soybean production than the northwest (NDAWN, 2019b).

The timing of growing season precipitation appears to be crucial in order to obtain maximum soybean yields. Soil moisture is most critical during pod elongation to seed enlargement (Kadhem et al., 1985), which would usually be August in northwest/north central North Dakota. Soybean planted on May 15 in northwest and northcentral North Dakota soybean typically enters the reproductive stage in mid to late July and is mature the last week of August to the first week of September (NDAWN, 2019b). Soybean water demand is greatest during this time (Kadhem et al., 1985 and Klocke et al., 1989).

Klocke et al., (1989) compared soybean irrigation timing. Irrigation treatments were irrigated all season, irrigated at flowering, and irrigated during pod elongation. Irrigation during pod elongation was the most critical timing for irrigation. However, temperatures tend to be greatest (NDAWN, 2019a) and rainfall becomes sparse during the last month of the soybean

growing season. August is also typically the driest growing season month in northcentral and northwest North Dakota (NDAWN, 2019b).

No-till cropping systems predominate cropland areas in western North Dakota. Approximately five percent of farmland west U.S. Highway 83 is still intensively tilled. Most farm land east of U.S. Highway 83 is conventionally tilled (NASS, 2019). No-till management helps reduce water stress from dry soils through reducing water loss at seeding and aiding precipitation infiltration (Dick et al., 1989). The previous crop residue acts as a mulch one the soil surface and thereby aids late season soybean water demand from reduced evaporation.

Deibert et al. (1986) reported the advantages of residue in no-till fields that through greater snowfall retention and a growing season reduction evaporation rate. These factors increase soil profile moisture that can be used by soybean when dry surface soil conditions are present. Brun et al. (1985) recorded a 516 kg ha^{-1} yield advantage of no-till soybean over conventional till soybean. This was a result of 67.8 mm more soil water available to the soybean during the growing season. A long-term no-till project with 37 site years (1999-2014) in central North Dakota saw a four percent yield advantage of continuous no-till soybean over soybean grown under conventional till management (Endres, 2015).

1.10. Iron Deficiency Chlorosis

Plants need iron (Fe) to produce chlorophyll required for photosynthesis (Zocchi et al., 2006). Iron is also needed for electron transport and redox reactions within plants (Broadley et al., 2012). Soybean is susceptible to Fe deficiency chlorosis (IDC) when soils have carbonate minerals present. The symptoms of IDC typically occur during the V1 through V5 growth stages (Fehr and Caviness, 1974), although under severe conditions in North Dakota, the symptoms can continue until maturity. The symptoms of IDC are interveinal yellowing of younger leaves,

extending to entire leaf yellowing if the soil and environmental conditions causing the IDC are severe. The lack of Fe and presence of IDC reduces soybean yield (Anderson, 1982).

Soil pH, water content, redox potential, and oxygen content influence the type of iron present in the soil (Lindsay, 2001). Iron solubility is regulated by ferric hydroxide ($Fe(OH)_3$) when aerobic and siderite (Fe_3CO_3) when highly reduced. Iron in intermittently reduced/oxidized soils is controlled by ferrosic hydroxide ($Fe_3(OH)_8$) (Lindsay and Schwab, 1982). The solubility of the $Fe^{2+/3+}$ hydroxides greatly influence plant available Fe. The solubility of Fe^{2+} and Fe^{3+} are inversely related to soil pH. As pH increases, Fe solubility decreases. As pH decreases, solubility Fe increases (Lindsay, 2001).

Anoxic soil conditions reduce ferric (Fe^{3+}) to ferrous (Fe^{2+}) (Lindsay, 2001). However, these conditions are not conducive to crop growth as ND crops tend to die from a lack of oxygen for root respiration (Hillel, 1998). Iron toxicity can occur in rice under flooding which reduces iron to the ferrous form in some soils high in Fe (Fageria et al., 2008).

Calcium carbonate ($CaCO_3$) can increase soil pH and decrease Fe availability (Lindsay, 2001). Calcium carbonate has a low solubility (Hammond, 2009), but when dissolved in water it results in increased pH by producing bicarbonate (HCO_3^-) and hydroxyl (OH^-) anions. As soil pH increases, Fe precipitates as $FeCO_3$ and cannot be taken up by plants thus preventing plant Fe uptake (Lindsay, 2001).

Iron solubility is very complicated as carbonates are not the only IDC factor. Salinity, water content, and pH have been correlated with soybean IDC. Salinity further stresses the plant and exacerbates IDC while water increases HCO_3^- in the soil solution (Franzen and Richardson, 2000; Goos and Johnson, 2000, Hansen et al., 2003; 2004). The amount of soil Fe is not the issue; as roughly six percent of the soil mineral is Fe. Iron is problematic to plants because Fe

can be insoluble and toxic, however, plants still require Fe for optimal growth and development (Hell and Stephan, 2003).

Plants use various mechanisms to increase their ability to take up iron. Soybeans are a Strategy I type plant. Strategy I plants increase Fe solubility and improve Fe uptake by releasing protons that acidify the area immediately around the roots. The action of proton secretion decreases the pH by approximately one unit (Hell and Stephen, 2003; Romheld and Marschner, 1984). Besides acidifying the soil, soybean roots secrete organic acids that are reducing agents that convert Fe^{3+} to the much more soluble Fe^{2+}. Secreted organic acids also chelate iron and acidifies the soil directly next to plant roots which increases the solubility of Fe^{+3} (Hell and Stephen, 2003).

Once Fe has entered the root *via* Fe diffusion to the plasmalemma, the Fe must be chelated to prevent oxidization and the formation of poisonous O_2 radicals (Hell and Stephen, 2003). Nicotianamine and citrate chelate Fe play an important role in Fe transport. Nicotianamine has the ability to form complexes with Fe^{3+} and Fe^{2+} (Stephen et al., 1996) and can assist with the transport of other micronutrients. Iron is transported to plant tissues by Fe-citrate complexes carried through the xylem (Hell and Stephen, 2003).

Chelated Fe fertilizers are a management tool that can reduce IDC and improve soybean yields if effective Fe fertilizers are used (Lucena, 2003). Chelate is the Greek word for “claw”, and it describes the configuration of a chelating compound with a metal ion. The use of chelates can improve plant nutrient availability of metallic nutrients subject to precipitation (Havlin et al., 1999).

Chelates improve nutrient uptake by protecting the metal nutrients from precipitation, thus increasing their availability for a time. (Lindsay, 2001). Ortho-ortho-ethylene diamine-

N,N`-bis(hydroxyl phenyl acetic acid (o-o-EDDHA) is a chelating agent that improves the solubility of Fe applied fertilizers (Schenkeveld et al., 2008). Iron (Fe) placed in front of 'o-o-EEDHA' indicates that it is Fe-o-o-EDDHA.

Different chelates have different formation constants. The formation constant is expressed as Log K. The formation constant is used to determine the stability and likeliness the chelate will remain intact. EDDHA has a higher formation constant with Fe than other common chelates (Lindsay, 2001). The formation constant of EDDHA with Fe^{+3} is 35.40 Log K, diethylene triamine pentaacetic acid (DTPA) has a Fe^{+3} Log K of 29.19, and ethylene diamine di-hydroxyl phenyl acetic acid (EDTA) has a Fe^{+3} Log K of 26.50 (Lindsay, 2001).

Chelates can assist plant iron uptake, but do not raise bulk soil iron activity and need to be stable in the soil (Lindsay and Schwab, 1982). Computer simulations by Halvorson and Lindsay (1972) indicate that EDDHA is stable in a hydroponic solution with pH 4 to pH 9. Whereas DTPA and EDTA became unstable at pH 7.2 and 6.5 respectively. Sunlight exposure also effects the stability of EDDHA. Wallace et al., (1967) observed in a greenhouse study that sunlight and acidic conditions decreased the stability of EDDHA.

The o-o-EDDHA can rejuvenate by chelating more Fe from Fe-hydroxides after Fe has been taken up by a plant (Lucena, 2003). Goos and Germain (2001) observed more DTPA extractable Fe in EDDHA treated pots than Fe-EDTA, Fe-DTPA, and five other Fe chelates.

There are isomers of Fe-o-o-EDDHA that are structurally different and therefore respond differently chemically with respect to Fe availability. Schenkeveld et al. (2010) compared the Fe-o-o-EDDHA chelates racemic and meso Fe-o-o-EDDHA and concluded that racemic Fe-o-o-EDDHA may be a better iron chelating agent than meso Fe-o-o-EDDHA. Besides Fe-o-o-EDDHA, there is Fe-ortho-para-EDDHA (Fe-o-p-EDDHA). The Fe-o-p-EDDHA has been

found to chelate iron, but is not as effective as the Fe-o-o-EDDHA (Lucena, 2003; Rojas et al., 2008; Schenkeveld, 2007) EDDHA because once it provides Fe to the soybean, it does not have the same ability to re-chelate soil Fe as does Fe-o-o-EDDHA (Lovas, 2013).

Lindsay (2001) stresses that chelates are not guaranteed to be effective at remediating a nutrient deficiency, however, a number of studies have reported positive results from the use of Fe-o-o-EDDHA. Lucena (2003) and Schenkevel et al., (2008) both observed an increase in yield and plant iron content from the use of Fe-EDDHA. Goos et al. (2004) observed that Fe-o-o-EDDHA increased the content of leaf chlorophyll and soybean growth. The increased iron content of plants suggests that Fe-o-o-EDDHA improves soybean Fe uptake. However, others did not observe a yield response or Fe content increase from foliar and seed treated Fe-EDDHA (Goos and Johnson, 2000) or seed and/or in-furrow EDDHA treated (Wiersma, 2005).

The rate of Fe-o-o-EDDHA impacts the crop response and has been problematic as analyzing for the isomers of Fe-o-o-EDDHA is difficult. In most studies, the ratio of ortho vs para Fe-o-o-EDDHA is unknown and unreported. A high ratio of para to ortho EDDHA may be the reason why a soil or seed-based FeEDDHA application did not increase soybean yield. The mixed results of studies could be a result of Fe-o-o-EDDHA concentration in the fertilizer, the ratios of Fe-o-o-EDDHA Fe-o-p-EDDHA isomers, or a combination of the two variables (Lovas, 2013; Lucena, 2003).

Several recent studies have shown a reduction in soybean IDC through an application of Fe o-o-EDDHA chelate (Goos, 2004; Kaiser et al., 2014; Lucena, 2003; Schenkeveld et al., 2008). Foliar applications of o-o-EDDHA generally result in little if any improvement in soybean yield versus in-furrow o-o-EDDHA applications. (Mallarino et al., 2005 and Kaiser et al., 2014; Liesch et al., 2011). Kaiser et al. (2014) observed IDC improvements in severe

conditions from the use of oat companion crop, probably due to oat uptake of soil NO_3^- and a lower soil moisture content. Excess NO_3^- in the plant prevents cells from using Fe because NO_3^- reduces to NH_4^+ which alkalinizes the plant and reduces Fe solubility (Lucena, 2000) However, care needs to be practiced with the timing of termination of the companion crop.

If the soil becomes dry, oat will compete with soybean for moisture and may reduce yield. Variety selection is the most important soybean IDC management tool. Planting an IDC tolerant soybean variety is a more practical, effective, and agronomically viable IDC management tool than using an iron chelate (Helms et al., 2010; Kaiser et al., 2014; Kandel, 2016), although the combination of tolerant soybean cultivar and application of an in-furrow band of Fe-o-o-EDDHA may result in highest potential yield.

1.11. Various Micronutrients

The majority of soils in the Midwest United States provide soybean with a sufficient supply of available micronutrients. Soybean rarely responds positively to the application of boron (B), manganese (Mn), copper (Cu), sulfur (S), or zinc (Zn). Mallarino et al. (2015) completed a recent research review that encompassed the states of Indiana, Iowa, Kansas, Minnesota and Wisconsin. Eight different studies were reviewed and each state study consisted of multiple site years. One study from Indiana saw a yield improvement when Mn was applied with 10-34-0. The rest of the Mn, Cu, S, and Zn studies did not observe a yield or quality response (Mallarino et al., 2015).

Manganese deficiency is common in Michigan. The deficiency occurs on lakebed and alluvium sediments with a pH greater than 6.5. Dark sands and mucky soils with a pH greater than 5.8 can also have Mn deficient soybean. The deficiency can be managed by a foliar application of 1.1 to 2.2 kg Mn ha^{-1} mixed with 114 L water ha^{-1} (Staton and Warncke, 2009).

Sutradhar et al., (2017) studied the effects of B, Cl, Mn, and Zn broadcasted on soybean in Minnesota. No yield response was observed and B applied at 2.2. kg ha^{-1} occasionally reduced soybean yield.

Sulfur as a fertilizer is becoming more important in the Midwest of the United States due to increasing deficiencies noted in small grains and corn across the region (Franzen, 2018a). One reason for this is the de-sulfurization of emissions from industry using coal and oil as fuel, and from smelting industries. These emissions are regulated by the US-EPA through the Clean Air Act of 1970 and its many amendments where soils receive much less amounts of S from precipitation (EPA, 2019).

Soil analysis of available S is not reliable as a diagnostic tool. A better predictor of the need for supplemental S is whether the soil texture is coarser than loam and where the winter, spring, and/or fall was abnormally wet (Franzen 2018a; 2018b). The frequency of S deficiency is also high in corn and small grains, as well as canola, which has a special requirement for S. If the soil and weather conditions are favorable for a S deficiency, corn and small grains may require the application of about 11 kg ha^{-1} S applied as a sulfate form of fertilizer, such as ammonium sulfate (AMS) or gypsum (Franzen 2018b). Other SO_4 fertilizers include thiosulfate (S_2O_3) fertilizers include ammonium thiosulfate (ATS) and potassium thiosulfate (KTS). Recent research conducted in North Dakota did not observe a yield or quality response from the use of S fertilizer in soybean (Augustin, 2017; Endres et al., 2018). Kaiser and Kim (2013) observed an inconsistent soybean yield response to S fertilizer in Minnesota. The only time the yield occurred was when soil organic matter was less than 20 g kg^{-1}. Sawyer et al. (2012) paired soybean experiments with corn S experiments in Iowa. Although corn response to S was frequent, soybean was non-responsive.

1.12. Summary

Soybean does not require supplemental N fertilizer if the proper rhizobia are present in the soil through residual bacteria population or through inoculation of the seed. Grain yields tend to be greater when plants have active nodules than if the soybean was fertilized with N only. Inoculum is required to culture the soil with rhizobia that fix N. Inoculum is only necessary if the field has no previous soybean history or the last soybean crop was poorly nodulated. Soybean requires P and K; however, a yield or quality response will not necessarily occur even if the soil test P and K analysis is perceived as 'low'. Foliar fertilizers have provided little benefit to soybean yield or quality in experiments from the Midwestern USA. Iron deficiency chlorosis can result in yield decreases to soybean on alkaline soils with carbonates present. Iron deficiency chlorosis severity is increased with high soluble salts, wet soils and the presence of other plant stresses. To date, in-furrow Fe-o-o-EDDHA has been most effective fertilization strategy in reducing yield loss to IDC; however, the most effective management on IDC-susceptible fields is the sowing a highly tolerant soybean cultivar. Liming soils is important to soybean production if the soil pH is less than 5.5 as nodulation is greatly reduced.

2. MATERIALS AND METHODS

2.1. Treatment, Planting, Soil, and Agronomic Practices

In order to establish annual experiments at one high pH (pH > 7), low P (Olsen P < 8 ppm) soil, and one acidic pH (pH < 6) soil. To screen sites for suitability for the experiments, six cores were collected at the 0-15 cm and 15-60 cm depth by a hand probe with a 19 mm diameter at each prospective site. The cores were composited and sent to the North Dakota State University Soil Testing Laboratory in Fargo North Dakota for analysis (Table 1). All soil tests were conducted using approved and standard practices (Grafton et al., 2015).

The Noonan and Columbus site soil types were Williams loams (fine-loamy mixed superactive frigid Typic Argiustolls). The Minot site soil types were Aastad loams (fine-loamy mixed supractive frigid Pachic Argiudolls). The Riverdale site soil type was a Wilton silt loam (fine-silty mixed superactive frigid Pachic Haplustoll) (USDA-NRCS, 2019b).

Soybean cultivars were chosen based on maturity and iron deficiency chlorosis rating (IDC). Kandel et al., 2017; Kandel et al., 2016; Kandel et al., 2015). Soybeans planted at the Columbus sites were rated as IDC tolerant as described by Kandel et al. (2017), Kandel et al. (2016) and Kandel et al. (2015) (Table 2).

Experimental units were 3.04 m wide and 9.14 m long. Experimental sites were managed using best management practices as described by Kandel (2016). Soybeans were seeded at a rate of 150,000 pure live seeds per acre with a single disk opener cone plot planter. The planter row spacing was 16.8 cm.

Table 1. Location and soil nutrient levels of experiment sites.

Site	Year	Location	NO_3-N		P	K	Zn	Fe	EC*	pH
			0-15 cm depth	15-60 cm depth	---------- 0-15 cm depth ----------					
		latitude, -- longitude --	- kg ha^{-1} -		------- mg kg^{-1} ------				dS m^{-1}	
Columbus 1	2016	48.795444°N, 102.853044°W	30	73	6	224	0.29	11	0.35	7.6
Minot 1	2016	48.179167°N, 101.316367°W	8	30	8	316	0.29	48	0.47	6.2
Columbus 2	2017	48.8891°N, 102.8701°W	27	43	5	276	0.48	7	0.2	7.2
Riverdale	2017	47.5018°N, 101.2781°W	30	40	7	223	0.69	56	0.31	5.8
Noonan	2018	48.866667°N, 103.114722°W	20	40	14	338	0.67	14	0.46	7.3
Minot 2	2018	48.169111°N, 101.316320°W	17	7	7	315	1.01	54	0.28	5.8

*Electrical conductivity (EC) was determined by 1:1 soil to water dilution

Pesticide applications were made based on weed species present at each location and applied according to their respective label and recommendations (Zollinger et al., 2016; 2017; 2018). Pesticide use is reported on Table 3. The experimental design for all locations was a randomized complete block (Montgomery, 2013). with twelve treatments and four replications. The fertilizer treatments were: check, inoculation (*B. japonicum* L.), hand applied urea (46-0-0) (55 kg N ha^{-1}), hand applied monammonium phosphate (11-52-0) (110 kg P ha^{-1}), hand applied sugar beet (*Beta Vulgaris* L.) waste lime (4.4 and 8.8 Mg ha^{-1}). Nutrient contents of sugar beet waste lime are reported in Table 5. The urea was treated with N-(n-butyl)-thiophosphoric

triamide (Agrotain Advance 1.0®) to reduce ammonia volatilization (Koch Agronomic Services, 2018). Waste sugar beet waste lime treatments were applied exclusively at the Minot and Riverdale sites because of the acidic soil pH (Table 1). A composite sugarbeet waste lime sample was analyzed by the North Dakota State University Soil Testing Laboratory,Fargo, North Dakota.

Table 2. Soybean cultivar, cultivar source, maturity, iron deficiency chlorosis tolerance, and field cropping history.

Site	Seed Company	Soybean Cultivar	Maturity*	Iron Deficiency Chlorosis Tolerance*	Previous Crop	Year of Previous Soybean Crop
Columbus 2016	NorthStar Genetics	NS0081NR2	0.8	2	Durum	2014
Minot 2016	Proseed	20-30	0.3	2.1	Soybean	2014
Columbus 2017	Legend	009R20	0.9	1.9	Durum	2015
Riverdale 2017	Hefty	H009R3	0.9	1.9	Spring Wheat	2016
Noonan 2018	Peterson	17x009	0.7	2	Soybean	2017
Minot 2018	NDSU	ND17009GT	0.9	2.7	Spring Wheat	2015

*Information gleaned from Kandel et al., 2017.

Ammonium polyphosphate (10-34-0), orthophosphate-polyphosphate (6-24-6), Fe ortho-ortho-EDDHA (Soygreen®, West Central Inc, 2018a), and naked ortho-ortho-EDDHA (Levesol®, West Central Inc., 2018b) fertilizers were applied as a liquid in furrow at 7.1 L ha^{-1} (Table 5) The ortho-ortho-EDDHA treatments with and without Fe were applied only at the Columbus and Noonan sites.

Foliar treatments (Table 5) were applied with a hand boom sprayer at the V5 (@V5) and R2 (@R2) growth stage (Fehr and Caviness, 1977). The foliar treatments were a mixture of

anhydrous ammonia-phosphoric acid-potassium hydroxide based liquid fertilizer (3-18-18) and 3-18-18 with ammonium sulfate (+AMS) (1.1 kg ha^{-1}) applied at a rate of (28 L ha^{-1}).

Table 3. Dates of soybean sowing, foliar fertilizer applications, and harvest.

Site	Planting	V5 Fertilizer Application	R2 Fertilizer Application	Harvest
	----------Date----------			
Columbus 2016	5/30/2016	7/8/2016	7/27/2016	9/23/2016
Minot 2016	5/29/2016	7/8/2016	7/28/2016	9/25/2016
Columbus 2017	5/22/2017	7/6/2017	8/4/2017	9/29/2017
Riverdale 2017	5/24/2017	7/8/2017	8/5/2017	10/1/2017
Noonan 2018	5/24/2018	7/3/2018	7/18/2018	9/26/2018
Minot 2018	5/25/2018	7/3/2018	7/19/2018	10/6/2018

Table 4. Herbicides used by site and date of application.

Site	Herbicide Application Date	Chemical Common Name	g Active Ingredient ha^{-1}
Columbus 2016	6/10/2016	Glyphosate	1,262
Minot 2016	6/20/2016	Glyphosate	787
Columbus 2017	6/21/2017	Glyphosate	1,262
Riverdale 2017	6/10/2017	Imazethapyr	53
		Glyphosate	1,262
Noonan 2018	6/4/2018	Glyphosate	1,262
	6/19/2018	Glyphosate	1,262
Minot 2018	5/29/2018	Glyphosate	787
		Carfentrazone	17
		Saflufenacil	30
	6/8/2018	Bentazon	560
		Glyphosate	1,576
	6/14/2018	Bentazon	560

Soybeans were harvested using a small plot combine and cleaned using a vacuum-type seed cleaner before yields, protein, and oil content were determined. Grain yield was determined

by dividing the cleaned harvested seed mass (kg) by the plot area (ha). Oil and protein content were measured using a DA 7200 NIR analyzer (Perten Instruments Incorporated, 2017) and was corrected to 13% moisture.

Table 5. Rate and nutritional component of treatments.

Treatment	Rate	NO_3^-	P_2O_5	K_2O	S	Fe
		----------kg ha^{-1}----------				
46-0-0	56 kg ha^{-1}	25.36	-	-	-	-
11-52-0	112 kg ha^{-1}	12.13	57.34	-	-	-
10-34-0	28 l ha^{-1}	3.86	13.12	-	-	-
6-24-6	28 l ha^{-1}	2.21	8.82	2.21	-	
Sugar Beet Waste Lime *	4.4 Mg ha^{-1}	12.75	44.28	4.39	-	15.11
Sugar Beet Waste Lime *	8.8 Mg ha^{-1}	25.49	88.56	8.79	-	30.22
Foliar 3-18-18	28 l ha^{-1}	1.16	6.98	6.98	-	-
Foliar 3-18-18 +AMS	28 l/ha^{-1} + 1.1 kg ha^{-1}	2.12	6.98	6.98	1.10	-
Soygreen	7.1 l ha^{-1}	-	-	-	-	0.49
Levesol	7.1 l ha^{-1}	0.11	-	-	-	-

*Nutrients reported are based off of three year mean (Table 5).

Table 6. Nutrient composition of sugar beet waste lime.

Year	pH	EC	NO_3^- –N	P	K	Zn	Fe	Cu	Mn	Moisture	CCE*
		dS m^{-1}	----------mg kg^{-1}----------							---%---	
2016	7.8	2.18	3,000	6,400	1,300	27	2,128	10	123	20	55
2017	8.1	2.31	2,638	3,679	520	110	4,500	136	340	27	61
2018	8.3	1.721	3,032	3,065	660	35	3,650	17	143	35	73
Mean	8.0	2.07	2,890	4,381	827	57	3,426	54	202	27	63

*Calcium carbonate equivalence

2.2. Statistical Analysis

Analysis of variance was performed using the PROC GLM procedure of SAS software version 9.4 (SAS Institute Incorporated, 2012). Environments were considered homogenous when the variance across sites were less than a factor of 10 (Tabachnick and Fidell, 2001). Environments were treated as a random effect. The Pearson Correlation procedure of SAS

software version 9.4 (SAS Institute Incorporated, 2012) was used to determine if there was a relationship among nutrients (N, P, and K) applied based on the initial soil test and soybean grain yield, protein, and oil content. Mean separation was conducted at the 95% significance level.

3. RESULTS AND DISCUSSION

3.1. All Environments

The individual environment range and means of soybean yield, oil content, and protein content are reported in Table 7. The lowest yield occurred at Minot 2018 (1.07 Mg ha^{-1}), which was also the driest environment (NDAWN, 2018). The highest yield occurred at Minot 2016 (3.19 Mg ha^{-1}) and was the wettest environment (NDAWN, 2018). The lowest soybean oil content occurred at Columbus 2016 and Riverdale 2017 (14.4%). The highest soybean oil content occurred at Noonan 2018 (16.6%). Noonan 2018 had the lowest protein (30.72%) and Minot 2018 had the highest protein (35.66%). Water stress can cause seed abortions which tends to increase seed size. Protein is more likely to accumulate in a larger source to sink ratio of fewer and larger seeds (Rotundo and Westgate, 2009).

Table 7. Mean and range of yield, oil content, and protein content of grain at each environment

Environment	Parameter	Yield	Oil	Protein
		--Mg ha^{-1}--	----------%----------	
Minot 2016	Mean	2.50	14.8	34.5
	Range	2.04 - 3.19	14.6 - 15.2	33.9 - 34.9
Columbus 2016	Mean	2.07	14.8	33.6
	Range	1.98 - 2.12	14.4 - 14.9	33.2 - 34.0
Riverdale 2017	Mean	1.86	14.7	34.9
	Range	1.72 – 1.99	14.4 - 14.9	34.6 - 35.2
Columbus 2017	Mean	1.74	15.8	31.7
	Range	1.50 – 1.86	15.6 - 16.1	31.0 - 32.2
Minot 2018	Mean	1.24	16.0	35.0
	Range	1.07 – 1.39	15.8 - 16.5	33.7 - 35.7
Noonan 2018	Mean	1.46	16.3	31.4
	Range	1.25 – 1.63	16.0 - 16.6	30.7 - 31.8

Table 8. ANOVA table of all sites grain yield.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Location	5	10611.99981	2122.40000	72.58	<0.0001
Replication (Location)	18	1751.49822	97.30546	3.33	<0.0001
Treatment	9	190.84615	21.20513	0.73	0.6853
Location * Treatment	45	1368.81843	30.41819	1.04	0.4167
Error	198	4678.54158	29.24088		
Total	237	18621.54728			

Table 9. ANOVA table of all sites protein content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Location	5	457.17350	91.43470	142.85	<0.0001
Replication (Location)	18	27.93433	1.55191	2.42	0.0018
Treatment	9	7.04357	0.78262	1.11	0.2845
Location * Treatment	45	26.86680	0.59704	0.93	0.5965
Error	160	102.41148	0.64007		
Total	237	625.27405			

Table 10. ANOVA table of all sites oil content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Location	5	101.99944	20.39989	133.43	<.0001
Replication (Location)	18	3.19444	0.17747	1.16	0.3001
Treatment	9	1.72698	0.19189	1.26	0.2655
Location * Treatment	45	5.01721	0.11149	0.73	0.8916
Error	160	24.46255	0.15289		
Total	237	137.06955			

Fertilizer treatments did not impact soybean grain yield (Table 8), protein content (Table 9), and oil content (Table 10) at the 90% significance level. Pre-plant soil NO_3^- values (0-60 cm depth) ranged from 24 to 103 kg NO_3^- ha^{-1} (Table 1). Excess soil NO_3^- can hinder rhizobia nodulation (Weber, 1966). Soil NO_3^- levels greater than 224 kg ha^{-1} reportedly prevented soybean nodulation (Bhangoo and Albritton, 1976). Manitoba recommendations indicate that soybean is best grown in soils with less than 55 kg NO_3^- ha^{-1}, including both residual soil NO_3^- and fertilizer N (Manitoba Pulse Soybean Growers, 2019).

Soil NO_3^- can contribute to greater IDC incidence and severity (Bloom et al., 2011). Bicarbonates are released (HCO_3^-) from roots to balance the soil charge as NO_3^- is taken up by roots (Lucena, 2003). Soybean leaves become alkaline from the reduction of NO_3^- to NH_4^+. The alkaline leaves prevent cells from using Fe in the apoplastic fluid (Lucena, 2000). In spite of half of the experimental sites having pH greater than 7, IDC was not observed at any environment and inspection of random roots indicated that all soybean in the experiments were adequately nodulated (Franzen et al., 2019). The sites with alkaline environments (Table 1) were theoretically susceptible to IDC as CO_3^{2-} were present in those soils (USDA-NRCS, 2019b) which could neutralize soybean root secreted acids that are essential for the activity for the Fe reducing substance secreted by soybean roots to facilitate reduction of Fe^{3+} to Fe^{2+} (Kaiser et al., 2014). Excessive moisture can result in increased IDC by solubilizing more acid neutralizing HCO_3^- (Bloom et al., 2011). In these experiments, soil moisture was never in excess (Akyuz, 2016, 2017, and 2018), so the solubility of carbonates present was likely very low. Soil pH was less than 8 (Table 1) where IDC is more likely to occur (Hansen et al., 2003). Most importantly, IDC tolerant soybean cultivars (Kandel et al., 2016; 2017; 2018) were planted at the alkaline sites, which would decrease the potential for IDC (Helms et al., 2010).

A yield response was expected from the P applications at Minot 2016, Minot 2018, Riverdale 2017, Columbus 2016 and Columbus 2017 based on Olsen P soil test results (Table 1) The Olsen P analysis of the soils (Table 1) indicated "very low" to "low" levels of P, thus indicating that a positive response to P was likely. However, the Noonan 2018 environment was in the "high" Olsen P test category (Franzen, 2018b). According to Franzen (2018b), 11 to 60 kg ha^{-1} of P_2O_5 should be applied to soybean fields under the soil P conditions which were present at the sites. The broadcast 11-52-0 treatment applied nearly met or exceeded the recommendation depending on the site. The row-placed starter P fertilizer treatments (Table 5) delivered fertilizer P at rates that were less than current P fertilizer recommendations (Franzen, 2018b). Soybean has been reported as an efficient scavenger of soil P (Kalra and Soper, 1968), which might explain the lack of a fertilizer P response in our experiments, or the current North Dakota P recommendations were based more on Minnesota and South Dakota trials than North Dakota experiments (Franzen, 2018b).

Regional research indicates that broadcast P applications are generally superior to banded applications (Buah et al., 2000; Edwards, 2017; Rehm, 1986). In-furrow applications of P can reduce or delay germination without negatively impacting yield (Bardella, 2016; Rehm and Lamb, 2010; Schatz, 2005). The 10-34-0 and 6-24-6 fertilizers applied in these experiments had no effect on yield. Rates of in-furrow 10-34-0 greater than 37 L ha^{-1} have reduced soybean stand and yield in previous studies (Endres and Hendrickson, 2008). The 10-34-0 and 6-24-6 application rates (28 l ha^{-1}) in these experiments were less than the rate that resulted in stand/yield reduction by Endres and Hendrickson (2008) and were not expected to negatively impact soybean germination or growth, but neither did they increase soybean yield or quality.

Soil test K was categorized as “very high” (Franzen, 2018b) and ranged from 223 to 338 ppm (Table 1), which indicated that the response from K application would be unlikely. Clay mineralogy can impact K response, so a K treatment was included in the methods to determine whether the mineralogy might lead to an unexpected K response (Breker, 2017). The Noonan 2018 site was located in a region where the smectite to illite clay ratio is greater than 3.5, which might lead to K being ‘fixed’, or ‘temporarily retained’ during dry periods. Soil at the other sites were in regions characterized with having lower smectite to illite clay ratios and were less prone to K retention during dry periods of the growing season (Franzen and Bu, 2018d).

Foliar fertilizers applied at the V5 and R2 growth stage (Fehr and Caviness, 1977) did not affect yield, protein, or oil content. These data indicate that foliar fertilizer application during the soybean vegetative and reproductive stages is not an effective fertilizer strategy, agreeing with the results of Haq and Mallarino (2000 and 2005) for the V5 growth stage timing and Haq and Mallarino (1998) at the R2 growth stage. One of the fertilizer treatments used by Haq and Mallarino (1998, 2000, and 2005) was a 3-8-15 liquid fertilizer applied at a rate of 28 L ha^{-1}, which was similar to the 3-18-18 liquid fertilizer treatments used in these experiments. Haq and Mallarino’s (1998, 2000, and 2005) research was conducted on soils where P and K were at sufficient or greater levels. In our studies, five of six sites had Olsen P test values categorized in the “very low” and “low” (Table 1) range, leading us to believe that a positive response to foliar fertilizer might be more likely (Franzen, 2018d), but no response to P was observed.

Adequate soil moisture is important to soybean production during the R1 to R6 growth stages (Fehr and Caviness, 1977) which leads to more complete pod development and seed-fill (Klocke et al., 1989). Rainfall in our experiments during the 2016, 2017, and 2018 growing seasons were below the long-term regional average (Akyuz 2016, 2017, and 2018) and less than

the 406 mm required by a North Dakota soybean crop (Bauder and Ennen, 1981). Furthermore, rainfall was particularly low during the important R1 to R6 growth stages (Fehr and Caviness, 1977). Ideal rainfall has been defined as approximately 70 mm at the R3 to R4 growth stages (Kandhem et al., 1985), but this amount of rainfall did not occur during our experiments (Akuyz 2016, 2017, and 2018). The lack of adequate and timely rainfall likely impacted soybean yield and may have resulted in a lack of fertilizer response. Water stress shortens the period of seed fill which reduces grain yield (Mechel et al., 1984). Water stress also decreases protein and oil content (Rotundo and Westgate, 2009).

Planting date influences oil content. As sowing soybean is delayed, oil concentration and yield decreases (Assefa et al., 2019). The critical planting date within North Dakota's latitude for maximum oil content and yield is between the 145^{th} and 151^{st} days of the year (May 25-May 31). After the critical dates, oil and yield greatly decrease (Assefa et al., 2019). All sites were planted by May 31, but within one week of May 25 (Table 3), therefore planting date could have negatively influenced soybean yield and oil content.

A strong negative correlation across all environments was observed between protein and oil content (r = -0.929***). The inverse relationship of oil and protein content are dependent on each other as they are expressed by a percentage and dependent on the total weight of the seed (Rotundo and Westgate, 2009). Pearson correlation analysis indicated that as yield increased, oil content decreased. Also, oil content was negatively related to N and P application. Protein was positively correlated with N and P fertilization (Table 11). However, fertilizer treatments did not statistically affect protein and oil concentration (Table 9, 10). Rotundo and Westgate (2009) observed that N treatments greater than 100 kg N ha^{-1} can increase seed protein content.

Table 11. Pearson Correlation Coefficients of nutrient amount and soybean component of all sites.

	Nitrogen	Phosphorus	Potassium	Oil	Protein
Yield	0.45	0.33	-0.12	-0.71**	0.65
Oil	-0.75**	-0.54*	-0.26	-	-0.93***
Protein	0.60*	0.62*	0.32	-	-

+Significant at the 0.10 level.
*Significant at the 0.05 level.
**Significant at the 0.01 level.
***Significant at the 0.001 level.

3.2. Acidic Environments

Fertilizer treatments did not affect soybean yield (Table 12), protein content (Table 13) and oil content (Table 14) at the 90% significance level. Nodulation of soybean roots in soils with a pH less than 5.5 has shown to reduce soybean nodulation (Kopittke and Menzies, 2007). However, soil pH at the 0-15 cm depth was never less than 5.8 (Table 1). Poor nodulation can result in N deficient soybean and a reduction in yield and protein content. Supplemental N can improve yields of poorly nodulated soybean. However, nodulation tended to out-yield N fertilized soybean in Canadian experiments (Heard et al., 2011; 2014). Furthermore, ammonium-based N fertilizer can increase soil acidity through the release of H^+ during the nitrification process (Fox and Hoffman, 1981).

Table 12. ANOVA table of acidic sites grain yield.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Location	2	10300.67944	5150.33972	148.19	<.0001
Replication (Location)	9	1389.07496	154.34166	4.44	<.0001
Treatment	11	363.93494	33.08499	0.95	0.4950
Location * Treatment	22	1036.34883	47.10676	1.36	0.1569
Error	99	3440.75886	34.75514		
Total	143	16530.79703			

Table 13. ANOVA table of acidic sites protein content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Location	2	8.96533	4.48266	6.97	0.0015
Replication (Location)	9	4.18564	0.46507	0.72	0.6868
Treatment	11	10.61704	0.96519	1.50	0.1433
Location * Treatment	22	10.36696	0.47123	0.73	0.7959
Error	99	63.68265	0.64326		
Total	143	97.81761			

Table 14. ANOVA table of acidic sites oil content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Location	2	56.02989	28.01494	181.89	<.0001
Replication (Location)	9	1.89301	0.21033	1.37	0.2140
Treatment	11	2.09579	0.19053	1.24	0.2731
Location * Treatment	22	2.79919	0.12724	0.83	0.6871
Error	99	15.24828	0.15402		
Total	143	78.06616			

A strong negative correlation among the acidic sites was observed between protein and oil content (r = -0.83***). The inverse relationship of oil and protein content are dependent on each other as they are expressed by a percentage and dependent on the total weight of the seed (Rotundo and Westgate, 2009). Even though fertilizer treatments did not impact grain yield or quality, as N increased, protein increased and oil decreased. (Table 15). Rotundo and Westgate (2009) observed that N treatments to soybean increased protein, but had little effect on oil content. Nitrogen and P had a positive correlation with protein in our experiments. There was a negative correlation between K and soybean yield (Table 15). Soybean grain removes more K than small grains, sunflowers, and sugar beet (Franzen and Gerwing, 1997). With the dry soil

conditions, K may have been rendered temporarily unavailable through temporary retention in the smectitic clays (Breker, 2017).

Table 15. Pearson Correlation Coefficients of nutrient amount and soybean component of all acidic sites.

	Nitrogen	Phosphorus	Potassium	Oil	Protein
Yield	0.18	0.08	-0.62*	0.20	0.20
Oil	-0.75**	-0.38	-0.12	-	-0.83***
Protein	0.68*	0.51^{+}	0.01	-	-

$^{+}$Significant at the 0.10 level.
*Significant at the 0.05 level.
**Significant at the 0.01 level.
***Significant at the 0.001 level.

3.3. Alkaline Environments

Treatments did not impact soybean yield (Table 16), protein content (Table 17), or oil content (Table 18) at the alkaline environments at the 90% significance level. Weber (1966) observed that 165 kg N ha^{-1} were required to equal the yield of well nodulated soybean. Nitrogen fixation has been observed to cease due to application of N rates greater than 224 kg N ha^{-1} (Bhangoo and Albritton, 1976). At the Columbus 2016 site, total N available to soybean (soil N plus fertilizer urea application) was 159 kg N ha^{-1}. Though not reported, nodules were present at all experimental units.

Table 16. ANOVA table of alkaline sites grain yield.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Location	2	2059.29364	1029.64682	46.86	<.0001
Replication (Location)	9	118.93436	13.21493	0.60	0.7930
Treatment	11	166.86318	15.16938	0.69	0.7446
Location * Treatment	22	196.83554	8.94707	0.41	0.9908
Error	97	2131.13935	21.97051		
Total	141	4673.06607			

Table 17. ANOVA table of alkaline sites protein content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Location	2	137.22090	68.61045	132.68	<.0001
Replication (Location)	9	25.07806	2.78645	5.39	<.0001
Treatment	11	5.56621	0.50602	0.98	0.4711
Location * Treatment	22	13.39460	0.60885	1.18	0.2860
Error	97	50.15918	0.51711		
Total	141	234.60728			

Table 18. ANOVA table of alkaline sites oil content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Location	2	59.00892	29.50446	235.73	<.0001
Replication (Location)	9	2.39096	0.26566	2.12	0.0346
Treatment	11	1.07928	0.09812	0.78	0.6553
Location * Treatment	22	2.41106	0.10959	0.88	0.6254
Error	97	12.14065	0.12516		
Total	141	78.02093			

A strong negative correlation was observed at the alkaline sites between protein content and oil content (r = -0.83***). The inverse relationship of oil and protein content are dependent on each other as they are expressed by a percentage and dependent on the total weight of the seed (Rotundo and Westgate, 2009). Even though fertilizer treatments did not impact grain yield or quality, as N increased, protein increased and oil decreased (Table 19). Rotundo and Westgate (2009) observed that N treatments increase protein, but have little effect in oil content and do not postulate why N increases protein. Oil content decreases as yield increased (Table 19).

Table 19. Pearson Correlation Coefficients of nutrient amount and soybean component of all alkaline sites.

	Nitrogen	Phosphorus	Potassium	Oil	Protein
Yield	0.47	0.21	0.23	-0.73**	0.54^{+}
Oil	-0.63	0.23	0.12	-	-0.83***
Protein	0.71**	-0.17	0.02	-	-

$^{+}$Significant at the 0.10 level.
*Significant at the 0.05 level.
**Significant at the 0.01 level.
***Significant at the 0.001 level.

3.4. Individual Environments

There were no statistical differences for yield (Table 20, 23, 26, 29, 32, 35), protein content (Table 21, 24, 27, 30, 33, 36) and oil content (Table 22, 25, 28, 31, 34, 37) due to any fertilizer treatments within individual environments at the 90% significance level. Factors that may have influenced the lack of a response include the abnormally dry growing seasons (Akyuz, 2016, 2017, 2018); and soybean being one of the more efficient soil nutrient scavenger cash crops (Kalra and Soper, 1968).

Fertilizer treatments did not impact soybean yield, oil or protein at Minot 2016 (Table 20, 21, 22) and Crosby 2016 (Table 23, 24, 25) environments. The 2016 growing season was slightly warmer than the 30-year mean. June precipitation in Columbus was near normal, while Minot was slightly dry. The July precipitation was slightly above normal in Minot and slightly below normal in Columbus. The August precipitation at both sites was abnormally dry (Akyuz, 2016). Minot 2016 received 420 mm of rain and Columbus 2016 received approximately 447 mm of precipitation (NDAWN, 2018). There were no differences in yield, oil or protein content with treatment at Columbus 2017 and Riverdale 2017. In these experiments, the reproductive growth stages occurred during mid-July through August (NDAWN, 2018a). Nearby NDAWN weather

stations recorded 19 to 30 mm of rainfall during August, which likely depressed soybean yields (Kadhem et al., 1985).

Table 20. ANOVA table of Minot 2016 grain yield.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	999.47078	90.86098	1.30	0.2692
Replication	3	608.16668	202.72223	2.89	0.0498
Error	33	2311.33768	70.04054		
Total	47	3918.97513			

Table 21. ANOVA table of Minot 2016 protein content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	5.02804	0.45709	1.18	0.3363
Replication	3	0.87113	0.29038	0.75	0.5297
Error	33	12.76146	0.38671		
Total	47	18.66064			

Table 22. ANOVA table of Minot 2016 oil content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	1.52548	0.13868	1.04	0.4395
Replication	3	0.92269	0.30756	2.30	0.0959
Error	33	4.42060	0.13396		
Total	47	6.86877			

Table 23. ANOVA table of Columbus 2016 grain yield.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	113.84313	10.34938	0.53	0.8676
Replication	3	32.52028	10.84009	0.56	0.6479
Error	32	623.86486	19.49578		
Total	46	771.81919			

Table 24. ANOVA table of Columbus 2016 protein content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	2.82421	0.25675	0.76	0.6753
Replication	3	2.87917	0.95972	2.84	0.0534
Error	32	10.81162	0.33786		
Total	46	16.51500			

Table 25. ANOVA table of Columbus 2016 oil content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	1.31861	0.11987	0.96	0.5021
Replication	3	0.38957	0.12986	1.04	0.3893
Error	32	4.00604	0.12519		
Total	46	5.71526			

Fertilizer treatments at the Riverdale 2017 and Columbus 2017 environments did not statistically impact soybean yield (Table 26, 29), protein content (Table 27, 30) and oil content (Table 28, 31) at the 90% significance level. The dry weather of the 2017 growing season (Akyuz, 2017) could have depressed soybean growth (Kadhem et al., 1985). Border row plants were inspected during the later reproductive growth stages. Several pods had shriveled or aborted beans thus indicating that water stress was a factor in soybean grain production (Kadhem et al., 1985).

Table 26. ANOVA table of Riverdale 2017 grain yield.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	60.86729	5.53339	0.83	0.6093
Replication	3	500.01394	166.67131	25.10	<0.0001
Error	33	219.16127	6.64125		
Total	47	780.04250			

Table 27. ANOVA table of Riverdale 2017 protein content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	1.71688	0.15608	0.32	0.9753
Replication	3	0.82078	0.27359	0.56	0.6426
Error	33	16.00706	0.48506		
Total	47	18.54472			

Table 28. ANOVA table of Riverdale 2017 oil content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	0.87474	0.07952	0.50	0.8878
Replication	3	0.41477	0.13826	0.87	0.4647
Error	33	5.22350	0.15829		
Total	47	6.51202			

Table 29. ANOVA table of Columbus 2017 grain yield.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	99.52147	9.04741	0.34	0.9706
Replication	3	20.25957	6.75319	0.25	0.8595
Error	33	885.17365	26.82344		
Total	47	1004.95470			

Table 30. ANOVA table of Columbus 2017 protein content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	6.25460	0.56860	1.52	0.1698
Replication	3	14.34078	4.78026	12.81	<0.0001
Error	33	12.31361	0.37314		
Total	47	32.90899			

Table 31. ANOVA table of Columbus 2017 oil content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	11	0.88448	0.08041	0.76	0.6765
Replication	3	1.33956	0.44465	4.20	0.0128
Error	33	3.49741	0.10598		
Total	47	5.71585			

Treatments at the Minot 2018 and Noonan 2018 environments did not impact yield (Table 32, 35), protein content (Table 33, 36), and oil content (Table 34, 37) at the 90% significance level. Precipitation was a limiting factor as the Noonan 2018 experiment started the growing season in a Moderate Drought (D1) and concluded as Abnormally Dry (D0). The growing season at Minot 2018 was very dry as the start of the growing season was in a Severe Drought (D2) and concluded the season as a Moderate Drought (D1). The temperature was near normal (Akyuz, 2018).

Noonan 2018 received approximately 310 mm of precipitation (NDAWN, 2018). The Noonan 2018 soil P test was 14 ppm (Table 1) and considered in the high range, which reduces the chance of a response from P (Franzen, 2018b). The goal of this project was to evaluate various fertilizer treatments on low soil testing soils. Finding a low soil testing site was difficult in the spring of 2018. Soil test nutrient levels across the region were abnormally high in the fall of 2017 (AGVISE Laboratories Inc. 2017) and spring of 2018 which was likely caused by the abnormally dry 2017 growing season (Augustin, 2018).

Table 32. ANOVA table of Minot 2018 grain yield.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	12	115.02001	9.58500	1.09	0.4002
Replication	3	31.71392	10.57131	1.20	0.3245
Error	36	317.78269	8.82729		
Total	51	464.51632			

Table 33. ANOVA table of Minot 2018 protein content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	12	13.90348	1.26395	1.28	0.2811
Replication	3	4.26224	1.42075	1.43	0.2507
Error	36	32.71136	0.99125		
Total	51	50.87708			

Table 34. ANOVA table of Minot 2018 oil content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	12	2.51882	0.20990	1.27	0.2762
Replication	3	0.75371	0.25124	1.52	0.2251
Error	36	5.93788	0.16494		
Total	51	9.21041			

Table 35. ANOVA table of Noonan 2018 grain yield.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	12	72.98106	7.29811	0.90	0.5453
Replication	3	54.32508	18.10836	2.23	0.1015
Error	35	301.11099	8.13814		
Total	50	430.07049			

Table 36. ANOVA table of Noonan 2018 protein content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Treatment	12	9.82403	0.81867	1.00	0.4713
Replication	3	7.16611	2.38870	2.91	0.0481
Error	35	28.73045	0.82087		
Total	50	46.41453			

Table 37. ANOVA table of Noonan 2018 oil content.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Model	15	2.38139	0.15876	1.08	0.4110
Treatment	12	1.68729	0.14051	0.95	0.5091
Replication	3	0.63925	0.21308	1.44	0.2466
Error	35	5.16516	0.14758		
Total	50	7.54655			

3.5. Conclusions

Soybean acres have greatly increased in northcentral and northwestern North Dakota (Jantzi et al., 2018) resulting in a need for modern regional soybean fertility research to serve this area. These experiments did not observe a yield, protein, or oil content response from any of the fifteen fertilizer treatments over six site years. Conclusions for this research are:

1. Fields that have had soybeans within the past four years, are unlikely to express a yield (Table 8, 12, 16, 20, 23, 26, 29, 32, 35) protein content (Table 9, 13, 17, 21, 24, 27, 30, 33, 36) and oil content (Table 10, 14, 18, 22, 25, 28, 31, 34, 37) response from an inoculation treatment.
2. Phosphorus applications did not have a positive yield response in soils that have Olsen P values now considered in the ‘very low’, “low”, and ‘high’ categories (Table 1). However, not fertilizing soybean may lower subsequent soil P tests. Which would require increased P fertilization use for crops within the rotation that are more sensitive to low soil P, such as small grains or corn.
3. Soil water content was likely the biggest factor affecting soybean yield in these experiments.
4. Lime application on soils with pH as low as 5.7 did not impact grain yield or quality.

5. Use of Fe-EDDHA fertilizer did not affect soybean yield or quality in an environment that might be considered susceptible to IDC. Soils were dry enough that IDC was not observed. Use of 'naked'-EDDHA (no Fe) had no influence on soybean yield or quality.
6. Use of foliar fertilization at V5 or R2 growth stages did not impact soybean yield or quality at any location.
7. With the lack of fertilizer P response, future research should identify locations with very low P values (2-3 ppm) to establish a rate response for soybean and determine soil test value where P fertilization is likely to be profitable.
8. These data indicate that foliar fertilization, starter P application, N application, and inoculation on land previously grown to soybean with successful nodulation are not cost-effective practices.

4. AMELORATION OF NORTH DAKOTA ACIDIC SOILS

4.1. Abstract

Soils acidify from root exudates, biological weathering, and the use of N fertilizers due to the nitrification process that produces H^+. No-till soils are more susceptible to acidification than conventional tilled fields due to the lack of mixing of subsurface alkaline products and the tendency to apply ammonium-based fertilizers at or near the soil surface. As a result, the zone of acidification is likely in the area of N fertilizer placement. Sugar beet waste lime, or sugar beet processing waste lime, is a by-product of the sugar refinement process that is readily available to North Dakota producers for use. Sugar beet waste lime was surface applied at 4.4 and 8.8 Mg ha^{-1} two days after planting soybean. Fall soil samples indicated that surface applied sugar beet waste lime increased soil pH to a depth of 10 cm. However, sugar beet waste lime did not impact soybean grain yield or quality. Additional research is needed to assist producers with the management of acidic soils.

4.2. Acidic Soil pH Literature Review

4.2.1. Soil pH

pH is defined as the negative logarithm of the activity of hydrogen ions (H^+) in solution. Therefore, assuming activity equals concentration, as pH decreases by one unit, the concentration of H^+ increases ten-fold (Thomas, 1996). Acids donate protons (H^+) while alkaline compounds accept protons (Havlin et al., 1999). The presence of more hydroxyl anion (OH^-) than hydrogen ions (H^+) results in alkalinity. A solution having equal concentrations of H^+ and OH^- is neutral, with a pH of 7. Alkalinity (pOH) is defined as the negative logarithm of the OH^- activity. Thus, pOH is to the inverse of pH. The sum of the concentration of OH^- (pOH) and H^+ (pH) is always 14 (Green and Green, 2013).

The soil factor pH has been referred to as the ‘master variable’ due to its role in directing many soil biological, biochemical, chemical and physical processes (Fisk, 2016). Soil pH influences the rate of chemical weathering of mineral components due to the solubility of minerals at a different pH. Dissolved minerals become detached into the soil solutions and can be physically transported to other locations within a soil profile through water movement. With further pH changes, dissolved minerals can precipitate (Schaetzl and Anderson, 2005).

Soil pH influences nutrient availability to crops and may result in release of essential nutrients from soil minerals. As pH changes, the solubility of some plant nutrients change. The majority of plant nutrients are most soluble and plant available when the soil pH is approximately 6.3 to 6.8. Most field crops in North America are most productive in a pH range from 6.0 to 7.3 (Havlin et al., 1999). Phosphorus is sensitive to soil pH, as dissociation of H_3PO_4 that is present when a soil solution pH is greater than two changes to $H_2PO_4^{1-}$, then HPO_4^{2-} to PO_4^{3-} as the solution becomes alkaline (Lindsay, 2001). The $H_2PO_4^{1-}$ and HPO_4^{2-} are most available for plant use.

Nitrogen deficiencies can be more severe when soils are too acidic. Soil biological activity is reduced with soil pH < 5.5, particularly in leguminous crops. Symbiotic N-fixing bacteria growth and activity declines with soil pH < 6 (Graham, 1992). The rate of nitrification, the bacterial transformation of ammonium to nitrate, is greatly influenced by pH. As soils acidify, the rate of nitrification decreases. Fall-applied anhydrous ammonia was found to be 89% nitrified the following spring with soil pH > 7.5. Whereas, fall applied anhydrous ammonia was only 39% nitrified the following spring with soil pH < 6 (Kyveryga et al., 2004).

Cation exchange capacity (CEC) is the summation of exchangeable cations on clay and organic matter surfaces. Soils have anion exchange capacity (AEC) where there are anions on the

clay and organic matter surfaces. Anion exchange capacity and CEC are expressed as $cmol_c\ kg^{-1}$ (Roth et al., 1996). Soil CEC changes as soil pH changes. The charge that changes with pH is called pH-dependent charge. As soil pH increases, CEC increases from the increase of OH^- that attracts the H^+ from the micelle (Helling et al., 1964). Inversely, anion exchange capacity increases as pH decreases (Havlin et al., 1999). However, other than Ca^{2+}, liming soils has been found to not improve retention of minerals (Edmeades, 1982).

The laboratory value of CEC is dependent on the determination method. Clay content and soil organic matter greatly influence CEC as those colloids possess CEC. Soil CEC can be estimated by summing the amount of organic matter and clay content and clay mineralogy (Gilmour, 2003). However, when soil organic matter content is less than 20 $g\ kg^{-1}$, the accuracy of CEC estimation decreases (Essington, 2004).

Cation exchange capacity can be estimated by summing the $cmol_c\ kg^{-1}$ of exchangeable bases. This procedure extracts Na, Ca, Mg, and K by using a 1 mol NH_4OAc solution buffered at pH 7. The slurry is shaken then filtered. Atomic adsorption is then used on the filtered solution to determine cation content and type. Mehlich 3 can be substituted for the NH_4OAc solution on non-calcareous soils (Warncke and Brown, 1998). A sodium acetate-ammonium acetate solution with a pH of 8.6 has been substituted for the NH_4OAc solution and found to estimate CEC well on alkaline soils (Gupta et al., 1985). Estimating CEC by summation of base cations works well, but can over estimate CEC of calcareous soils. (Warncke and Brown, 1998).

Cations can be leached from a soil column to estimate CEC. A 1 mol NH_4OAc solution buffered at pH 7 is applied to a leaching tube and allowed to stand overnight. A successive leaching of 1 mol KCl is used to displace the NH_4^+. The concentration of NH_4^+ in the leachate is then measured to determine soil CEC (Sumer and Miller, 1996). Several washes of an extraction

solution require more time, but is less likely to overestimate the CEC when compared to a single washing of the soil (Essington, 2004).

Differing extraction methods can influence CEC. A long-term N study in Kansas observed a change in CEC using an unbuffered calcium-chloride ($CaCl_2$) solution. Whereas determining CEC by summation of cations by ammonium acetate extraction solution did not provide a CEC difference (Schwab et al., 1989).

Soil acidity includes active acidity and reserve acidity. Active acidity is the activity of H^+ in the soil solution, which directly impacts the immediate measurement of soil pH (Gilmour, 2003). Active acidity is usually determined by mixing a 1:1 slurry of soil to deionized water (Warnke and Brown, 1998). Approximately 55% of U.S. soil testing laboratories use the 1:1 slurry method (Miller and Kissel, 2010) although other dilutions are also utilized. Soil pH measurement changes from 1:5 and 1:10 soil to water dilutions, but the change is less than 0.5 pH units (Thomas, 1996). After being mixed for five seconds and allowed to equilibrate for ten minutes, the slurry pH is measured with a pH electrode (Watson and Brown, 1998). Many laboratories use a dilute salt solution, such as 0.01 mol L^{-1} $CaCl_2$. The dilute salt solution may be useful in a soil with low ionic strength (Miller and Kissel, 2010).

Before 1918, colorimetric dyes with known endpoints were used to estimate soil pH. The accuracy of this method was less than the measurement with pH sensitive probes used today. Between 1918 and 1931, platinum-hydrogen gas electrodes were developed. The platinum-hydrogen gas electrodes increased the speed and accuracy of pH testing. In the 1930's, the glass electrodes used in the pH probes of today were invented and commercialized (Thomas, 1996).

The pH electrode measures the difference in electrical potential between the pH meter reference electrode and a H^+-sensitive semi-permeable glass electrode. The reference electrode

has a constant electrical potential while the glass electrode's electric potential changes as pH changes (Gilmour, 2003). The glass electrode electric potential changes as H^+ diffuse through a porous glass membrane that is usually fritted glass. The change in H^+ is compared with the reference electrode with constant electric potential. The difference in electrical potential between the reference and glass electrodes are used to determine pH. Routine calibration of the pH electrode increases the accuracy of the soil pH measurement (Holman, 2013).

Change in active acidity is dependent on soil exchangeable (reserve) acidity. Exchangeable acidity is acidity released from the soil and gives a soil its pH buffering characteristic. Aluminum (Al^{3+}) and H^+ are adsorbed to CEC sites and within soil colloids. When released, the H^+ decreases pH as it increases the hydrogen molar concentration of the solution (Sims, 1996b). Aluminum is abundant in most soils as it is main component of aluminosilicate clays. pH impacts the activity of Al^{3+}. When soil pH is less than 5.5, Al^{3+} can enter soil solution (Lindsay, 2001). When Al^{3+} is released from micelle, it hydrolyzes and dissociates three H^+ from water (H_2O). This action further decreases soil pH. Exchangeable acidity is determined by measuring the buffer pH (Sims, 1996b).

The pool of Al^{3+} and H^+ inside soil colloids is much greater than the bulk soil solution. The concentration of active acidity is much smaller than the reserve acidity, which is dependent on clay mineralogy and the sand, silt, clay, and organic matter content of the soil (Sims, 1996b). After a lime application, the active acidity can be easily neutralized; however, the soil buffering ability due to the reserve acidity counteracts the lime effect, by releasing acidifying H+ into the soil solution which tends to move the active acidity back to the initial pH. The buffering ability and the amount of reserve/exchangeable acidity makes neutralizing acidic soil pH difficult and

perpetual. Factors that affect the liming agent include the particle size of the liming agent, the source of liming agent and its calcium carbonate equivalence (CCE) (Sims, 1996b).

When calcium carbonate dissolves, it reacts with the H^+ and produces calcium ions (Ca^{2+}), water (H_2O), and carbon dioxide (CO_2). Calcium carbonate equivalence (CCE) refers to the relative capacity of the liming agent to neutralize acidity relative to pure calcium carbonate (USDA-NRCS, 1999). Common liming materials include calcitic limestone ($CaCO_3$), marl ($CaCO_3$ from shells), dolomitic limestone ($CaMg(CO_3)_2$, quick lime (CaO), hydrated lime ($Ca(OH)_2$), and wood ash (calcium, magnesium, and potassium oxides). Their CCE range is 80-100, 70-90, 110, 150-180, 120-140, and 30-70 respectively (USDA-NRCS, 1999). Quick lime is refined from CaCO3 by a burning process. Hydrated lime is produced when CaO is mixed with water. Both liming agents reactive with soil faster than CaCO3 and benefit the soil when acidic soils require rapid remediation (Havlin et al., 1999).

Particle size influences the reactivity of the lime. Smaller particle sizes have more surface area and allow the liming agent to be more reactive for the purpose of neutralizing soil acidity. Effective calcium carbonate equivalence (ECCE) accounts for the liming material chemical composition (CCE) and particle size. Particle size is determined by sifting through different sized mesh screens. Lime particle size greater than 2 cm is too large to react with the soil and is relatively chemically inert. Lime particle size smaller than 0.28 mm is highly reactive with the soil and has a relative liming effectiveness of 100% (USDA-NRCS, 1999).

4.2.2. Use of Buffer pH and Amending Acidic Soils

Sims (1996b) outlines three factors to consider when developing a lime requirement: (1) the measured lime requirement must correctly predict the lime needed to increase the soil pH to a predetermined soil pH; (2) lime requirement analysis must measure total soil acidity so that all

acidity variables can be accounted for in order to properly predict a lime application; and (3) the analysis must be calibrated and suitable for the soil properties (organic matter content, clay mineralogy, clay amount, parent materials, and climate) likely in the respective geographic area. The third reason is why different lime requirement determination methods have been developed in different regions of the US. Minnesota, Iowa, and Nebraska typically use the Shoemaker-McLean-Pratt (SMP) method, whereas Florida, Georgia, Mississippi, and South Carolina use the Adams-Evans method (AEM) (Sims, 1996b). Soil testing laboratories have or are replacing the SMP method with the Sikora method (Lee, 2019). The Sikora method has been found to produce similar results as the SMP method, but has the benefits of not handling the hazardous wastes of chromium and paranitrophenol (Sikora, 2006).

The SMP was developed from a soil-buffer pH test and soil-lime incubation study that used 14 acidic soils from Ohio. The SMP buffer procedure uses a solution of paranitrophenol, potassium chromate, calcium chloride anhydrous, calcium acetate, and triethanolamine with a pH adjusted to 7.5 by sodium hydroxide (Shoemaker et al., 1961). Active acidity of soil is first measured (1:1 soil to deionized water solution and pH electrode). Then the SMP solution is added and mixed for 15 minutes. The slurry's acidity is then measured with a pH meter after allowing the slurry to rest for 15 minutes. The lime application is then determined based off of a chart produced from incubation studies with regional soils (Shoemaker et al., 1961).

The SMP was developed for use on soils that have substantial amounts of exchangeable Al^{3+}, soil pH is less than 5.8, organic matter is less than 10 percent, and when lime applications are usually greater than 4.5 Mg ha^{-1}. Soils that have more than 10 percent organic matter buffer the effect of SMP solution and prevent the release of soil H^{+} which lowers the reserve acidity. Accuracy of the SMP procedure is reduced when the soil-buffer pH exceeds 6.9. The factors of

high organic matter and soil-buffer pH decrease the reliability of the SMP buffer analysis in many soils (Sims, 1996b).

McLean et al., (1977) developed the double-buffer option method using the SMP buffer to account for inaccuracies in low lime requirements possible using the original SMP method (Watson and Brown, 1998). This method is based on the initial SMP procedure but with the additional steps of measuring the SMP solution neutralizing activity from the addition of 1 ml of about 0.21 M hydrochloric acid. The slurry is shaken for 15 minutes and allowed to rest for 15 minutes, and pH is again measured. This procedure is more arduous, but allows the testing laboratory to produce a liming requirement for the individual soil. Neutralizing effectiveness is determined by the soil slurry pH from the initial SMP and the double SMP buffer solutions (Watson and Brown, 1998).

The Sikora buffer method is similar to SMP buffer method, except the toxic chemical paranitrophenol and the carcinogenic chromate ion has been replaced with imidazole and 2-(N-morpholino) ethanesulfonic acid monohydrate (MES monohydrate) respectively. Imidazole and MES monohydrate were chosen as they have similar pKa values. Potassium chloride (KCl) is substituted for $CaCl_2$. A 1 M KCl solution is similar to $CaCl_2$ for extracting exchangeable Al^{3+}. Potassium salts are more soluble than Ca^{2+} salts so KCl is less likely to resulting anion precipitation compared to $CaCl_2$. The Sikora method has been found to produce similar results to the SMP method (Sikora, 2006).

The Adams and Evans method (AEM) was developed for ultisols in the southeast region of the United States. Ultisols are characterized by low organic matter, low CEC, and are predominately made of 1:1 clays (kaolinites) and therefore have a low pH buffering capacity (Sims, 1996b). The Adams-Evans buffer solution has a pH of 8.0 and is comprised of potassium

chloride, potassium hydroxide, *p*-nitrophenol, and boric acid (Adams and Evans, 1962). The active acidity is first measured. Then the Adams-Evans buffer solution is added and mixed with a glass rod for 10 minutes and allowed to rest for 30 minutes. The pH is then remeasured. Using the two measured soil pH's, Adams and Evans developed a chart based off incubation studies, and least squared regressions to determine lime requirement (Adams and Evans, 1962). This procedure tends to overestimate lime requirements for fields. This may be due to the pH 8.0 of the Adams and Evans solution. Many labs in the southeastern United States have developed their own calibration methods to account for the AEM lime requirement overestimation (Sims, 1996b).

The Mehlich buffer is similar to the AEM in that they both work well on soils with low CEC (Sims, 1996b). The Mehlich buffer is comprised of triethanolamine, acetic acid, sodium glycerphosphate, hydrochloric acid, and aluminum chloride. Lime requirements is then determined by a table developed or equation developed by Mehlich. A benefit of the Mehlich buffer solution is that it does not contain chromate or paranitrophenol. However, it does contain barium (Mehlich, 1976), which is considered a hazardous waste. Hoskins and Erich (2008) observed similar titration curves when barium chloride is replaced with CaCl (modified Mehlich method). Lime requirements using the modified Mehlich, Mehlich, and SMP methods were similar when the soil pH was 3.0 to 6.6. The modified Mehlich procedure was also found to be less damaging to pH electrodes than the SMP buffer method.

Estimating exchangeable Al^{3+} is a method to help determine lime application rate in very acid soils (Sims, 1996b). However, the procedure has not been widely adopted because of added time and cost. Applying lime based on exchangeable acidity tends to produce similar lime

requirements as measuring exchangeable acidity. Measuring exchangeable acidity is a more simple procedure than estimating exchangeable Al^{3+} (Sims, 1996b).

Cation exchange capacity and determining the amount of H^+ and Al^+ in a soil can be used to determine lime applications (Sims, 1996b). The method described by Warnke and Brown (1998) uses 1-N NH_4OAc as the extraction solution. Once the soil is shaken for five minutes and filtered, extracted cations are then determined using atomic adsorption spectroscopy or inductively coupled plasma spectroscopy. Following cation determination, saturation of the soil exchange complex with Al^{+3} and H^+ help determine the lime rate required to increase soil pH to the target value (Warncke and Brown, 1998).

The Woodruff buffer method (Woodruff, 1948) is a buffer pH method that was widely adopted, but has since been replaced by the aforementioned buffer pH tests. The test has been found to be accurate when liming to increase pH of 6.5 or more (van Lierop, 1983; Sims, 1996b). However, the Mehlich and NH4OAc buffer tests have been found to be more precise at predicting lime requirement (van Lierop, 1983).

4.2.3. Acidification of North Dakota Soils

Many areas in a single field can have near neutral or alkaline pH (Franzen et al., 2006). Soil pH can skew a composite soil test towards a more alkaline condition than many areas of the field possess. Site-specific soil sampling, particularly zone sampling in North Dakota, can be utilized to pinpoint acidic soils and thereby enable their management (Franzen, 2002). Historically most soil sampling in North Dakota was performed through the use of composite soil sampling. Since 2010, site-specific soil sampling has increased from 20% to 40% depending on state region (Agvise Laboratories Inc., 2018b). The use of 20 soil cores in a composite soil sample results in soil test value within 15% of the true mean value 80% of the time (Swenson et

al., 1984). The variability possible within a composite soil test and those observed by Franzen et al. (2006) demonstrates the importance of site specific soil sampling to identify acidic soils and enable their neutralization when advantageous. Since soil carbonates are highly dependent on landscape position (Schaetzl and Anderson, 2005), topography-based zone sampling is far more useful and profitable compared with grid soil sampling when identifying acidic areas (Franzen et al., 1998). Site specific soil sampling reduces input costs and conserves resources to effectively manage the acidic areas.

A review of soil testing laboratory results showed that 34% of United States soils had a pH less than 6.0. The same review found that only 2% of North Dakota's soils were less than 6.0 (Fixen, 2002). However, this review was completed at a time where 80% or more of soil samples were collected by composite soil sampling means. Therefore, the Fixen (2002) statistics are misleading.

Franzen et al. (2006) looked at the distribution of soil pH across various North Dakota catenas. Soil was collected from every North Dakota county in 1996 at a depression, side slope, and summit landscape position. Of 156 soil samples, the average upland soil pH and range was 7.4 and 5.6 to 8.5 respectively. The slope position mean pH was 7.3 and range was 5.4 to 8.5. North Dakota depressional area mean pH was 7.0 and the range was 5.3 to 8.4. Acidic soil areas tended to be most prevalent in the counties bordering the Missouri River, extending northward through Minot through Mohall in Renville county (Franzen et al., 2006).

Agvise Laboratories Inc. is a North Dakota and Minnesota based soil testing laboratory. Every year they publish regional soil testing result trends. North Dakota is divided into eight regions and based off of zip code. The 2018 land base in North Dakota with a pH less than 6 ranged from 1-12%. The region with the highest incidence of acidic soil test results was south

and west of the Missouri River. Samples in North Dakota with pH greater than 7.3 was 33-80%. Six to thirty-two percent of North Dakota soils have a 0-15cm depth CCE of five percent or greater. Northeast North Dakota was the area with the greatest frequency of alkaline soils and relatively high CCE (Agvise Laboratories Inc., 2018b).

Alkaline soils in North Dakota are the result of limestone deposited by glaciers within the past 600,000 years in areas north and east of the Missouri River (Bluemle, 2000), and the property of CO_2 solubility greater in cold water than warmer water (Schaetzl and Anderson, 2005) which has resulted in greater surface carbonates in northern ND compared to southern ND (Agvise Laboratories Inc., 2018b). Much of southwest North Dakota is formed from limestone, siltstone and sandstone beds, which are exposed due to either their unglaciated past, or the nearly complete erosion of the Laurentian glacier that covered most of the area before the most recent glaciation that helped form the present Missouri River course (Bluemle, 2000).

Acidic soil pH is present in areas where carbonates are not present, as carbonates neutralize H^+ by the products Ca^{2+}, CO_2, and H_2O are fashioned (Loeppert and Suarez, 1996) and buffer the soil against acidification. Acidic areas tend to be in depressional areas where carbonates can be leached deeper into the soil (Franzen et al., 2006). Carbonates are relatively insoluble and difficult to eluviate in arid, semiarid, and subhumid climates. Because of this, carbonates tend to be located near the soil surface where carbonate leaching has been minimal (Schaetzel and Anderson, 2005) on backslopes and shoulders of hilly toposequences (USDA-NRCS, 1995). Calciaquolls are an exception as ground water can concentrate carbonates due to many centuries of upward capillary water movement from relatively shallow groundwater (Schaetzel and Anderson, 2005). Calciaquolls are most prevalent in discharge depressions and other discharge areas (USDA-NRCS, 1995). Nitrogen fertilizer application and manures use

lowers soil pH due to their ammonium component. Hydrogen ions are released during nitrification. Over time, H^+ accumulates and acidify the soil. Acidity tends to intensify at the depth of N application. Since no-till soil management leaves the soil in place any tillage is less than about 5 cm, acidity tends to stratify near the surface in no-till systems (Blevins et al., 1983; Dick, 1983; Fox and Hoffman, 1981; Rehm et al., 1995; Schwab et al., 1989). No-till soils also generally contain more available soil water, and have better paths of water infiltration, which encourages leaching of basic cations (Blevins et al., 1983).

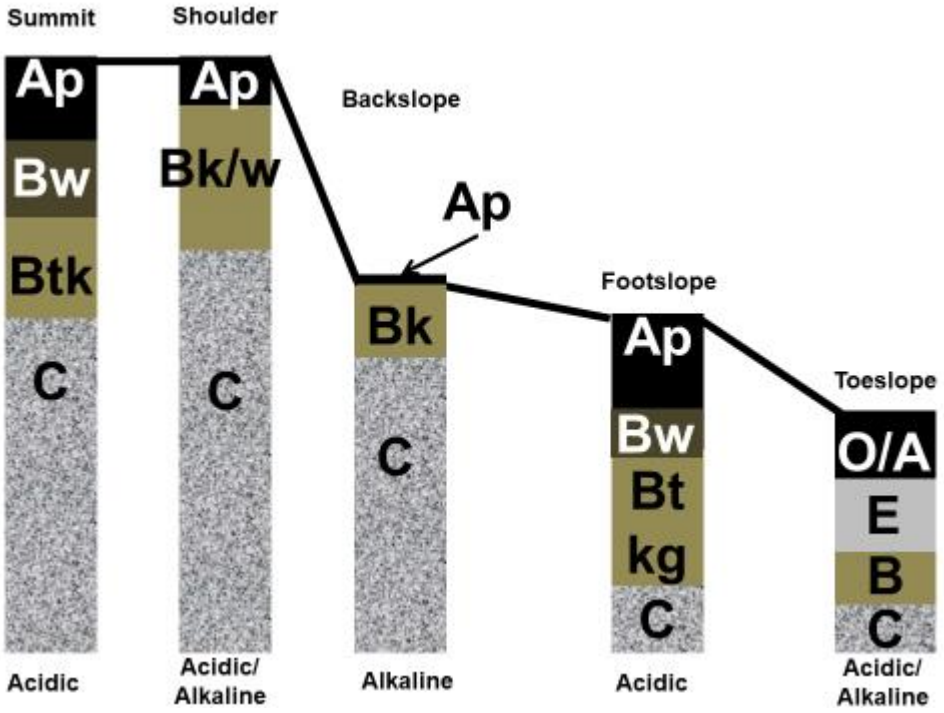

Figure 1. Typical catena with soil horizons and areas that tend to be acidic or alkaline.

The resulting acidity may result in mineral toxicity and nutrient deficiencies. The Ca^{2+} adsorbed on clay micelles can be replaced by H^+ which may dissolve alumino-silicates, resulting in a release of Al^{3+} (Blevins, 1983). As soils acidify, Al^{3+} becomes soluble, resulting in aluminum toxicity to many crops. Aluminum toxicity is characterized by misshapen roots and redced root growth (Kochian, 2000). Phosphorus may be more readily adsorbed to soils as pH

deceases or it may form insoluble Al-P compounds (Von Tucker et al., 2018). When Al^{3+} is released from micelle, it hydrolyzes and dissociates three H^+ from water (H_2O). This in turn can have a 'snowball' effect on soil pH and lower pH even more as more Al^{3+} enters soil solution and hydrolyses even more H_2O. This reaction produces gibbsite ($Al(OH)_3$) (Bohn et al., 2001).

North Dakota fields west of U.S. highway 83 tend to be no-till and are subsequently (USDA-NASS, 2019), where soil acidification is most prevalent (AGVISE Laboratories Inc., 2018b). It has been hypothesized that ammonium-based fertilizers combined with no-till farming are acidifying North Dakota's soils (Agvise Laboratories Inc., 2018c). Soil acidification can be remediated by applying agricultural lime and sugar beet waste lime. Another possible liming agent that is readily available for use and low-cost is municipal waste water treatment lime (WWL). Municipalities with a water treatment plant use finely ground limestone to remove P, N, and other impurities and/or adjust drinking water pH (National Lime Association, 2019). Some producers today are utilizing WWL in the USA (Norman, 2017) as it is distributed throughout the state and hauling costs can be cheaper than other lime sources. If using WWL it is imperative to test it for lime purity or for undesirable constituents including sodium (Farm Forum, 2015).

Lime requirement recommendations have not been developed for North Dakota (Sims, 1996b) due to the incorrect assumption of alkaline soils from the composite sampling history. Most in-state laboratories are making liming recommendations based on information from adjacent states. If the subsoil pH is alkaline, the suggested lime application is usually reduced by one-third or half (Breker, 2019). North Dakota research is needed to verify the cause and provide an agronomic solution for acidic soil remediation. Smectite clays are common throughout North Dakota. Whereas, chlorite, illite, and kaolinite clays are prevalent in areas west of the Missouri river (Franzen and Bu, 2018d). Because of the clay mineralogy in western North Dakota, the

AEM lime requirement methods may be applicable. Whereas in other areas of North Dakota, the Sikora (2006) method may be applicable. Carbonates are prevalent throughout North Dakota (USDA-NRCS, 2019b) which likely lessens the need to lime in many soils. A reliable method for estimating cation exchange capacity is required to base a lime requirement rate. The present practice of a water slurry for pH measurement shows the active acidity, but provides no information regarding the buffer capacity of North Dakota soils.

A greenhouse study conducted by DeSutter and Godsey (2010) used acidic soil collected from southwest North Dakota to observe the effects of pH change due to the application of sugar beet waste lime, agricultural lime, and reagent-grade lime. The sugar beet waste lime, agricultural lime, and reagent-grade lime ECCE was 73.7, 90, and 100% respectively. When applied at equal ECCE rates, sugar beet waste lime was found to increase soil pH more than agricultural lime and it was as effective as reagent grade lime. The particle size of sugar beet waste lime is much smaller than the quarry-run agricultural lime and was therefore much more reactive with the soil than coarser materials. Hard red spring wheat (*Triticum aestivum*, L.) root and above ground biomass was collected. Root biomass was similar across all treatments. However, sugar beet waste lime application resulted in greater aboveground biomass than the other treatments. Greater above-ground biomass with sugar beet waste lime may be the result of the N, P and other nutrients contained in sugar beet waste lime in small amounts.

Using liming guidelines from other states on North Dakota soils are not scientifically based. Research is needed in North Dakota to provide better guidance on what soil tests .should be utilized to determine lime application rates within the state. A collective of pH, different buffer tests, CEC, H%, and Al^{3+} ppm soil tests completed in North Dakota is provided in Table 38.

No-till has been a common practice in western North Dakota for more than 40 years (MacPherson, 2004). Surface stratified soil acidity has now become a problem severe enough in some soils that aluminum toxicity in wheat and other crops has been identified. Aluminum toxicity has increased in the number of fields affected in recent years (AGVISE Laboratories Inc., 2018a; Franzen, 2018d). While N fertilizers have been continually used since 1950 (Cao et al., 2018), soil pH data dating back from 1950 is nonexistent, and what data is available is whole-field in nature, and would not identify soils within a field with lower buffer capacity and more natural acidic soils. Soil acidification resulting from the combination of no-till and N fertilizers have been observed to occur in five (Moschler et al., 1973) to ten (Blevins et al., 1983) to eighteen years (Dick, 1983). Some North Dakota soils were likely carbonate free and can be easily acidified. However, it is likely that it took 60 years of continuous N fertilizing to neutralize soil carbonates causing soils to not be basically buffered.

Table 38. Soil pH, buffer pH, CEC, H^+ and Al^{3+} concentration of selected soils in western North Dakota

Active Acidity pH*	Sikora pH**	AEM pH†	CEC	H^+	Al^{3+}
				%	mg kg^{-1}
4.6	6.2		20.1	38.8	14.37
5.1	6.5		24.1	18.5	2.16
4.4	5.9		19.2	57.9	69.49
4.9	6.1	7.2	19.1	46.4	38.2
5.0	6.3	7.3	18.3	36.5	37.1
5.1	7.0	7.6	4.1	8.1	17.3
4.6	6.8	7.5	4.3	26.1	51.3

*pH determined by 1:1 deionized water:soil.
**Sikora, 2006.
†Adams and Evans, 1962.

4.2.4. Sugar Beet Waste Lime Impacts on Soils

Sugar beet processing purifies and concentrates sucrose, resulting in various forms of granular sugar and a molasses byproduct. The process begins with washing and slicing beets in a

mash. The sliced beet material is immersed in warm water diffusion batteries to extract sugar from sugar beet cells. The beet mash passes through a series of diffusion batteries and carbonations where each step increases the solution sugar concentration. Very finely ground limestone (>200 mesh) is added to the solution to neutralize organic acids and remove impurities through a precipitate reaction, since calcium results in flocculation. The resulting beet juice goes through a series of filtrations and centrifuges to cool, purify, and crystalize it into table sugar (Nicholson and Beal, 1916). The lime falls out of the liquid stream during the process, and the resulting sediment is sugar beet waste lime, that has approximately 86% CCE by dry weight, and includes ammonium-N, P, K, S and other nutrients. The sugar beet processing facilities of North Dakota and Minnesota produce approximately 454,000 Mg of sugar beet waste lime every year (Sims et al., 2005). Sidney Sugars in Sidney, Montana, produces approximately 26,800 Mg of sugar beet waste lime annually and the location has been stockpiling a majority of the sugar beet waste lime for 50 years (Reisig, 2019). Sugar beet waste lime has many benefits to soils and crops. Applications of sugar beet waste lime has been found to reduce crop diseases in canola (*Brassica rapa subsp.* L.) clubroot (*Plasmodiophra brassicae* L.) (Chapara et al., 2018), and sugar beet Aphanomyces (*Aphanomyces cochlioides* L.) (Bresnahan et al., 2002; Franzen et al., 2002) are diseases found to be reduced from sugar beet waste lime applications. Agricultural lime has reduced clubroot and *Aphanomyces*, but sugar beet waste lime has been found to be more effective than agricultural lime to reduce these diseases. The cause for sugar beet waste lime being more effective than agricultural lime is unknown, but it may be related to its active biology. There is an odor to the sugar beet waste lime which might be the result of organic material and biological activity of organisms using the organic material as a substrate in their metabolism. *Aphanomyces* reduction has been observed ten years after a sugar beet waste lime

application (Brantner et al., 2014). If there is an organism that colonizes the sugarbeet root before *Aphanomyces* infection, that might result in reduced root rot disease infection. A precedent for this can be found in work by Goos et al. (1994) with *Penicillium bilaji* application on spring wheat seed. The *Penicillium bilaji* has the property to release small amounts of P from calcareous soils with occluded P. At one acidic site there was a yield increase with application, with no relationship to P nutrition. Goos's hypothesized that yield was probably increased due to a reduction in common root rot (*Fusarium sp*) due to the application. The *Penicillium bilaji* may have colonized the spring wheat root, inhibiting infection by *Fusarium*. Sugar beet waste lime contains many essential plant nutrients (Table 5) and land applications might supplement the N and P required for crop production (Sims et al., 2010). However, only a small portion of P appears to be available (Sims and Lamb, 2010). Sugar beet waste lime application increased Olsen soil test P and yield, but was not as effective at increasing yield as a conventional P fertilizer. Phosphorus in the sugar beet waste lime may be a slow release fertilizer or its efficiency may be reduced due to tie-up with Ca^{2+} because of its alkalinity (Sims and Lamb, 2010).

Calcium added to a soil may improve flocculation and soil structure (Walworth, 12). Sims et al. (2005) analyzed the nutrient content of sugar beet waste lime collected from seven sugar beet factories located in the Red River Valley of the North. The amount of Ca^{2+} ranged from 233 to 255 mg kg^{-1} with a mean Ca^{2+} content of mg kg^{-1}, there is a possibility that its application improves soil structure and reduces soil compaction in susceptible soils. Sugar beet waste lime applications up to 35 Mg ha^{-1} did not decrease penetrometer resistance nine months after application (Franzen, et al., 2014). However, sugar beet waste lime has been used effectively to improve sodic soils. The rate of sugar beet waste lime applied for sodic soil

remediation should be much greater than gypsum as the calcium content of pure gypsum is greater and lime solubility is more than 300 times less (Kalwar, 2019). Solubility of the calcium amendment for sodic soil remediation influences sodic soil remediation rate efficacy (Oster and Frenkel, 1980). The solubility of gypsum is 2.05 g L^{-1} water and is 310 times more soluble than calcium carbonate as the solubility of calcium carbonate is 0.0066g L^{-1} water (Hammond, 2009). Solubility and Ca^{2+} content impact the time required for reaction and the rate of amendment required for remediation. When considering equal amounts of Ca^{2+}, the amount of sugar beet waste lime required for remediation is much greater than gypsum, and probably makes its use for that purpose impractical (Kalwar, 2019). However, sugar beet waste lime used to remediated sodic areas near sugar beet processing plants might be cost effective due to reduced delivery costs.

Despite sugar beet waste lime having 86% the acid neutralizing ability of agricultural lime (Sims et al., 2005) thus requiring an additional 14% of lime to remediate acidic soils compared to pure calcitic lime on a dry matter basis; sugar beet waste lime is much more cost effective for use in North Dakota than agricultural lime. Sugar beet waste lime can be a pollution source, but has beneficial uses, therefore, sugar beet waste lime can be land applied (Minnesota Pollution Control Agency, 2009). Beet processing factories in North Dakota, Minnesota, and Montana generally do not charge for sugar beet waste lime. However, there is a hauling expense to carry the sugar beet waste lime to the field for application. Sugar beet waste lime delivered from Sidney Montana to the North Central Research Extension Center in Minot costed \$46 Mg^{-1} (Norby, 2019). A local agricultural product distributor (name redacted) quoted \$101 Mg^{-1} of agricultural lime delivered to the North Central Research Extension Center. Even accounting for the 63% calcium carbonate equivalence of Sydney Sugars sugar beet waste lime (Table 6) there

is an economic advantage for sugar beet waste lime versus ag lime. However, sugar beet waste lime properties can vary (Table 6). Sims et al. (2005) observed a great difference of N, P, Na, and K across seven difference sugar beet processing plants in North Dakota and Minnesota. There is a difference of sugar beet waste lime composition within the same sugar beet processing plant. As such, sugar beet waste lime should be tested on a regular basis for field use.

4.2.5. Remediating No-till Acidic Soils

Soil pH should fall between 5.5 and 7 depending on the crop (Sims, 1996). Sugar beet waste lime can neutralize soil acidity in North Dakota (Franzen, (2002). Surface applied sugar beet waste lime improves soil acidity near the surface (DeSutter and Godsey, 2010). Increased soil pH from surface applied lime on no-till fields has been observed by many (Blevins et al., 1983; Conyers et al., 2003; Godsey et al., 2007; Fox and Hoffman 1981; Moschler et al., 1973). Incubation studies show an improvement of soil acidity to a depth of 2 cm from surface lime application. However, incorporation of sugar beet waste lime can improve the soil pH to the depth of incorporation (DeSutter and Godsey, 2010). DeSutter and Godsey (2010) simulated no-till practices by surface applying sugar beet waste lime. However, long-term no-till fields are well aggregated and have a greater abundance of macropores that may better (VandenBygaart, et al., 1998) facilitate sugar beet waste lime infiltration than disturbed collected soil used by DeSutter and Godsey (2010).

Lime applied to no-till fields have improved soil pH down to a depth of 15 cm. Conventional till can raise soil pH to greater depths, but no-till will have a higher near surface pH (Blevins et al., 1983). The critical pH for consideration of lime application for most crops occurs at soil pH 5.5 or less, since those soils may be susceptible to Al toxicity. Because lime

reaction takes time to react with soil pH and move deeper into the soil profile, lime should be applied before the soil pH is less than 5.5 (Godsey et al., 2007).

4.3. Materials and Methods

This project looked at the impacts of sugarbeet waste lime when surface applied on a long-term no-till field. The study site soil type was Aastad loam (fine-loamy mixed superactive frigid Pachic Argiudolls) (USDA-NRCS, 2019b) in a long-term no-till field where the last tillage pass has been more than seven years. Sugar beet waste lime was surface applied at rates of 4.4 Mg ha^{-1} and 8.8 Mg ha^{-1} two days after planting soybean. Experimental units were 3.04 m wide and 9.14 m long. A buffer plot of 1.52 m wide and 9.14 m long was planted between each plot to prevent edge effects. There were four replications; however, the fourth replicate topsoil pH was greater than 6. As a result, the fourth replication was discarded from the statistical analysis. The three remaining replications had pH values at the 0-15 cm depth from 5.4 to 5.7. The sugar beet waste lime was obtained from Sidney Sugars, Sidney, MT. The North Dakota State University Soil Testing Laboratory, Fargo, ND analyzed the lime for nutrient content. The analysis of the sugar beet waste lime was 3,030 mg kg^{-1} NO_3^-, 3,070 mg kg^{-1} P, and 660 mg kg^{-1} K. The lime CCE was 73% and moisture content was 35% (Table 5).

Sample cores for soil pH analysis were collected immediately before sugar beet waste lime application (May 26, 2018) in 5 cm increments to a depth of 15 cm. A sample was collected from the 15 to 30 cm depth and a subsoil depth was collected at 30 to 60 cm. Soil was collected similarly after soybean harvest on October 9, 2018. The soil sampling tool used was a hand soil sampling tube with a 19 mm diameter tip. Mean soil pH was compared by depth and individual profiles. Comparison of means was performed using the Student's T-test procedure of SAS software version 9.4 (SAS Institute Incorporated, 2012).

4.4. Results and Discussion

Past N fertilizer applications at the site were surface-applied urea in most years. Urea was sometimes applied using mid-row banding at seeding at the 5 cm depth. Because N was mostly surface applied, the 0-5cm depth was the most acidic (Table 39).

Both surface treatments of lime increased the soil pH measured at the 0 to 10 cm depth (Table 39). The subsoil has a calcic horizon that resulted in increased pH at depths below 30 cm. Sugar beet waste lime did not improve yield, protein, or oil content of soybean. Aluminum toxicity was not observed or measured at this site, but the data indicate that surface- applied sugar beet waste lime can be a useful amendment to manage acidic soils. Sugar beet waste lime that is not incorporated needs precipitation to eluviate into the soil. The 2018 growing season was abnormally dry. The nearest NDAWN weather station, approximately 1 km north-northeast of the experiment recorded 246 mm precipitation received (NDAWN, 2018) between the lime application May 27 and the October 9 experiment soil sampling date. The mean 30-year rainfall recorded over these dates from that station is 313 mm (NDAWN, 2019a).

Table 39. Surface applied sugar beet waste lime effects on soil pH by depth and soil horizon.

Depth (cm)	Horizon†	Initial pH	4.4 Sugar Beet Waste Lime (Mg ha^{-1})	8.8 Sugar Beet Waste Lime (Mg ha^{-1})
			----------pH----------	
0-5	Ap	5.33ax‡	6.5bx	6.7bx
5-10	Ap	5.4ax	6.1bx	6.2bx
10-15	Ap	5.4ax	5.6ay	5.7ay
15-30	Bt	5.8ay	5.9ay	5.9ay
30-60	BtK	7.7az	7.7az	7.7az

†Horizons were determined by observing push probe samples.
‡a and b show significance across treatments. x, y, and z show significance across depths within a treatment. Significance is at the 0.05 level.

This data indicates that applications of sugar beet waste lime on acidic topsoil can increase soil pH. This occurred when moisture was lacking and a drought where infiltration and downward movement of sugar beet waste lime was limited. Incorporation of sugar beet waste lime might increase soil pH at deeper depths. However, tillage will reduce the no-till benefits of aggregation, infiltration, nutrient cycling, and increased water holding capacity. All tillage practices reduce soil organic matter and assist with soil erosion.

Future research needs to focus on developing liming recommendations for semi-arid North Dakota and evaluate lime impacts on economically important crops. Future studies should monitor soil pH for a few years after lime treatments to determine the frequency of future lime applications. Godsey et al., (2007) observed acidic soil improvements from surface applied lime on no-till fields five years after a lime application.

4.5. Conclusions

1. Many no-till soils in North Dakota are acidifying from N fertilizers.
2. Precision agriculture is needed to better pinpoint acidic areas and efficiently manage those areas.
3. Surface applied sugar beet waste lime in the spring can increase soil pH to a depth of 10 cm by fall (Table 39), however, this may not increase crop yield (Tale 12, 20, 26, 32).
4. This study indicates that surface applied sugar beet waste lime can improve no-till acidic soils. More research is needed to verify these findings and better guide producers on lime application rates.

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APPENDIX A. SOIL DESCRIPTIONS

Table A1. Description of Aastad soil series.

Horizon	Depth -cm-	Color Dry	Color Moist	Texture	Structure	Redox Features	Other Features
Ap	0-23	10 YR 3/1	10YR 2/1	clay loam	moderate fine & medium subangular blocky		abrupt smooth boundary, four percent coarse fragments
Ap	23-58	10 YR 3/1	10YR 2/1	clay loam	moderate fine & medium subangular blocky		
Bt	58-97		2.5Y 4/4	clay loam	medium prismatic parting to moderate medium angular blocky		10YR 3/2 clay films, four percent coarse fragments,
Bk1	97-127		2.5Y 5/2	clay loam	moderate medium prismatic parting to moderate medium angular blocky	Many medium 2.5Y 5/6 redox concentrations	masses of common fine carbonate, five percent coarse fragments, violent effervescence
Bk2	127-163		2.5Y 5/2	clay loam	extremely coarse prismatic parting to moderate medium and coarse angular block		
BC	163-200		2.5Y 5/2	clay loam			

Adapted from USDA-NRCS, (2019a)

Table A2. Description of Williams soil series.

Horizon	Depth -cm-	Color Dry	Color Moist	Texture	Structure	Redox Features	Other Features
Ap	0-15	10 YR 4/2	10YR 2/2	loam	weak medium subangular blocky		few pebbles, common very fine roots,
Bt1	15-25	20 YR 4/3	10YR 2/2	clay loam	strong medium prismatic parting to strong medium angular blocky		many distinct clay films on ped faces and pore linings, sticky and plastic, common very fine roots, few pebbles, neutral, wavy boundary
Bt2	25-38	10 YR 5/2	10YR 2/2	clay loam			
Btk	38-61	2.5 Y 5/4	2.5Y 4/4	clay loam	moderate coarse prismatic parting to moderate medium subangular blocky		sticky and plastic, hard, friable, common very fine roots, few faint clay films on ped faces, few pebbles, common medium irregular masses of carbonates, violent effervesces, gradual wavy boundary
Bk	61-91	2.5 Y 6/2	2.5Y 7/2	clay loam	weak medium prismatic parting to weak medium subangular blocky		soft, friable, sticky and plastic, few very fine roots, few cobbles, common masses of carbonates disseminated throughout, violent effervescence, gradual wavy boundary
C	91-152	2.5 Y 6/2	2.5Y 5/2	clay loam	massive	few fine 10YR 5/6 redox concentrations and 10YR 7/2 redox depletions	soft, friable, plastic and sticky, few pebbles and cobbles, strong effervescence

Adapted from USDA-NRCS, (2019a)

Table A3. Description of Wilton soil series.

Horizon	Depth -cm-	Color Dry	Color Moist	Texture	Structure	Redox Features	Other Features
Ap	0-20	10 YR 4/2	10YR 2/2	silt loam	weak medium subangular blocky parting to moderate fine granular		slightly hard, very friable, slightly sticky and plastic, common roots
Bw1	20-33	10 YR 4/2	10YR 2/2	silt loam	moderate medium prismatic parting to weak medium subangular blocky		very friable, slightly hard, slightly sticky and plastic, many fine roots, common fine pores, neutral
Bw2	33-46	10 YR 5/2	10YR 3/2	silt loam			slightly hard, very friable, slightly plastic and sticky; common fine roots; common fine pores; faint clay films on some vertical faces of peds; very dark brown (10YR 2/2) moist coatings on peds
Bw3	46-69	10 YR 5/2	10YR 3/2	silt loam			slightly hard, very friable, slightly plastic and sticky; common fine roots; common fine pores;
2Bk1	69-91	2.5Y 6/2	2.5Y 4/2	clay loam	weak coarse prismatic structure parting to weak coarse and medium subangular blocky		hard, friable, plastic and sticky; few fine roots; common fine pores; five percent coarse fragments; strong effervescence, carbonates in many medium and few large masses; slightly alkaline; gradual wavy boundary
2Bk2	91-152	2.5Y 6/2	2.5Y 4/3	clay loam	massive	few fine 7.5YR 5/6 redox concentr ations	hard, friable, plastic and sticky; few roots; five percent coarse fragments; strong effervescence, masses of common carbonates

Adapted from USDA-NRCS, (2019a)

APPENDIX B. EXPERIMENT DATA

Table B1. Data of all check treatments.

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	30.82	33.53	14.94
Columbus	2016	2	31.46	33.45	14.82
Columbus	2016	3	39.56	33.93	14.77
Columbus	2016	4	34.57	34.19	14.75
Columbus	2017	1	25.19	32	15.45
Columbus	2017	2	27.94	31.43	15.72
Columbus	2017	3	28.35	30.6	16.41
Columbus	2017	4	26.28	32.89	15.74
Noonan	2018	1	20.64	30.29	16.59
Noonan	2018	2	26.01	31.05	16.68
Noonan	2018	3	19.71	30.82	16.5
Noonan	2018	4	16.98	30.75	16.45
Minot	2016	1	42.46	35.35	14.6
Minot	2016	2	40.63	35.5	14.52
Minot	2016	3	38.4	33.95	15.1
Minot	2016	4	47.87	33.55	15.2
Riverdale	2017	1	21.36	34.61	15.05
Riverdale	2017	2	28.74	35.48	14.51
Riverdale	2017	3	29.06	33.96	14.92
Riverdale	2017	4	36.72	35.99	14.49
Minot	2018	1	20.28	35.72	16.06
Minot	2018	2	23.16	34.51	16.56
Minot	2018	3	18.34	35.3	15.81
Minot	2018	4	25	33.47	16.77

Table B2. Data of all inoculation treatments.

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	34.78	32.91	14.51
Columbus	2016	2	35.02	32.99	14.7
Columbus	2016	3	28.76	33.65	14.9
Columbus	2016	4		Missing Data	
Columbus	2017	1	31.89	32.15	15.43
Columbus	2017	2	34.38	32.43	15.35
Columbus	2017	3	30.95	31.44	15.76
Columbus	2017	4	24.72	32.76	15.69
Noonan	2018	1	24.27	30.92	16.44
Noonan	2018	2	26.57	32.03	15.81
Noonan	2018	3	31.55	32.81	15.73
Noonan	2018	4	19.69	31.69	16.11
Minot	2016	1	74.24	34.27	14.81
Minot	2016	2	57.66	33.11	15.35
Minot	2016	3	41.78	33.73	15.12
Minot	2016	4	35.32	34.53	14.39
Riverdale	2017	1	24.53	34.45	15.05
Riverdale	2017	2	31.34	34.74	14.97
Riverdale	2017	3	25.18	34.84	13.88
Riverdale	2017	4	40.31	34.46	14.72
Minot	2018	1	19.09	35.03	15.99
Minot	2018	2	23.48	33.92	16.59
Minot	2018	3	22.14	34.22	16.45
Minot	2018	4	17.36	34.99	16.18

Table B3. Data of all 46-0-0 treatments applied at 55 kg ha^{-1}.

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	39.28	33.81	14.11
Columbus	2016	2	35.38	34.12	14.58
Columbus	2016	3	32.72	33.43	14.49
Columbus	2016	4	38.81	33.89	14.51
Columbus	2017	1	31.04	31.65	15.83
Columbus	2017	2	21.25	30.74	16.12
Columbus	2017	3	36.82	32.31	15.99
Columbus	2017	4	29.5	33.09	15.43
Noonan	2018	1	24.12	31.22	16.09
Noonan	2018	2	22.83	32.53	16.68
Noonan	2018	3		Missing Data	
Noonan	2018	4	21.72	33.84	15.29
Minot	2016	1	43.94	34.71	14.31
Minot	2016	2	47.19	34.86	14.67
Minot	2016	3	62.38	34.1	14.93
Minot	2016	4	28.79	34.71	14.64
Riverdale	2017	1	25.69	36.4	13.55
Riverdale	2017	2	26.6	35.07	14.74
Riverdale	2017	3	31.76	33.35	15.07
Riverdale	2017	4	32.47	35.93	14.23
Minot	2018	1	21.36	35.38	16.12
Minot	2018	2	19	35.07	15.81
Minot	2018	3	19.79	35.29	16.04
Minot	2018	4	17.09	36.27	15.38

Table B4. Data of all 11-52-0 treatments applied at 110 kg ha^{-1}.

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	27.47	34.36	14.69
Columbus	2016	2	31.07	32.72	15.24
Columbus	2016	3	46.29	34.6	14.45
Columbus	2016	4	34.33	34.41	14.61
Columbus	2017	1	36.19	30.39	16.09
Columbus	2017	2	23.16	30.01	16.58
Columbus	2017	3	24.21	31.04	16.16
Columbus	2017	4	33.34	32.42	15.55
Noonan	2018	1	20.6	31.78	16.13
Noonan	2018	2	26.59	31.84	15.84
Noonan	2018	3	23.04	28.61	17.05
Noonan	2018	4	26.4	32.99	15.72
Minot	2016	1	44.26	34.86	14.89
Minot	2016	2	37.9	35.32	14.27
Minot	2016	3	49.23	34.83	14.83
Minot	2016	4	36	34.73	14.47
Riverdale	2017	1	25.98	35.15	14.45
Riverdale	2017	2	33.69	35.33	14.42
Riverdale	2017	3	31.25	34.93	14.86
Riverdale	2017	4	35.2	34.72	14.73
Minot	2018	1	13.76	34.73	15.95
Minot	2018	2	16.4	35.06	16.12
Minot	2018	3	24.3	34.23	16.4
Minot	2018	4	20.26	36.15	15.72

Table B5. Data of all 10-34-0 treatments applied at 28 L ha^{-1}.

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	37.49	33.58	14.45
Columbus	2016	2	35.74	33.43	15.17
Columbus	2016	3	33.08	33.84	14.77
Columbus	2016	4	29.54	33.6	15.15
Columbus	2017	1	34.65	32.86	15.3
Columbus	2017	2	29.87	31.93	15.67
Columbus	2017	3	25.24	30.62	16.34
Columbus	2017	4	20.98	32.97	15.39
Noonan	2018	2	23.93	32.29	16.1
Noonan	2018	3	27.9	31.32	16.28
Noonan	2018	4	23.76	31.25	16.25
Minot	2016	1	49.4	34.5	15.36
Minot	2016	2	44.09	34.42	15.17
Minot	2016	3	47.19	33.43	15.73
Minot	2016	4	41.74	34.32	14.7
Riverdale	2017	1	28.01	34	15.18
Riverdale	2017	2	28.95	34.99	14.85
Riverdale	2017	3	35.21	35.3	14.42
Riverdale	2017	4	38.37	34.28	14.56
Minot	2018	1	14.71	36.63	15.64
Minot	2018	2	13.76	34.65	16.37
Minot	2018	3	21.8	35.73	15.79
Minot	2018	4	20.74	34.88	15.93

Table B6. Data of all 6-24-6 treatments applied at 28 L ha^{-1}.

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	35.47	32.7	14.91
Columbus	2016	2	35.35	33.41	14.54
Columbus	2016	3	29.53	33.48	14.92
Columbus	2016	4	44.02	33.99	14.65
Columbus	2017	1	16.99	31.47	15.65
Columbus	2017	2	27.07	30.63	16.09
Columbus	2017	3	35.42	31.23	15.9
Columbus	2017	4	28.88	32.71	15.49
Noonan	2018	1	23.5	30.62	16.36
Noonan	2018	2	26.71	31.36	16.32
Noonan	2018	3	28.32	32.4	15.9
Noonan	2018	4	30.4	31.42	16.25
Minot	2016	1	32.3	34.51	14.19
Minot	2016	2	45.44	33.65	15.21
Minot	2016	3	33.07	34.34	15.29
Minot	2016	4	42.54	33.79	15.13
Riverdale	2017	1	26.37	35.22	14.86
Riverdale	2017	2	31.03	35.35	14.64
Riverdale	2017	3	33.15	34.59	14.68
Riverdale	2017	4	30.85	33.74	15.41
Minot	2018	1	25.04	34.72	16.06
Minot	2018	2	24.33	34.64	16.31
Minot	2018	3	20.85	35.99	15.37
Minot	2018	4	17.73	35.96	15.74

Table B7. Data of all Soygreen and Levesol treatments.

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus*	2016	1	30.32	33.86	14.18
Columbus*	2016	2	26.71	33.19	14.62
Columbus*	2016	3	29.29	33.42	15.07
Columbus*	2016	4	31.26	32.83	15.39
Columbus*	2017	1	17.52	31.77	15.89
Columbus*	2017	2	26.73	30.86	16.11
Columbus*	2017	3	23.1	30.28	16.33
Columbus*	2017	4	30.99	32.75	15.51
Noonan*	2018	1	19.42	30.72	16.76
Noonan*	2018	2	26.12	30.57	16.39
Noonan*	2018	3	28.7	31.76	16.1
Noonan*	2018	4	24.9	31.91	16.46
Columbus**	2016	1	41.63	34.18	13.84
Columbus**	2016	2	30.05	33.42	14.11
Columbus**	2016	3	26.05	33.48	14.72
Columbus**	2016	4	39.65	34.23	14.76
Columbus**	2017	1	36.65	31.48	15.97
Columbus**	2017	2	19.61	31.81	15.59
Columbus**	2017	3	27.4	30.01	16.6
Columbus**	2017	4	30.36	32.82	15.55
Noonan**	2018	1	28.01	31.86	16.04
Noonan**	2018	2	25.29	31.01	16.58
Noonan**	2018	3	19.09	28.47	17.12
Noonan**	2018	4	25.35	31.55	16.27

*Soygreen 7.1 L ha^{-1}

**Levesol 7.1 L ha^{-1}

Table B8. Data of all foliar 3-18-18 treatments applied 28 L ha^{-1} during the V5 growth stage (Fehr and Caviness, 1977).

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	39.00	34.36	14.21
Columbus	2016	2	28.55	33.79	14.92
Columbus	2016	3	35.18	34.02	14.21
Columbus	2016	4	30.28	33.66	15.2
Columbus	2017	1	31.37	32.3	15.52
Columbus	2017	2	33.62	31.91	15.99
Columbus	2017	3	23.32	32.09	15.95
Columbus	2017	4	27.89	32.81	15.63
Noonan	2018	1	24.7	29.39	16.89
Noonan	2018	2	27.92	31.61	16.09
Noonan	2018	3	22.04	31.04	16.82
Noonan	2018	4	25.95	31.31	16.2
Minot	2016	2	44.86	33.82	15.25
Minot	2016	3	36.99	34.81	14.93
Minot	2016	4	19.04	36.16	14.13
Riverdale	2017	1	28.21	33.94	15.1
Riverdale	2017	2	26.61	35.97	14.06
Riverdale	2017	3	27.02	34.84	14.48
Riverdale	2017	4	39.59	34.72	14.27
Minot	2018	1	21.4	34.97	15.94
Minot	2018	2	20.59	35.96	15.85
Minot	2018	3	20.98	34.88	16.13
Minot	2018	4	17.35	32.75	16.52

Table B9. Data of all foliar 3-18-18 treatments applied at 28 L ha^{-1} during the R2 growth stage (Fehr and Caviness, 1977).

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	29.23	33.66	14.82
Columbus	2016	2	34.66	32.35	15.17
Columbus	2016	3	29.55	33.32	14.88
Columbus	2016	4	39.13	33.9	14.62
Columbus	2017	1	28.05	31.15	15.73
Columbus	2017	2	32.54	31.39	15.85
Columbus	2017	3	35.87	31.89	15.61
Columbus	2017	4	25.1	31.69	16.32
Noonan	2018	1	23.68	30.67	16.78
Noonan	2018	2	27.98	31.86	16.22
Noonan	2018	3	26.87	32.36	15.61
Noonan	2018	4	21.98	32.1	15.99
Minot	2016	1	45.47	34.37	14.75
Minot	2016	2	49.79	34.79	14.97
Minot	2016	3	26.13	35.36	14.45
Minot	2016	4	12.24	35.18	14.05
Riverdale	2017	1	26.26	34.47	14.72
Riverdale	2017	2	32.89	34.69	14.68
Riverdale	2017	3	28.8	35.23	14.55
Riverdale	2017	4	36.89	34.72	15.15
Minot	2018	1	17.45	34.93	16.43
Minot	2018	2	24.56	34.05	16.55
Minot	2018	3	24.62	34.05	16.43
Minot	2018	4	22.67	36.42	15.61

Table B10. Data of all foliar 3-18-18 treatments applied at 28 L ha^{-1} with 1.1 kg AMS ha^{-1} applied at the V5 growth stage (Fehr and Caviness, 1977).

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	36.73	33.4	14.81
Columbus	2016	2	31.1	33.14	14.73
Columbus	2016	3	35.63	34.29	14.73
Columbus	2016	4	31.42	34.04	14.91
Columbus	2017	1	27.06	31.41	16.15
Columbus	2017	2	26.21	31.73	15.41
Columbus	2017	3	25.72	31.16	16.15
Columbus	2017	4	36.81	31.62	15.62
Noonan	2018	1	20.08	30.97	16.28
Noonan	2018	2	23.87	32.5	15.98
Noonan	2018	3	24.1	30.49	16.82
Noonan	2018	4	27.42	32.21	15.87
Minot	2016	1	33.51	33.84	14.69
Minot	2016	2	47.37	34.72	14.93
Minot	2016	3	47.3	34.2	14.68
Minot	2016	4	35.26	33.55	15.21
Riverdale	2017	1	22.07	35.09	14.61
Riverdale	2017	2	29.62	34.3	14.87
Riverdale	2017	3	29.11	34.68	14.97
Riverdale	2017	4	31.91	34.67	14.5
Minot	2018	1	18.8	34.59	16.33
Minot	2018	2	18.36	35.22	16.05
Minot	2018	3	22.65	32.94	16.92
Minot	2018	4	21.45	32.16	16.83

Table B11. Data of all foliar 3-18-18 treatments applied at 28 L ha^{-1} with 1 kg AMS ha^{-1} applied at the R2 growth stage (Fehr and Caviness, 1977).

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Columbus	2016	1	31.94	31.68	15.51
Columbus	2016	2	36.29	33.81	14.24
Columbus	2016	3	35.89	33.73	15.13
Columbus	2016	4	32.65	34.98	14.62
Columbus	2017	1	27.45	32.13	15.29
Columbus	2017	2	24.76	30.4	16.28
Columbus	2017	3	34.33	31.66	15.46
Columbus	2017	4	26.18	32.31	15.73
Noonan	2018	1	23.13	31.17	16.17
Noonan	2018	2	27.09	31.8	15.97
Noonan	2018	3	24.81	31.17	16.42
Noonan	2018	4	26.78	31.85	16.37
Minot	2016	1	46.11	35.36	14.23
Minot	2016	2	30.97	34.25	15.13
Minot	2016	3	33.18	33.47	15.24
Minot	2016	4	33.47	34.42	14.33
Riverdale	2017	1	24.88	34.09	15
Riverdale	2017	2	32.47	35.02	14.53
Riverdale	2017	3	32.44	35.13	14.49
Riverdale	2017	4	33.35	35.98	14.16
Minot	2018	1	22.66	34.65	16.32
Minot	2018	2	17.36	35.5	15.67
Minot	2018	3	14.92	34.14	16.45
Minot	2018	4	17.14	37.01	15.19

Table B12. Data of all sugar beet waste lime treatments.

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Minot*	2016	1	36.8	34.77	15
Minot*	2016	2	42.14	34.2	15.01
Minot *	2016	3	31.24	34.79	14.65
Minot *	2016	4	40.38	34.13	15.01
Riverdale*	2017	1	28.95	34.02	15.29
Riverdale*	2017	2	26.33	35.09	14.73
Riverdale*	2017	3	35.06	35.4	14.19
Riverdae*	2017	4	37.36	34.82	14.69
Minot*	2018	1	20.46	35.03	16.24
Minot*	2018	2	22.83	35.79	15.7
Minot *	2018	3	23.07	34.35	16.32
Minot *	2018	4	17.82	37.48	15.05
Minot**	2016	1	46.41	34.78	14.58
Minot**	2016	2	37.17	33.83	15.15
Minot**	2016	3	44.01	34.31	14.73
Minot**	2016	4	43.53	35.21	14.72
Riverdale**	2017	1	23.92	35.13	14.76
Riverdale**	2017	2	30.7	34.77	14.79
Riverdale**	2017	3	30.66	35.56	14
Riverdale	2017	4	33.57	35.08	14.76
Minot**	2018	1	14.24	36.54	15.48
Minot**	2018	2	26.97	35.17	16.42
Minot**	2018	3	24.3	35.32	15.55
Minot**	2018	4	22.53	35.55	15.78

*Sugar Beet Waste Lime 4.4 Mg ha^{-1}

**Sugar Beet Waste Lime 8.8 Mg ha^{-1}

Table B13. Data of all cobalt treatments applied at 1.1 kg ha^{-1}.

Environment	Year	Replication	Grain Yield (kg ha^{-1})	Protein% at 13% Moisture	Oil % at 13% Moisture
Noonan	2018	1	19.39	31.89	15.79
Noonan	2018	2	23.43	32.1	15.48
Noonan	2018	3	25.7	31.26	16.35
Noonan	2018	4	18.05	31.02	16.27
Minot	2018	1	22.24	34.76	16.36
Minot	2018	2	26.29	34.3	16.25
Minot	2018	3	20.24	35.17	15.87
Minot	2018	4	23.66	36.43	15.43

Table B14. Data of soil pH impacts from surface applied sugar beet waste lime.

Sugar Beet Waste Lime Treatment	Replication*	Depth	Initial pH	Final pH
-Mg ha^{-1}-		-cm-		
4.4	1	0-5	5.7	6.1
4.4	1	5-10	5.4	5.2
4.4	1	10-15	5.4	5.6
8.8	1	0-5	5.2	6.5
8.8	1	5-10	5.2	5.5
8.8	1	10-15	5.6	5.6
8.8	2	0-5	5.4	6.6
8.8	2	5-10	5.3	5.7
8.8	2	10-15	5.7	6
4.4	2	0-5	5.2	6.8
4.4	2	5-10	5.4	6.3
4.4	2	10-15	5.8	6.2
8.8	3	0-5	5.3	7.1
8.8	3	5-10	5.8	5.9
8.8	3	10-15	6.5	6.1
4.4	3	0-5	5.2	6.5
4.4	3	5-10	5.1	5.4
4.4	3	10-15	5.8	5.9
4.4	4	0-5	7	7.5
4.4	4	5-10	7.5	7.6
4.4	4	10-15	7.7	7.7
8.8	4	0-5	7.4	7.7
8.8	4	5-10	7.5	7.2
8.8	4	10-15	7.7	7.4

*Replication 4 was not used for statistical analysis due to alkaline pH