SOIL ACIDITY IN SOUTHERN CANADIAN PRAIRIE CHERNOZEMIC AGRICULTURAL SOILS

MARK HENRI WAGNER
Bachelor of Science, University of Lethbridge, 2020

A thesis submitted
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

GEOGRAPHY

Department of Geography and Environment
University of Lethbridge
LETHBRIDGE, ALBERTA, CANADA

SOIL ACIDITY IN SOUTHERN CANADIAN PRAIRIE CHERNOZEMIC AGRICULTURAL SOILS

MARK HENRI WAGNER

Date of Defense: 19 April 2024

Dr. Derek Peddle	Professor	Ph.D.
Dr. Tom Jensen	Sessional Instructor & Adjunct Professor	Ph.D.
Thesis Co-Supervisors		
Dr. Craig Coburn	Professor	Ph.D.
Thesis Examination Committee Member		
Dr. Philip Bonnaventure	Professor	Ph.D.
Chair, Thesis Examination Committee		

For my ever-supporting wife Jessica

and countless hours of entertainment and

adventuring from our cat Piper.

Thank-you for everything.

Abstract

Soil acidity is an increasing concern for growers in the southern prairies of western Canada. This study took place over a three-year period, starting in 2020, the research lime treatment plots were established in low soil pH zones, in the three cropped fields: Hilton, Sierra and Kings Lake. Both powdered or granular lime was surface applied on long-term no-till fields, with one of three placement methods: no incorporation, incorporation with harrowing, or incorporation using tillage. Soil sampling was followed by pH measurements conducted in November 2021 and 2022. In Fall 2021 only the treatment of powdered lime incorporated using tillage increased the soil to the pH target of 6.5 for the 0-15 cm depth. By Fall 2022 soil sampling, pH analyses showed that all lime treatments were effectively ameliorating the low pH soils. Further study investigated spatial variability of soil pH on the study fields, the most practical sampling density for accurate pH maps was shown to be 1 sample spot per 0.8 hectares. After this study, data was gathered on the incorporation methods and lime forms. It was determined all treatments sufficiently raised the pH to an acceptable level for crop growth, after two years. Furthermore, the assessment on pH variability was vital to understanding how variable soil pH can be in a field.

Acknowledgements

I would like to first and foremost thank my supervisors, Dr. Derek Peddle and Dr. Tom Jensen, and my third committee member, Dr. Craig Coburn, for helping me along on this research journey. Additionally, for my field site cooperators for allowing me unlimited access to their fields, set up research plots on their land, and monitor the soil pH changes yearly. This includes Mr. Henry Kleinsasser from Sierra Farming near Shaunavon, SK, Mr. Mike Waldner from Kings Lake Farming near Skiff, AB, and Mr. Spencer Hilton from Hilton Acres, near Strathmore, AB, thank-you to all three landowner cooperators. As well as the Miller farm near Olds, AB, the Andrew farm near Bashaw, AB and the Haenni farm near Falun, AB for their interest in this project and allowing further grid soil sampling research to assess how pH can be spatially variable throughout fields. Thanks to Down to Earth Labs for allowing me access to the buffer solution for determining the lime requirement for the soil analyses taken during grid sampling and for the soil samples from the lime application research plots. Lastly, the Department of Geography & Environment, University of Lethbridge for allowing me access to store and analyze my soil samples, and use of the geographic information system (GIS) software to analyze my research data.

Table of Contents

List of Tables

List of Figures

Figure 4.6: Displays the initial statistical comparison of the natural variation amongst the plots, Kings Lake site. Then it carries into how these variations of pH slowly returns to a neutral pH, changing due to the treatments applied to the soil and how the 0 to 15 cm growing zone of the soil is changing.

Figure 4.7: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 0 to 5 cm growing zone of the soil pH levels vary, Kings Lake Site. At this site and depth, the was no significant changes between the years.

Figure 4.8: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 5 to 10 cm growing zone of the soil pH levels vary, Kings Lake site. At this site and depth, the was no significant changes between the years.

Figure 4.9: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 10 to 15 cm growing zone of the soil pH levels vary, Kings Lake site. At this site and depth, the was no significant changes between the years.

Figure 4.10: Displays the initial statistical comparison of the natural variation amongst the plots, Sierra site. Then it carries into how this variations pH slowly returns to a neutral pH, changing due to the treatments applied to the soil and how the 0 to 15 cm growing zone of the soil is changing.

Figure 4.11: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 0 to 5 cm growing zone of the soil pH levels vary, Sierra site. At this depth, the treatments that showed improvement from 2021 to 2022 was the granular surface and harrowed. However, they also performed less than the other treatments for increasing the soils pH in 2021.

Figure 4.12: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 5 to 10 cm growing zone of the soil pH levels vary, Sierra site. All treatments performed similarly from 2021 to 2022, however the powdered tilled treatment significantly increased from 2021 to 2022.

Figure 4.13: Displays the statistical comparison of the variation amongst the plot, Sierra site, with the treatments applied to the soil and how the 10 to 15 cm growing zone of the soil pH levels vary. At this site and depth, the was no significant changes between the years.

Figure 4.14: Displays the three-site combination statistical comparison of the six-lime form-incorporation treatments, before lime application to years 1 and 2.

Figure 4.15: Displays the three-site combined statistical comparison of the variation amongst the treatments applied to the soil and how the 0 to 5 cm layer of the soil pH was affected.

Figure 4.16: Displays the statistical comparison three-site combined of the variation amongst the treatments applied to the soil and how the 5 to 10 cm growing zone of the soil pH levels was affected.

List of Abbreviations

ATP	Adenosine Triphosphate
NH_4	Ammonium
$CaCO_3$	Calcium carbonate/calcitic lime
$Ca(NO_3)_2$	Calcium nitrate
CSSC	Canadian System of Soil Classification
CO_2	Carbon dioxide
H_2CO_3	Carbonic acid
DNA	Deoxyribonucleic Acid
$CaCO_3$ $MgCO_3$	Dolomitic Lime
FA	Factorial Analysis
Fe2O3	Ferric Oxide
GIS	Geographic Information System
NO_3^-	Nitrate
NO_2^-	Nitrite
StS	Statistically Significant
SO_2	Sulfur Dioxide Gas
TWFA	Three-Way Factorial Analysis
UAN	Urea Ammonium Nitrate

Chapter 1 – Introduction

1.0 Canadian Soil Attributes & Soil Acidity

Since the start of agriculture in the middle east in an area called the Fertile Crescent around 10,000 B.C., there has been an increasing demand on cultivated soils, and the crops grown for food production, because of the world's growing population. This has led to the need for replacing and maintaining plant essential nutrients in the soils that are removed in grains and forages during harvest operations. With newer high-yielding varieties of crops that require more nutrients to grow, nutrients that were once naturally occurring from soil organic matter (SOM) are no longer a sufficient resource. As well as with soils being cultivated over the years, nutrients are slowly being depleted unless replenished from applying fertilizers. Soils often are under appreciated for the important ecological functions they perform due to the complex interactions of chemical, physical, and biological processes (Brady & Weil, 2008; Bridges & Van Baren, 1997).

First, it is important to discuss the soil order in Canada that this study was conducted on, the Chernozemic Order. This soil covers a vast majority of the Canadian Prairies, with a mean average annual temperature of 0 degrees Celsius to 6 degrees Celsius and usually experiences water deficit during the growing season (Soils of Canada, 2020). The soils developed in the parent material are soils of coarse sands through to fine textures of silts and clay loams (Soils of Canada, 2020). Other soil orders do exist amongst the Chernozems with some differences, like heavy clays for the Vertisolic Order and soils with higher sodium concentrations of the Solonetzic Order. The Chernozems are a very arable soil and excellent for crop production across the world. They are in middle latitudes in the northern hemisphere, occurring in Canada, Russia, and steppe regions in other Asia countries and for the southern hemisphere, Argentina (Soils of Canada, 2020).

There can be mismanagement of soils, and in this thesis, it specifically emphasizes the gradual acidification of the cropped soils; due to the continued use of ammonium (NH_4^+) based nitrogen (N) fertilizers (Figure 1.1). Soil factors also contribute greatly to soil acidification such as climate, minerals, parent material and texture. For example, soils with a higher clay content tends to have the Hydrogen Ions (H^+) bond with the clay colloids and build up reserve acidy. This is also known to be a buffer, which prevents the rapid change in soil pH. The soils in Western Canadian Prairies cultivated land tend to be more neutral to alkaline in pH, however this is beginning to change. The main cause is over the past 30 to 40 years of agriculture there has been widespread use of ammonium base nitrogen fertilizer, this is causing the soil to lower in pH. The two points in the process that leads to this is during nitrification when H^+ are released and when nitrate is leached from the soil (Figure 1.1). According to data in 1965 the consumption in Canada was 750,000 metric tonnes of N fertilizer (Contributions to Canada and the World: Canadian Fertilizer Industry). Currently these numbers have risen to 25,719,000 nutrient metric tonnes as of 2022 (Statistics Canada, 2023) (Table 1.1).

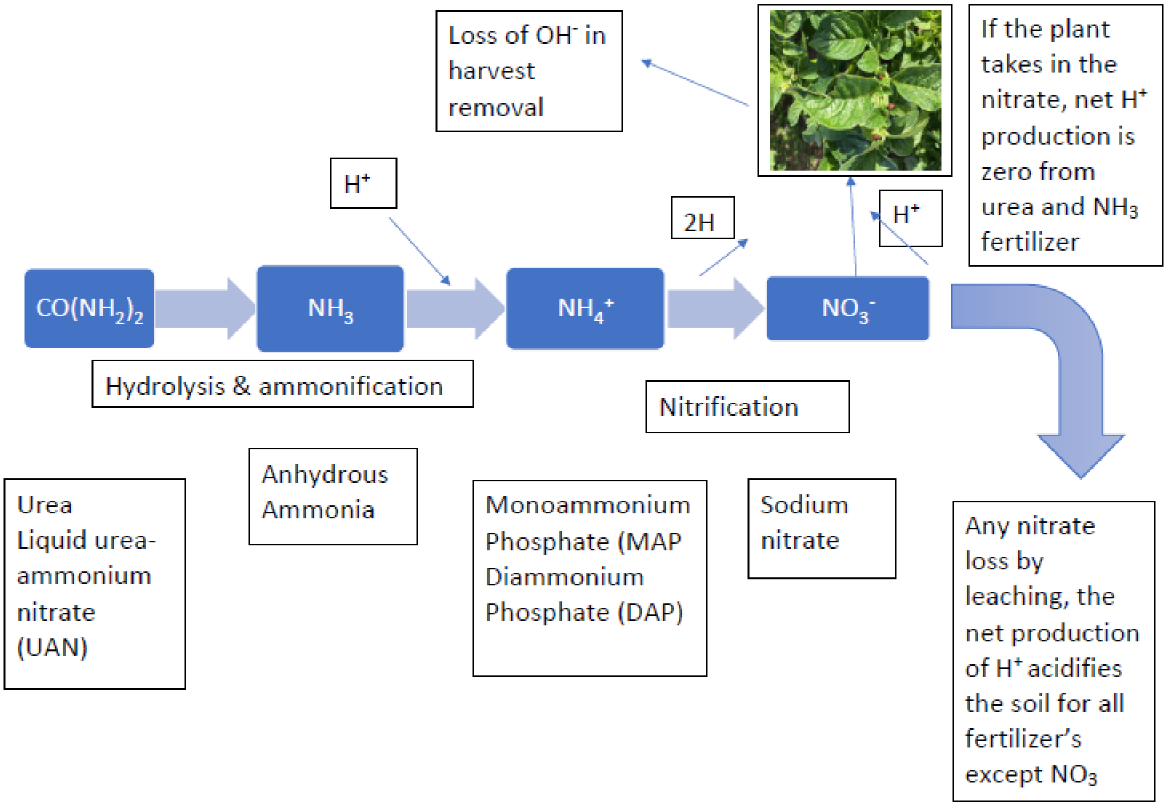
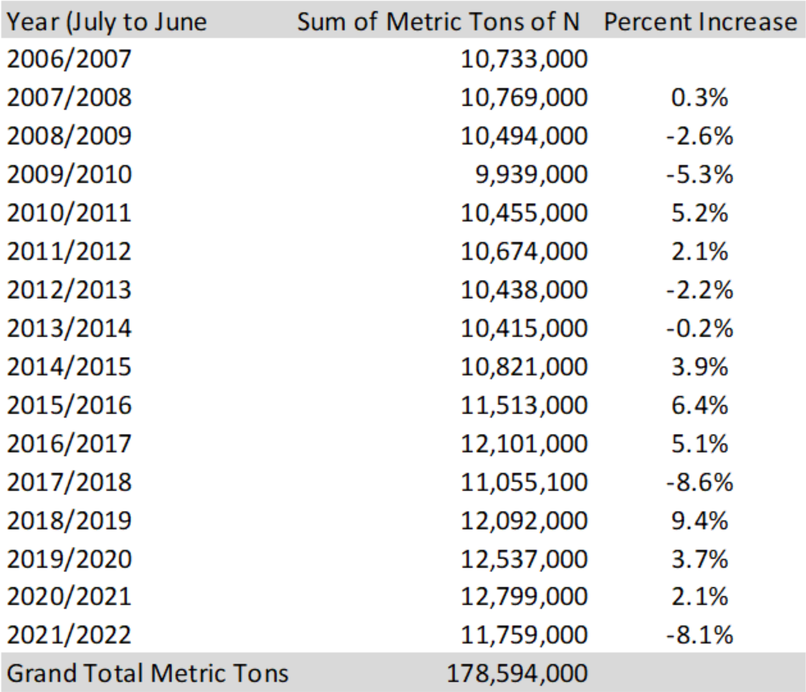


Figure 1.1: Illustration of the nitrification process and how its impacts may vary depending on crop intake of nutrients on soil acidity. (Adapted From Brady & Weil, 2008)

Table 1.1: Amount of N fertilizers used in the last 17 years, with percent increase from the year prior. Data sourced from Statistics Canada: Statistics Canada. (2023) Table 32-10-0037-01 Canadian fertilizer production, by product type and fertilizer year, cumulative data (x 1,000). (Last Accessed 2023) DOI: https://doi.org/10.25318/3210003701-eng



Year (July to June	Sum of Metric Tons of N	Percent Increase
2006/2007	10,733,000	
2007/2008	10,769,000	0.3%
2008/2009	10,494,000	-2.6%
2009/2010	9,939,000	-5.3%
2010/2011	10,455,000	5.2%
2011/2012	10,674,000	2.1%
2012/2013	10,438,000	-2.2%
2013/2014	10,415,000	-0.2%
2014/2015	10,821,000	3.9%
2015/2016	11,513,000	6.4%
2016/2017	12,101,000	5.1%
2017/2018	11,055,100	-8.6%
2018/2019	12,092,000	9.4%
2019/2020	12,537,000	3.7%
2020/2021	12,799,000	2.1%
2021/2022	11,759,000	-8.1%
Grand Total Metric Tons	178,594,000	

Soil acidity will be discussed in detail, from its causation to its effects on nutrient availability, soil organisms, and the impact on crop production. This will lead into what are the current methods in coping with acidified soils and what the potential of remediation going forward can be. Furthermore, research was undertaken to determine what are the most efficient ways of raising these pH levels and more accurate ways of determining these soil pH variations throughout fields. Soil being a complex medium, there are various aspects to consider from the abiotic influencing factors as well as the numerous biotic components in the soil. Both components are vital to their own aspect, however for this study the abiotic is the most important aspect. Since it is the mineral N fertilizer source that is a main cause of the acidification. The lime to ameliorate it is also a mineral source. The abiotic factor which would play a role is the rate and the minerals in the N cycle, whereas the biotic role comes in during the cycle converting over different forms of N in the soil. Also, how these soil attributes are vital to the impacts they have on the plants. Therefore, it is important to establish an understanding of how soil acidity affects soil processes, microbial populations, and common crops in the western Canada prairies.

1.1 Soil Acidification and Low pH Effects on Crops

Soil pH is the measurement scale of the hydrogen ion (H^+) concentration of the soil solution, and whether it has an alkaline, neutral, or acidic pH. The definition of pH alone is minus the log to the base 10 of H^+ ion concentration in a solution, it is expressed as a scale from 0 to 14. A pH of 7 is considered neutral, below 7 acidic, and above 7 is alkaline. Soil reaction is the pH value of the soil solution within a soil. Each change of one pH unit in a soil is a ten times increase or decrease in the concentration of H^+ ions in soil solution. So, a pH of 4 has ten times the concentration of H^+ ions compared to pH 5. Application of primarily ammonium-based nitrogen -fertilizers used in growing crops as resulted in soil acidification that can eventually result in a decline in crop productivity (Ghimire & Bista, 2016; Porter et al., 1980).

The impacts on crops of soil acidity varies, as some crops are more tolerant to the lowering in pH. For instance, a pulse crop like lentils do not tolerate lower pH, whereas a canola crop can be a bit more tolerant of these changes, and to timothy grass hay which can grow successfully in an even lower pH. Differences in soil pH, i.e., alkaline, neutral, or acidic, result in specific elements being more or less soluble in soil moisture solution. Meaning there are some nutrient elements that become less available under acidic soil pH levels. While in contrast, other elements can increase in solubility making them more available to crops, and in some cases become toxic in concentration, i.e., manganese, aluminum, or iron under acidic soil pH below or lower than pH 5.5. It is important to note that this gradual acidification also occurs by natural soil forming factors. For example, different parent materials that soils form in can be naturally more acidic, neutral, or alkaline in nature.

Two other factors are the climate, and the original native vegetation present. For example, as the needles from coniferous trees in the leaf litter layer above soil mineral layers in forest soils decompose organic acids are released, these acids leach down into the mineral parent materials below, this contributes to gradual acidification. Also, as precipitation infiltrates and leaches down through soils, base cations, i.e., calcium, magnesium, potassium, can leach down and out of the soils and to be replaced by H^+ on soil colloidal surfaces. Generally, regions of higher precipitation and greater vegetative growth tend to have a lower and more acidic pH. As a result of the organic matter, water and carbon dioxide reacting, the biproduct is a weak acid known as carbonic acid. Natural ecosystem acidification of soils can take hundreds of years to occur. Humans may also choose to actively acidify soils by the addition of soil amendments, for example a fine particle size elemental sulfur. This is to benefit certain crops that grow well in acidic conditions, for example blueberries prefer soil pH levels from 4.5 to 5.5. Considering different ecoregions in Canada, the Northern Boreal Forests for example. When it was cleared for farming, these regions tend to have more neutral or acidic soil pH values, in comparison to the southern prairies of western Canada.

The grassland ecosystems are initially alkaline in soil pH, having developed on glacial and or glacial meltwater parent materials containing weathered limestone parent materials, as well as being enriched in carbonates of calcium and magnesium when atmospheric carbon dioxide (CO_2) dissolved into the cold periglacial meltwaters and reacted with dissolved calcium and magnesium cations in the parent materials and precipitated out of soil solution (Inverse, 2019). However, one land formation in Alberta and in Saskatchewan was not covered by glaciers in the last ice age, and not formed by the run-off that followed and that is the Cypress Hills. During the last glaciation maximum, the ice went up to the Cypress Hills and carved the landscape surrounding it.

More importantly, in the context of this research, most soils are acidified by the on-going use of ammonium-based N fertilizers. Most N fertilizers used in commercial agriculture are ammonium based (Mosaic Fertilizer Technology Research Centre, 2013). Ammonium-based N fertilizers include urea, anhydrous ammonia, and the ammonium-N portions of ammonium sulfate and ammonium phosphate. The latter two fertilizers are added primarily as sulfur and phosphorus nutrient sources but do contain 21 and 11 percent N in the ammonium form. This gradual acidification is the result of a microbial process called nitrification. The ammonium ions from the dissolved fertilizers, noted above, are oxidized first to nitrite (NO_2^-) and then to nitrate (NO_3^-) and H^+ ions are released into soil solution during these N transformations. There is a release of two H^+ ions per molecule of urea, and three H+ from each molecule of anhydrous ammonia, and four H^+ ions from the molecule of ammonium sulphate. The rate of H^+ ion release to agricultural soils can be reduced by including N-fixing pulse crops such as lentils or field pea in crop rotations with small grain cereals and oilseed crops. This reduces the amount of ammonium-N fertilizer applied over a cycle of crop rotation (Cothren, 2014). However, this may vary if the entirety of the nitrate is leached down and out of the soil versus if some of it is taken up by the plants in the ammonium form before nitrification (Figure 1). The amount of nitrification causing the acidification can be reduced if crops absorb more ammonium-N relative to nitrate-N (Mosaic Fertilizer Technology Research Centre, 2013). In contrast if the N-fertilizer is already in the nitrate form, e.g., calcium nitrate Ca $(NO_3)_2$, it will not contribute to soil acidification (Giesseler & Scow, 2014).

In Northern Idaho and Eastern Washington people have become more aware of a trend of decreasing soil pH over time (Mahler et al. 2016). This landscape such as ours, has a remarkably similar history, current conditions, and drier climate. Where we are east of the Rocky Mountains, they are east of the Cascades, creating a similar climate. Also, like the Canadian Prairies, that area experienced glaciation from the Cordilleran Ice Sheet and a flooding event known as the Missoula Floods (Washington State Department of Natural Resources, 2024). As soil acidification affects element solubility there are certain plant nutrient elements that become less or more available (Figure 1.2). Also, certain microorganism groups thrive better or not (Geisseler & Scow, 2014; Zhalina et al., 2015), and there is reduced root growth for most crop plant species (Ghimire & Bista, 2010). Most notable is that low pH can negatively impact symbiotic bacterial activity. In legume crops, it reduces nodulation by *Rhizobia species* bacteria and can result in N deficiency along with the associated red coloring on legume stems, petioles, and chlorosis (yellowing) of the oldest leaves. Some of these older leaves become necrotic (die).

The main amelioration strategy for excessively acidic soils, e.g., < pH 5, is application of fine particle size agricultural lime ($CaCO_3$) to neutralize the acidity, which is a quite common method around the agricultural world. The gradual increasing problem of soil acidification in the Canadian Prairies is from intensive agriculture growing of high yielding crops that need higher rates of ammonium-based N fertilizers. This practice has been happening for the last four decades which has led to our once neutral to alkaline soils to slowly acidify. It can require from a few to close to 20 tonnes of agricultural lime per hectare to raise an acidic soil pH in the pH 4.5 range to a target level of pH 6.5, depending on soil properties of soil texture and organic matter content. From an agricultural management viewpoint soil with a pH range from 6.5 to 7.3 are considered to have neutral pH values. Most neutral pH soils have adequate nutrient availability, resulting in good nodulation on legume pulse grain crops such as field peas and lentils, and the legume forage crop alfalfa. Lime applications to remediate acidic soils up to a neutral soil pH have also been shown to be effective for reducing the risk to a crop root disease called clubroot, on canola fields (Donald & Porter, 2009). This yield reducing disease is an increasing concern in very acidic to slightly acidic soils, e.g., pH 4.0 to 6.0, in western Canada.

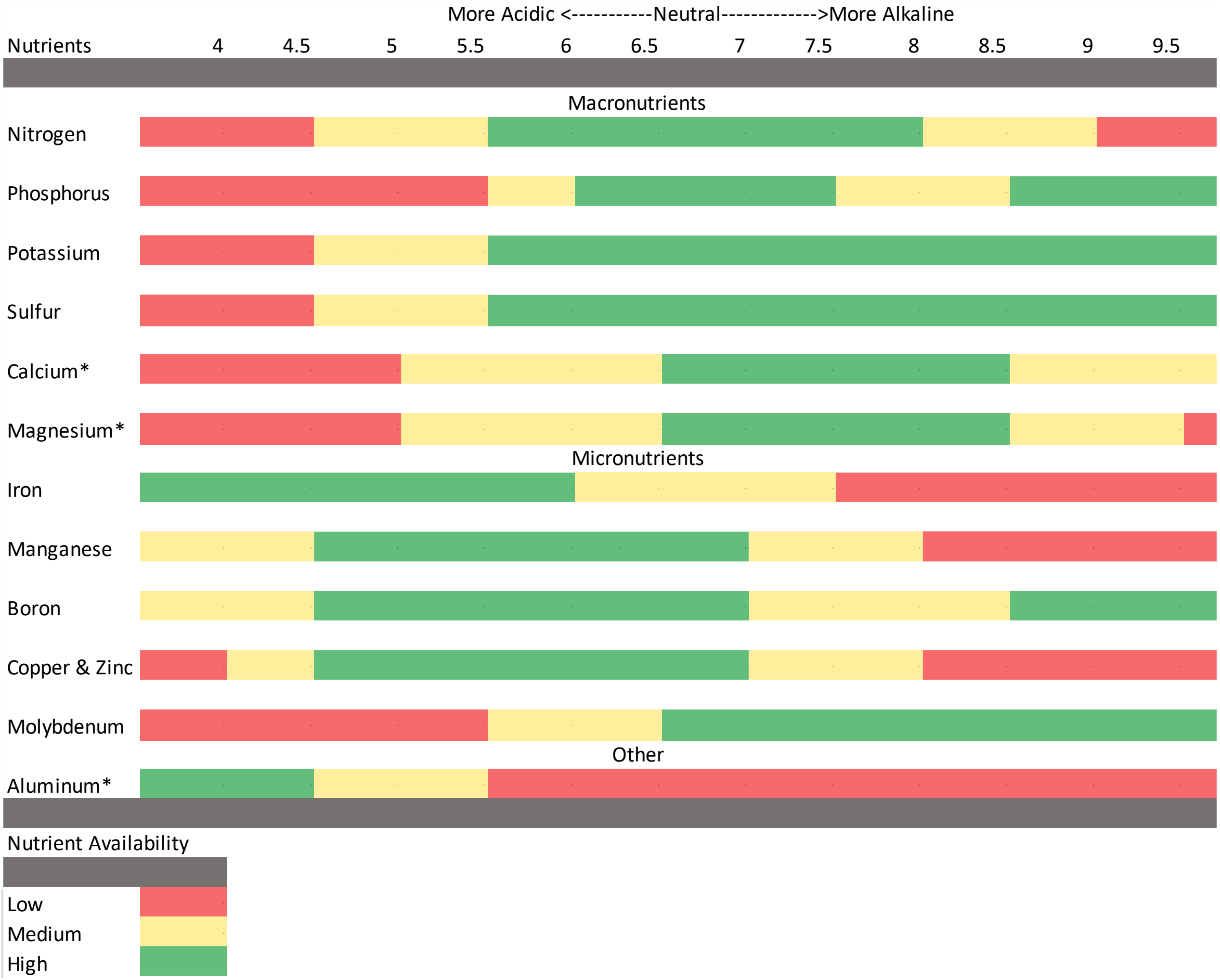


*Figure 1.2: Nutrient availability in differing soil pH conditions. Adapted from Soil Fertility Manual, The Fertilizer Institute Updated 2019. *Aluminum – Not a micronutrient but is detrimental to crops in low soil pH because of its toxicity.*

1.2 Geographic Information System (GIS) and Precision Agriculture

GIS is a versatile tool used whether it be for research applications or commercial needs. This research study includes the use of applying existing GIS methods for soil data gathered in the field and applying it using GIS software to be able to better assess spatial soil pH variability. Data gathered in field is used widely across precision agriculture to gather and apply a range of information and application treatments to agricultural fields. From improving on and advancing the characterization of agricultural productivity based on biophysical attributes of crops and/or soils (Liaghat & Balasundram, 2010). Precision agriculture is a practice established decades ago but is extremely important as it helps crops perform at a higher level and as well as improve environmental quality (Pierce & Nowak, 1999).

1.3 Soil Variability

Soils are extremely variable within the environment as affected by the soil forming factors influencing its composition and structure (Canadian Society of Soil Science, 2020; Jensen, 2018). Climate, parent geological material, organisms, topography, and time, are all-natural factors that influence the development soils. Also affecting agriculture soils are anthropogenic influences, and they are not always an improvement. As such, even with detailed mapping of soils throughout landscapes, soil variability and composition cannot be assumed to be uniform or accurately described by 1:50,000 scale soil survey maps of municipalities. However, agricultural areas can be described with a general description of averaged details over these scales. But any further detail requires further field work and data gathering.

1.4 Benefits of Lime on Soil

Adding an appropriate rate of agricultural lime to a soil can raise a low soil pH to a more neutral soil pH. Applications typically are done every 5 years (Michigan State University, 2015). This re-treatment is typical in the United States, but for the Western Prairies in Canada, liming has not been common. So, the time interval may vary and would likely be a couple years longer than the United States since we have lower yielding crops and shorter growing season, which would slow down the acidification process. Once the lime is applied to the soil, crop growth may improve initially if calcium is low in availability by dissolved calcium ions (Ca^{2+}) coming from smaller particles of lime and being absorbed by crop roots. The larger particles of lime ($CaCO^3$) dissolve at a lower rate which allows it to react with the soil over time, lime applications are repeated as needed. There are many benefits to liming the soil as it improves levels of availably of many needed nutrients and reduces toxicity of excess solubility of ions of aluminum (Al^{3+}), manganese (Mn^{2+}), and iron (Fe^{3+}) that can be adverse to root growth and function. The overall goal is to improve crop growth and yield and provide a return on investment in the limed farm fields.

1.5 Summary

The task of assessing and treating soil acidity needs accuracy to apply sufficient but not excessive rates of lime. This is most effectively done by accurately determining pH variability over a field, and only applying lime to the overly acidic areas. Over application of lime can induce nutrient deficiencies of elements that are less soluble at alkaline soil pH values, e.g., zinc (Zn), which has an increased adsorptive capacity by clay materials (Zinc: Nutri-Facts), and soluble phosphorus (P) which reacts with the increased calcium, precipitates out of soil solution and becomes less available to crops.

1.6 Research Objectives

The first objective of this study was to find an excessively low pH area in each of three cultivated fields and establish research plots for identifying effective lime application methods. Then apply a pre-calculated rate for each individual soil on rainfed agricultural fields of the Chernozemic Soil Orders, representing the Brown, Dark Brown, and Black Soil Zones. To accomplish this, fields thought by the cooperating farmers to have excessively acidic areas were assessed for spatial variability of soil pH. This was to ensure there was acidic soil areas in the fields to be candidates for treatment with lime.

The second objective of the study was added when other growers heard what research was being conducted at the Sierra, Hilton, and Kings Lake field research sites, and wanted to be a part of the research. Due to the lime application plots already being established at the first three sites and limited time to evaluate liming treatment effects, there was only grid soil sampling done on the other farms. Three more farms were added, the Bashaw, Haenni and Miller farms, which are all located in south-central Alberta. These additional fields allowed further assessment of spatial variability of soil pH at more farm fields, and whether variable rate lime applications could be feasible.

Chapter 2 – Literature Review on Soil Acidity

2.0 Soil Acidity Effects on Nutrient Availability

Regarding soil pH, whether it be more alkaline or acidic, has a substantial influence on nutrient availability for plants. For example, more acidic soils allow for plants to uptake the following nutrients in greater amounts: Iron (Fe), Boron (B), Copper (Cu) and Zinc (Zn). Whereas nutrients; Nitrogen (N), Potassium (K), Phosphorus (P), Sulfur (S), Calcium (Ca), Manganese (Mn) and Molybdenum (Mo) become less available or even to the point where it is not accessible to the crop. When there is an increasing amount of acidification occurring, crops less tolerant to low soil pH will have restricted growth and yield poorly. There are different alternatives that may be used to either prevent, remediate, or accommodate these changes. First, there are crops that can tolerate these changes or prefer the more acidic soils. Flax (*Linum usitatissimum*), a crop grown in the southern Prairies of Canada, it has a preferred pH level for growing of 5.0-5.5 (Dmitriev et al., 2019).

With the changes in soil pH there are other impacts that occur to affect the crops indirectly. One is how soil microorganisms are impacted by increasing soil acidity. For example, fungi can tolerate lower pH or acidity levels whereas, bacteria thrive in more neutral to slightly alkaline pH levels (Cheng et al., 2013). Additionally, the reduction of crop yields, can be attributed to the negative effects experienced by specific microorganisms when the pH drops below 5 (Geisseler & Scow, 2014). This is a result of denitrification efficacy being affected because of the soil pH change (Anderson et al, 2018). Aside from pH lowering from fertilizer use over time and natural pH change, there are methods of acidifying a soil with elemental sulfur, for example which can be done intentionally if a crop is needing lower pH or if the soil is too alkaline.

Since soil pH has a great influence on soil nutrient availability in crops, it is important to understand how much and how quickly pH is changing in agricultural soils in southern Alberta and Saskatchewan. This will help understand why it is important to understand and be aware of how crops are affected and the influences and interactions of nutrients in the soil. The Fertilizer Institute provides informative data on the current trends of soil pH, and for this example the data will be from Alberta reported ranging from the years 2000 to 2020. In the years 2000, 2005, 2010, 2015, and 2020 there were respectively 28,855, 35,960, 38,530, 59,958, and 36,271 soil samples included in soil test summary reports. The data observed will range from pH interval values of less than 5.0 (Figure 2.1), 5.1 to 5.5 (Figure 2.2), 5.6 to 6.0 (Figure 2.3), and 6.1 to 6.5 (Figure 2.4).

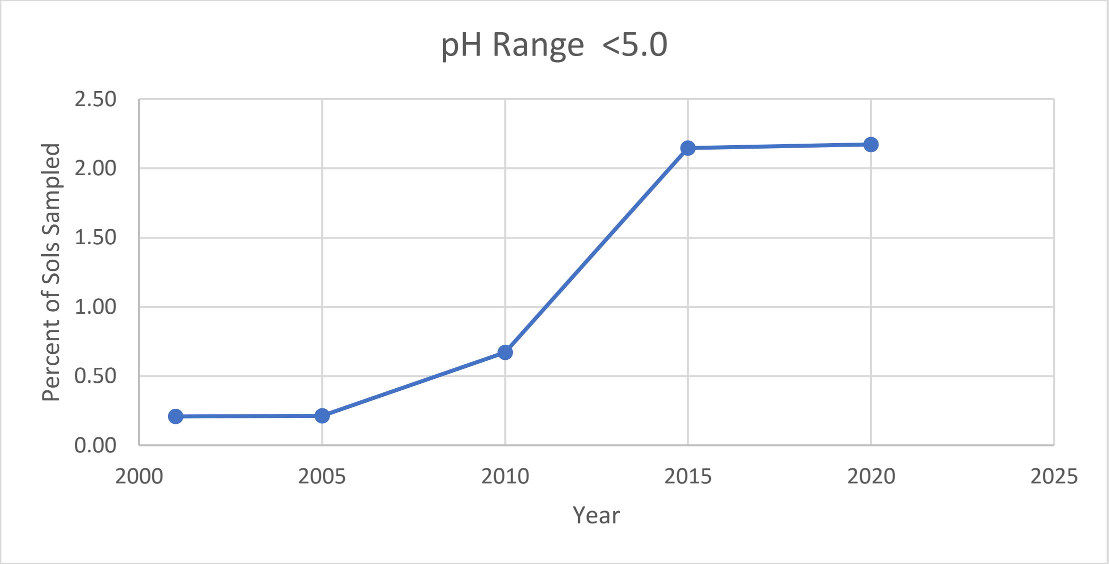


Figure 2.1: The percent soils samples with a pH of less than pH 5.0 increased from 0.21% in Year 2001 to 2.17% in Year 2020, Alberta, Canada. (Data retrieved from The Fertilizer Institute, 2023)

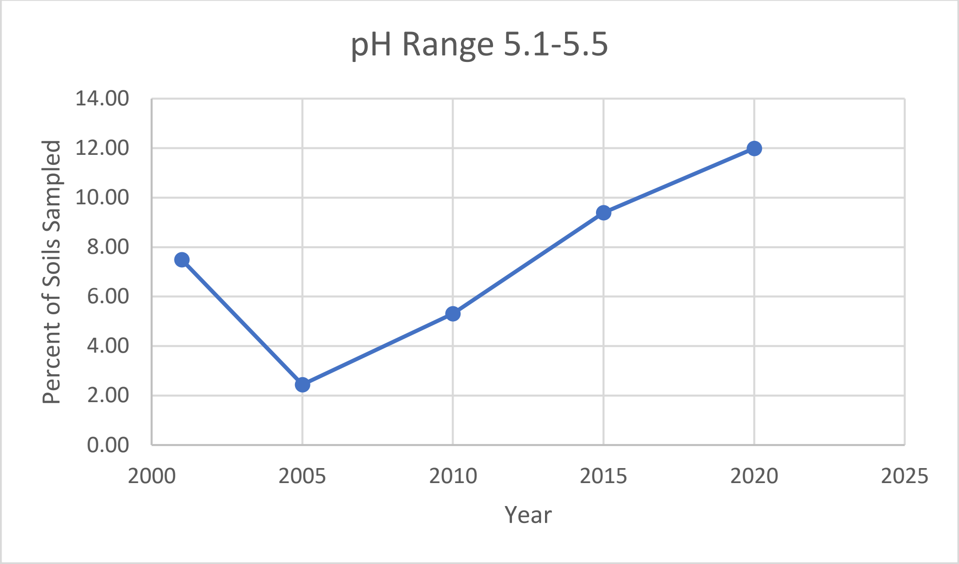


Figure 2.2: The percent soils samples with a pH range of 5.1-5.5 increased from 7.49% in Year 2000 to 11.99% in Year 2020, Alberta, Canada. (Data retrieved from The Fertilizer Institute, 2023)

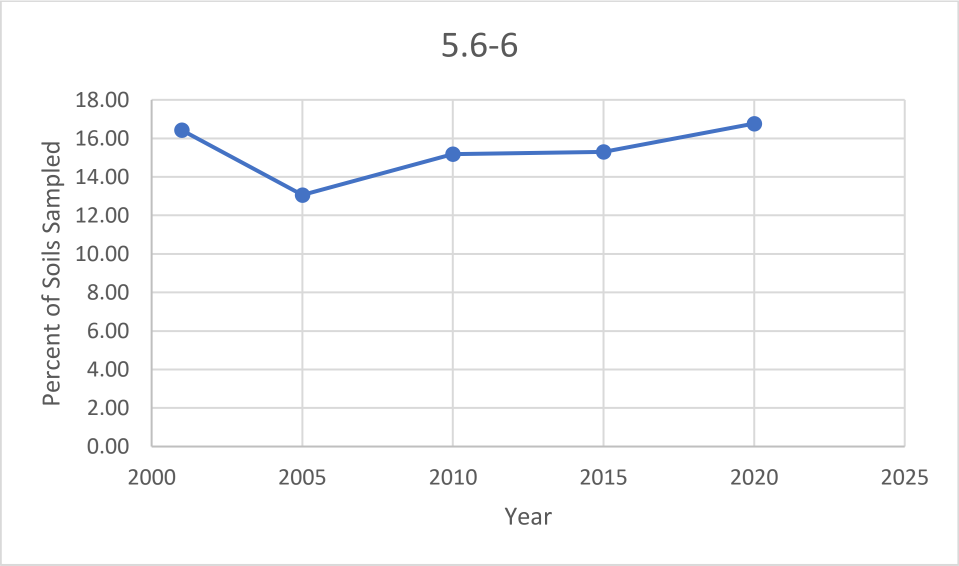


Figure 2.3: The percent soils samples with a pH range of 5.6-6.0 remained similar with 16.42% in Year 2000 to 16.42% in Year 2020, Alberta, Canada. (Data retrieved from The Fertilizer Institute, 2023)

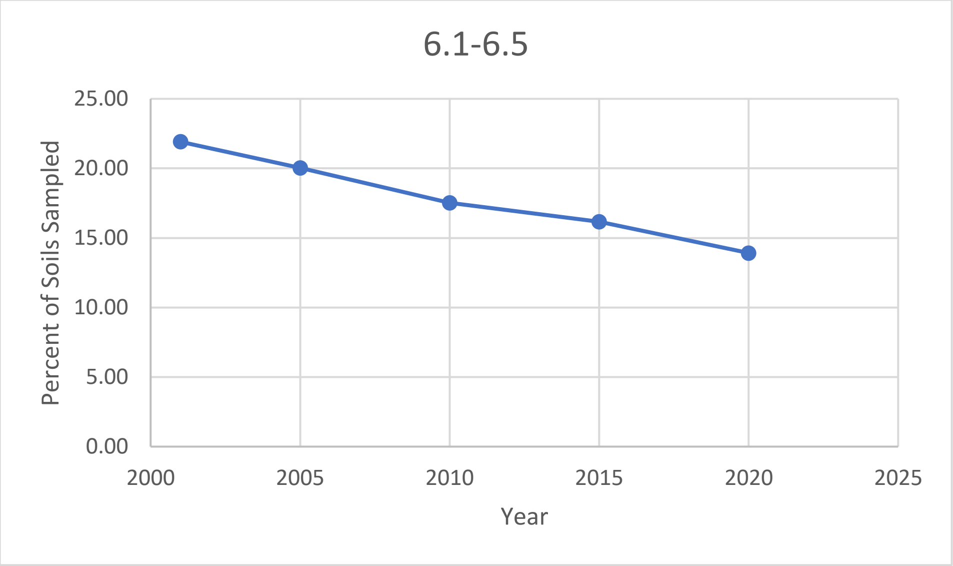


Figure 2.4: The percent soils samples with a pH range of 6.1-6.5 decreased from 21.91 % in Year 2000 to 13.92% in Year 2020, Alberta, Canada. (Data retrieved from The Fertilizer Institute, 2023)

By assessing the data reported here and displayed, there is a noticeable trend of the two lowest pH ranges, i.e., less than 5.0 pH and 5.1 to 5.5 pH that are increasing over the last two decades. The pH range of 5.6 to 6.0 is fluctuating but staying relatively the same size, with this range being on the somewhat acidic but still allowing crops to grow healthy. Lastly, the only slightly acidic range 6.1 to 6.5 pH has decreased in size. Taken in entirety this indicates that soils are acidifying over time and will influence crop growth and nutrient availability in soils.

2.1 Effects of Soil Acidity on Crops

2.1.1 Cereals

The most common small grain cereal crops in Western Canada are wheat and barley which will be the focus for the discussion about cereals. Cereals, for example, do have negative responses to acidic soils. Mainly, they are sensitive to Al^{3+} ion toxicity, and to a lesser extent Mn^{2+} ion toxicity. Both elements become more soluble the lower the pH (Dolling & Porter, 1984). However, there are techniques to add or keep barley and wheat in rotation. This is done by raising the pH to the less acidic levels or growing selected varieties that are more tolerant to mildly acidic soil pH. For instance, Al tolerant barley could grow better in acidic soil compared to non-Al tolerant barley. But this solution is recommended for shorter term fixes and not considered a permanent solution. Another temporary measure to combat these effects is banding P in the seed furrow because it will reduce P reaction with both Al and Mn, precipitating out of soil solution as a less soluble particles (Zhang et al., n.d.). These precipitated Al and Mn-phosphorus compounds will inhibit the toxicities of the Al and Mn in a small zone around the germinating seed and emerging seedlings, this can marginally improve crop yields.

2.1.2 Canola

Canola is an oilseed cash crop that can be grown in a rotation around every 3 years. It is not recommended to be grown year after year in the same field as insects, diseases and weeds begin to build up rapidly. Canola is a widely grown crop in western Canada and as such, the effects of acidity on the crop should be understood. A canola crop in a rotation is somewhat tolerant too more acidic soils compared to the small grain cereals. Typically, canola will start showing an impact on yields when the pH drops below 5.5 (Canola Encyclopedia, 2020), then there are observable benefits of applying lime to raise the soil pH. Soil remediation by having higher pH will result is improved yields. Also, there can be reduction of the growth and infection by the clubroot disease causing microorganism (*Plammodiophora brassicae)* that is less virulent in more neutral to alkaline soil pH conditions. Canola can yield well on soils with a pH of 5.6 to 6.5, but additional liming to raise the soil pH to near 7.0 to 7.3 will further reduce clubroot infection.

Very acidic soils, i.e., < 5.5 pH, will have characteristic effects on canola caused by toxic levels of H^+, Al^{3+}, Fe^{3+}, and Mn^{2+} toxicity, and deficiencies of Ca, Mg, K, P, Bo, N and Mo (Canola Encyclopedia, 2020; Figure 1.2). In figure 1.2, as the pH lowers to a level of 5.5 as noted in the figure, there are significant changes in nutrient availabilities. There is also a reduction in the rate of crop residue decomposition and reduced nutrient uptake by plant roots attributed to the impediment of root growth and lower levels of available nutrient cycling accomplished by many soil microbe species under acidic soil pH levels (Canola Encyclopedia, 2020).

2.1.3 Pulses and Legumes

The pulse crops such as lentils, chickpeas, and field peas, and the forage alfalfa are the most common legume crops grown in western Canada. A pulse crop is a crop in the legume family, they also have N-fixing capabilities. Much like other crops; legumes react adversely to acidic soils, resulting in a negative impact on growth. Primarily it is the Al and Fe toxicities that influences these crops to have restricted root growth (Negusse et al, 2022), additionally the acidic environments also adversely affect the symbiotic bacteria (e.g., *Rhizobia species*) needed for nodulation and N fixation. The symbiotic bacteria transform dinitrogen gas (N_2) to plant available ammonium ions (NH_4^+). Which happens when N_2 + Water reacts to form NH_4^+ as biochemically mediated by bacterial enzymes. This lower accessibility of ammonium to legume crop plants ultimately leads to lower plant vigor, lower N-fixing potential, resulting in a reduction in crop growth in areas of more severe acidity, e.g., <pH 5.5. Moreover, with these effects, pulses become more susceptible to other environmental stresses: colder temperatures, excess moisture, compaction, and some potentially residual herbicides.

2.1.4 Root and Tubers

The root and tuber crops that are commonly grown in western Canada are: sugar beets, onions, and potatoes. These crops have a broad range of tolerance to the effects on soil pH conditions. Potatoes grow best on mildly acidic soils (pH 6.0 to 6.5), onions on soils with a pH of 6.0 to 7.0, and sugar beets grow best on neutral soils (pH 6.5 to 7.3). Therefore, the group generally does well on slightly acidic to neutral pH soils If these crops are a part of a crop rotation it would be beneficial to raise the pH of an acidic soil to a more neutral level.

2.1.5 Solutions to Adverse Crop Effects

There has been mention of solutions for soil acidity to improve on crop production (Zheng, 2010). For instance, temporary solutions that may be considered if lime is unavailable at the current time or is just too expensive to acquire. Include growing more acidic soil tolerant crop varieties such as Flax, Al tolerant varieties of cereal crops, placing P fertilizer in the seed furrow to tie up the Al enough to reduce Al toxicity during the seedling stage of the affected crops (Zheng, 2010). The more long-term solution is to treat the problem areas in the field with lime. It is useful to take preventive measures to ensure it does not happen again or to reduce increasing the issue as much as possible. For example, not overapply the ammonium-based N-fertilizers that caused increased acidification over time, by taking grid soil samples over an entire field and produce variable rate lime maps and only apply the lime where it is needed and reduce the chance of causing the soil already neutral or slightly alkaline soil pH areas to become excessively alkaline. Calcitic lime ($CaCO_3$) and dolomitic lime ($CaCO3\ MgCO_3$) are the most common liming materials (Michigan State University, 2015). Another alternative liming material can be wood ash from the lumber industry if it is available locally in more northern prairie soils, e.g., Dark Gray Chernozemic, and Luvisolic soil near or within the Boreal Forest regions.

2.2 Macronutrients and the Effects of Soil pH

The macronutrients include nitrogen, phosphorus, potassium sulfur, calcium, magnesium, and sulfur. Macronutrients in soil are needed in greater quantities, for example that are plant available of around 1000 parts per million (PPM) (RX Green Technologies).

2.2.1 Nitrogen

Nitrogen (N) is one of the most important nutrients in the world for agricultural crops and in extension all plant types for all soil agroecosystems. N fertilizer is primarily manufactured through the Haber-Bosch process which takes hydrogen gas (typically from natural gas or methane) and atmospheric N to make ammonia, which is the first step to then produce other fertilizers like urea (Appl, 1997; Fertilizer Canada, 2021). With the world's population increasing and a rising demand for crops, it is important to have sustainable management and use of this nutrient. N is a vital part of all proteins and deoxyribonucleic acid (DNA) in plants and animals (Lal & Stewart, 2018). It is beneficial to ensure the correct amounts of N are available in the soil and to apply adequate but not excessive rates. The addition of N can be done using inorganic N-fertilizers, growing legume crops in rotation, and application of livestock manures or municipal biosolids. It is important to realize that there are natural N contributions in precipitation when N_2 gas in the atmosphere is oxidized by electrostatic lightning discharges to form NO_2 that subsequently is absorbed by condensing moisture and forms dilute nitric acid (HNO_3) in the rain. This is a low rate of natural fixed N, e.g., an average of 1.2 kg N/ha (Bala et al., 2013). Before understanding the impacts of N, its cycle should be discussed.

N has various ways that it interacts with the environment in its cycle. There are three main methods by which N enters the soil environment: protein containing organic material decomposition, N fertilizer, and N fixation from legume crops (University of Missouri, 2022).

The most common way of adding N to farm soils organically is livestock manure being spread and incorporated into soils. Many farmed soils however, especially on grain farms with little to no livestock, receive applications of inorganic manufactured N fertilizers such as dry granular urea (46-0-0), pressurized liquid anhydrous ammonia (82-0-0) and non-pressurized liquid urea ammonium nitrate (UAN) (28-0-0). N-fixation is when atmospheric di-nitrogen gas (N_2) is converted to a plant available form, usually ammonium (Appleby, 1984; Wagner, 2011). This occurs primarily by bacteria capable of causing this process, these are known as symbiotic bacteria and a common species known are *Rhizobia*. These live in the nodules of legume plants, but there are other free-living soil bacteria species capable of this process.

Fertilizer analysis numbers indicate N-P-K percentage in weight. For example, a 100-kilogram (Kg) bag of urea (46-0-0) would mean 46% is N (0.46x100 Kg = 46 Kg is N). This is done for both natural source and manufactured fertilizers. There are microorganisms that convert ammonium-N ($NH_4^{+)}$ to nitrite-N ($NO_2^-)^-$ and then to nitrate-N (NO_3^-), this is done by different soil bacteria species (Appleby, 1984; Wagner, 2011).

Another part of the cycle is the loss of N by denitrification when facultative microorganisms that use oxygen (O_2) gas as part of respiration during aerobic soil conditions of necessity use NO_2^- and NO_3^- as oxidizing sources under anaerobic conditions. Anaerobic soil are saturated soils (Wang et al, 2021). This denitrification converts NO_2^- and NO_3^- to gaseous forms of N, primarily N_2 gas, but a portion 0.5 to 5.0 %, depending on soil moisture conditions, can be nitrous oxide (N_2O) one of the contributing greenhouse gases. Additionally, there are surface runoff and leaching losses of soluble N out of the soils caused by various factors, this can contribute to eutrophication in water ecosystems. One other important process in the N cycle is nitrification when soil microbes decompose proteins and amino acids from plants, microbial and soil animal residues to ammonium. The ammonium ions can be used directly by plants but the majority of N in well-drained soils is converted to plant available nitrate-N, as mentioned above.

The addition of N to soil has numerous benefits for plants. Along with other nutrients, N is an important part of the chlorophyll molecule in plants. This gives plants a healthy green colour and is vitally important for photosynthesis; allowing the plant to convert CO_2 gas in the atmosphere into sugars initially and then later build cellulose, and other plant structural components. Even more so, N is a main component for plant protoplasm, a clear substance that is part of cells. In plants N is needed for quick shoot growth, budding of the flowers and in the end improve on the quality of the seed. Sufficient N availability in soils is important for plant growth. There are various methods for how N is applied and the types of N that are used. This is all based on assessment using soil and plant analysis prior to any supplemental N applications, to determine the most suitable form, rate, timing, and placement of the N-containing material (Government of Saskatchewan).

N is the main limiting growing factor for plant species and is essential for all living organisms, making it vital for all ecosystems (Bolin & Arrhenius, 1977; Rütting et al., 2018). Synthetic N fertilizer manufacturing has allowed the agricultural industry to expand to produce an estimated twice as much available food as previously (Ritchie, 2017). But as with many crop inputs, overuse can contribute to some negative effects: eutrophication of waters, loss of biodiversity, global warming, and stratospheric ozone depletion (Rütting et al., 2018).

There are also soil chemistry effects being noticed like the acidification of western Canadian fields (Figure 3.1). This occurs when N fertilizer like urea, anhydrous ammonia and other sources containing ammonium-N are applied to soils. This process occurs by microbial nitrification, where the hydrogen ions from the ammonium ions in the dissolved fertilizer are released into the soil gradually contributing to soil acidification. Therefore, it is beneficial to have soil sampling and analysis done on fields, and then have variable rates put down, so that only adequate but not excessive rates of N are applied. This doesn't stop soil acidification but slows it down.

N deficiency is notable for causing poor plant growth as well it can be one of the causes of turning the plant to a faded green or yellow colour, called chlorosis. Specifically, it means the leaves are turning chlorotic as N is very important to produce chlorophyll. Same with deficiency, toxicity is also extremely noticeable. It causes the plants to have much darker than usual green colour and to show signs of dying leaf tips or necrosis. N toxicity can also turn leaves yellow like N deficiency, but this is due to too much N and the reduction of other nutrients. Further proving why soil and plant testing, and variable N rates in fields are important, not just for N but other nutrients as well.

2.2.2 Phosphorus

Phosphorus (P) is one of the main nutrient sources for plant life around the world and is essential for adenosine triphosphate (ATP) as the energy and fuel for biochemical reactions in a plant cells. With P playing an essential role in photosynthesis and other plant forming factors, it is critical for the health and vigor for all plants (Mosaic, 2020; Balemi, & Negisho, 2012). Phosphate rock is dominantly a sedimentary rock containing elevated levels of phosphate minerals. P is an interesting nutrient since it is heavily recycled through animals, humans, and plants (Earth Institute, 2019). However, P can become an issue by being released into the environment in excessive amounts through various methods. First, rain events or snowmelt can remove soluble P from the surface of the soil and out of plant residues and leave a field in run-off to surface water bodies (Reid et al., 2018).

In an agricultural setting this could be reduced by banding the P fertilizer into the soil and not conducting a surface application. Another is if the P sorption of the soil is at the maximum, P can be released into the surrounding environment (Reid et al., 2018). Naturally, P would be reintroduced back to the soil by spreading manure or by the decomposition of plant material, which would mean P would be on or close to the soil surface. Therefore, proper amounts of manure should be spread evenly over fields and incorporated using tillage, if possible, to reduce environmental risks. With the increase of natural land being converted to agriculture and the biomass being removed this also removes the P that would be naturally returned to the soil. Therefore, P is applied by farmers onto fields to avoid P deficiencies.

P is sourced from phosphate rock deposits mined from the Earth as it formed over millions of years in the Earth’s crust, these rock phosphate P forms are chemically processed and converted, primarily using sulphuric acid, to readily available and soluble P forms. (Ruttenberg, 2003)

The P cycle is important to know as it is crucial to understand how P moves through the environment from the ground to plants, as there is a limit of how much P can be in the soil until it begins to leech out to surrounding environments. P has various amounts of movement from its inorganic forms and organic forms. To being absorbed into plants, animals and back to the soil. Microbes, specifically phosphate solubilizing microbes are a key part of the cycle, as they turn these different forms of P into a soluble form of P that can be assimilated by plants (Kalayu, 2019). Once taken in by plants, P remains there until it is either harvested or dies off. Then the plant residue decomposes, and P is released back into the soil. However, for P to be available in the first place, it has had to go through a global cycle to get there. There are four main components of this global cycle; it first started with the uplifting of tectonic plates and thus revealing minerals containing P. This allowed for there to be physical erosion like water erosion and glacier movement. Followed by the chemical weathering of rocks which breaks down the P containing minerals to release soluble P to developing soils. With these changes occurring, there was a lot of transport of P to lakes, rivers, and oceans by surface run-off. This results in P accumulation in sediments, these sediments form sedimentary rock, and the cycle repeats.

P undergoes many processes, and the cycle is not always beneficial. What happens to the plants remains is what determines where the P will end up. Because near the end of an annual crop plant's life cycle, most of the energy is being used for flowering and seed pod production, P tends to be concentrated in seeds and fruit. If this is harvested and removed there is a net removal of P, and it is removed spatially from the local ecosystem. There is little P in the stubble of the plants left on the field. The amount of P removed in the harvested portions of crops is a small, but over numerous crop cycles there is P reduction on cropped fields. This can be replaced by applying P containing livestock manures or chemical fertilizers.

Plants use about one-third as much P compared to N. For agricultural purposes rock phosphate is the main source of P used for manufacturing P fertilizer, which consists of two rock types igneous and sedimentary rock (Samreen & Kausar, 2019). These two rock forms have the same phosphate mineral calcium phosphate of the apatite group (Samreen & Kausar, 2019), ($Ca_{10}(PO_4)_6(OH)_2$, $Ca_{10}(PO_4)_6F_2$ and $Ca_{10}(PO_4)_6Cl_2$), is the chemical formula of apatite. The most common phosphate mined is fluorapatite and it contains impurities like Carbonate, Sodium and Magnesium (Samreen & Kausar, 2019). P fertilizer is frequently applied in areas where Fall frost is of concern, as it helps a crop grow more rapidly and achieves earlier maturity (McKenzie &

Middleton, 2013). Altogether, P is mainly used when there are noticeable benefits such as improved early growth and development, the benefits of earlier maturity, and increased yields are important for crop production.

The effects of P deficiencies are not as noticeable as other deficiencies, like N deficiency where it experiences chlorosis, P deficiency can be a slight change in green. Since it is known to aid in the following: photosynthesis, respiration, energy generation, nucleic acid biosynthesis, and plant structures like phospholipids (Balemi, & Negisho, 2012). P has important effects in a plant's overall life cycle. As discussed earlier, less P is needed for a plant in terms of quantity compared to N, but the role of P is vital in plants. Therefore, it becomes a concern in agriculture as usually being deficient, due to its natural low availability and low immediate use by crops from applied fertilizers of that year (Balemi, & Negisho, 2012).

P deficiency causes a delay in maturity, as growth progression is slowed and as a result, lower yields occur. There is a concern globally of a potential for less easily mined P reserves within this century. The issue with P availability after applying P containing fertilizers is because it forms insoluble complexes with cations such as aluminum and iron under acidic conditions and with calcium and magnesium under alkaline soil conditions. As well there is low P recovery from spread fertilizer because it is absorbed into the soil and is less available for plants (Balemi, & Negisho, 2012). As such, P effects on crops could turn out to be difficult to identify without the proper soil testing and could go unnoticed until decreased crop yields are observed. Yet these effects could be attributed to other factors like: a poor growing season, delay in seeding and since P is relatively more expensive compared to the other macronutrients N, K S, Ca, and Mg. It is economically and environmentally important to add sufficient but not excessive rates of supplemental P forms as fertilizers, livestock manures, or biosolids.

Phosphorus, unlike other macronutrients, does not have exceptionally noticeable symptoms when it comes to deficiency. This results in the overlook of P deficiencies, and it is useful to get the fields soil tested for plant availability. This is important because when there are visible symptoms it is too late into the growing season to change the yield at harvest time. As for toxicity, there are really no symptoms other than it causes restrictions on iron and zinc uptake by plants. Which means the only symptoms that show would be zinc and iron deficiency.

2.2.3 Potassium

Potassium (K) is an essential nutrient for plant growth and is abundant in most southern Canada Prairie soils. However, K is only available to plants in the form of the readily available K^+ cation, which needs to be soluble in soil water to be absorbed by plants. There are mineral forms of K, which are not soluble in water and thus not available to plants. The readily available K is 0.1-2% of total K, slowly available K is 2-8% and soil mineral particle K is 90-98% of all K in soils (Fu et al., 2020). As such, K deficiency can occur for plants even though the soil may have an abundance of the element. One of the main uses of K is that it helps provide resistance against biotic and abiotic stresses and contributes to plant physiological and metabolic processes (Sattar et al., 2019). In the soil there are many microbes that interact with K, and they are a diverse group like: rhizobacterial species, fungal species, arbuscular mycorrhizae, yeast, and many N fixing bacteria are capable of solubilizing K minerals (Sattar et al., 2019).

K is a nutrient source which comes from the product of weathering minerals like feldspar. Most mined K mineral deposits are soft ores called potash, usually a mixture of potassium chloride (KCl) and sodium chloride (NaCl). The process of potash separates the KCl from the NaCl crystals and it is the KCl that is used as a K fertilizer. This allows for there to be a K source in the soil whether it be soluble to the plants or not. At the start of this breakdown process there are crystalline K forms released which are not accessible to plants until it has been further broken down over long periods of time. This is fine for natural environments, but for agriculture, the availability of K is needed much sooner. Naturally, K is added back to the soil from K leached from leaves due to rainfall and as well residues from plants that are microbially decomposed. This is one of the main reasons why in agriculture there is a need for K to be supplemented as a fertilizer because a portion of the plant K is removed during harvest. Also, there is loss from the soil by run-off and leaching into ground water.

K is commonly added to fields is in the form of various potash fertilizers, that are mined from old, evaporated seabed's that leaves a K enriched salt. Once this source is mined, it is usually used as potassium chloride (KCl), potassium sulphate (K_2SO_4), potassium-magnesium sulphate (K_2SO_4, $2MgSO_4$) and potassium thiosulfate ($K_2S_2O_3$). K is added to make up for its removal during harvest and to supplement the need for slowly available potassium, this supplies readily available potassium for optimum plant growth.

K is a nutrient that is used in great amounts by crops, and it is important to maintain sufficient plant available levels in a soil. In environments such as fields that are cultivated, nutrients are removed every year in the harvested portion of the crops, and along with it goes valuable nutrients like K. It is important to add the right amounts of K back to the soil as it helps with the transport and regulation of water, nutrients, and carbohydrates in plant tissues (Kaiser & Rosen, 2018). Along with many other nutrients, it is involved in enzyme activation in the plant, which affects protein, starch, and ATP production (Kaiser & Rosen, 2018). This results in there being physical effects if there is too much or too little of K.

K is mobile in plants moving from older growth to newer, so it tends to show deficiency symptoms on the older leaves of the plant. This will eventually spread to newer growth, showing symptoms like yellowing or chlorosis on the edges of the leaves. There could be signs of defoliation if there is a high enough K deficiency present. Since K is important for plant tissues and structural development, it will delay the growth and may develop poor roots. Toxicity rarely occurs, as plants do not absorb K excessively but having too much of K can reduce the uptake of other needed nutrients, e.g., Mg, Zn, Fe and Mn.

2.2.4 Calcium

Calcium (Ca) is another important nutrient in the world and is adequately present in most soils. Making it a nutrient that one rarely must worry about adding supplements to cropped soils, rather it is common to have too much of it present. There are exceptions though, like areas with low base saturation and/or high levels of acidic soils (McLaughlin & Wimmer, 1999). Ca is vital for helping develop the cell walls and membranes and helps make plants less vulnerable to diseases and pests. It also contributes to the uptake of nitrate. Like other nutrients, Ca comes from the weathering of soil minerals and contributes to overall soil fertility. However, Ca may in fact have a reduction in its presence in soils. The increase of acidity in soils due to agricultural practices could impact Ca availability. For example, more acid rain from the increase in greenhouse gases, could wear away at the Ca in minerals resulting in greater leaching losses of Ca^{2+} ions, and adversely impact soil microbe and plant growth.

The Ca cycle is not as complex as other macronutrient cycles but there are important features to note. Ca can be added to the soil anthropogenically, Ca in minerals and some added through carcasses of dead animals, mostly the bones. These all are influenced by weathering, which allows for the release of soluble ionic Ca, i.e., Ca^{2+} and the movement of it through the soil. Which will be adsorbed onto some soil mineral and humic particle surfaces, absorbed by plant roots, and some lost to surface waters and groundwater through runoff and leaching respectively.

Ca forms that are commonly added to fields to increase its availability are liming materials such as lime or calcium carbonate ($CaCO_3$) and, wood ash. Gypsum ($CaSO_4$) is another form that adds Ca along with sulfur, and calcium nitrite ($Ca\ (NO_3)_2$) supplies both Ca and N. Other than lime being beneficial to crops for its own plant nutrition effects, it is also useful to ameliorate low pH or acidic soils by raising the soil pH to a neutral value, e.g., pH 6.5. This will help prevent other element toxicities and some deficiencies from occurring. Although it has many benefits, it should not be spread to deal with soil acidity uniformly. As soil acidity tends to occur in patches, thus needing variable application rates to prevent any adverse effects of raising soil pH to excessive alkaline levels in portions of a field.

When Ca is taken in by plants, its main use is to hold together cell walls and thus the structure of the plant. It also plays a role as a chemical messenger regarding developmental and physiological processes which can be due to environmental stresses (Thor, 2019). This can help progress root or pollen tube growth for the plants. In relation to excess soil acidity $CaCO_3$ can be applied to raise pH levels to neutral levels. But if it is added in neutral to alkaline areas of a field, it can raise the pH to be too alkaline causing other problems. Managing soil pH is the main soil factor and influence $CaCO_3$ has when applied to agricultural fields, but there are others.

Ca effects on plants are noticeable for both deficiency and toxicity. When there is a lack of Ca, it is most notable on new tissue like root tips, new leaves shoot tips. The reason why it displays in young leaves is because the tissues rely on resupply of Ca in the xylem, which is dependent on transpiration and new leaves are low in transpiration (White & Broadley, 2003). These symptoms tend to turn the areas affected, brown or like a burning effect or necrosis. As for toxicity, it can have multiple effects, one being that it can raise the pH to a high alkaline level and kill the plants. Also, it can potentially prevent germination of seeds and reduce plant growth rates (White & Broadley, 2003).

2.2.5 Sulfur

Sulfur (S) another important plant nutrient is needed for chlorophyll formation, which helps plants convert sunlight to biochemical energy forms. In the soil, elemental S can be converted to sulfuric acid by bacteria, which in turn can acidify the soil. For example, elemental S can be used to lower the pH if required to do so. Ideally in western Canada, soils pH values that perform the best for crops is a pH between 6.0 to 7.3. Due to this, the addition of elemental sulfur should be monitored to ensure no over application occurs and risk acidifying soils.
S that originates in soils comes from parent materials of the soil, it is also released when plant and animal residues are decomposed, if there is a deficiency in plant available S it can be added to soils as sulfate or elemental-S fertilizer forms (Prasad & Shivay, 2016;2018;). Microbial activity consists of mineralization of organic matter, and immobilization, oxidation, and reduction reactions (Prasad & Shivay, 2016;2018;).

Therefore, all these processes are essential for S because a plant does not absorb the elemental form of S. The sulfate ion ($SO4^{2-}$) is the form of S that plants absorb through their roots (Kertesz, 2014). There are other ways that S be used by plants, for example sulfur dioxide gas (SO_2) can be absorbed through leaves, but this is such a small amount that it has little influence unless plants are growing near an industrial area that has high levels of SO_2 emissions. This used to be the case in most areas of Europe, but there has been a very successful environmental initiative to reduce SO_2 emissions. The interesting result of this reduction in SO_2 emissions is that the need to use supplemental S containing fertilizers for S-deficient crops in

Europe has increased greatly. However, it is much better environmentally to add S fertilizer where it is needed compared to having acid rain deposition over the whole landscape (Peringe et al., 2020).

2.3 Micronutrients and Interactions in Soil

Micronutrients are just as important to a plant as macronutrients. However, they are just needed in trace amounts, e.g.,0.1 PPM to produce a healthy plant (RX Green Technologies). These micronutrients are boron, chloride, copper, iron, manganese, molybdenum, nickel, and zinc. For this research, reviewing the micronutrients that are more involved with soil acidity will be discussed. Additionally, aluminum is put in this section even though it is not considered a micronutrient, but in small amounts and in acidic soils, is one of the main contributors of negatively impacting plant health.

2.3.1 Iron

Iron (Fe) is considered one of the essential micronutrients in soil for plant health. It is usually in the form of ferric oxide (Fe_2O_3) or also known as hematite. This form of Fe in the soil gives it its common reddish hue to soil and these forms specifically are not soluble or available to plants. In fact, the solubility of Fe heavily depends on the pH level of the soil. When the pH is rising to become more alkaline, this causes the Fe to be more insoluble. Whereas if the pH decreases this allows for increased Fe solubility. The effects of Fe are assisting with enzyme development and chlorophyll synthesis, which is why Fe plays a role in displaying chlorosis (yellowing) (Hochmuth, 2011). On the other side, if there is too much Fe from applied means or if the pH is getting too low and there is a large increase of soluble Fe in the soil causing bronzing and stippling on the leaves due to Fe toxicity.

2.3.2 Aluminum

Aluminum (Al) is not considered a macro or micronutrient for plants, but it does impact growth of a plant when it becomes more soluble in the soil solution and has the potential for many negative effects. This can be due to various factors like metal concentration, the chemical form of Al, growth conditions and plant species (Bojórquez-Quintal et al., 2017). Aluminum has been found to have benefits for promoting root growth and as such if it is determined to be toxic or beneficial relies on the factors mentioned above (Bojórquez-Quintal et al., 2017). Aluminum is associated closely with soil acidity and toxicity. Which is why it is seldom looked at for positive benefits like root growth. However, Al toxicity causes roots to become stunted, brittle, poor root hair development and root apices are damaged. The most common observations of Al toxicity are in acidic soils of a pH less than 5.0, and it is called phytotoxic aluminum. This causes inhibiting effects to root growth, and this eventually impacts water and nutrient uptake. Other inhibiting factors is that toxic Al is shown to combine with plant available P in soil solution and precipitate as aluminum-phosphate particles, making P become less available for plants (Rahman, 2018).

2.3.3 Manganese

Manganese (Mn) is another important nutrient assisting with plant growth by keeping up metabolic roles in plant cells. As such, Mn is a common nutrient in soils and thus can provide enough of a source for plants. However, with increasing demands on agriculture and repeated use of fields there is always the potential for shortages of the nutrient or any nutrient for that matter. As such, the most effective way to reintroduce or build up the Mn supply is to apply manganese sulfate, which is a common fertilizer. Mn deficiency is common in dry, well-aerated, high organic matter and calcareous soils (Alejandro, 2020). The symptoms for this include leaves turning pale green between veins and usually the normal color stays in the plant tissue the closer to the veins it is. The more severe it is or the more it progresses, it gets more paler and can eventually begin to brown and die. As for the toxicity, Mn happens commonly on poorly drained and acidic soils, which makes the Mn much more soluble and available (Alejandro, 2020). This makes Mn similar to Al, in that soil pH on the acidic, < pH 5.5tends to make these element’s availability too high for plants to handle. The toxicity effects of Mn can be necrotic spots on older growth, it can cause chlorosis on the younger leaves. It can also cause other side effects such as iron deficiency.

2.3.4 Boron

Boron (B) is one of the most important micronutrients for plant growth and their health. In soil B is mobile, making it susceptible to leaching losses, on course textured and low organic matter soils. It is not required in high amounts for sustaining healthy plants. It assists by improving cell walls, membranes, assists with the sugar and energy movement, and pollination. This all ultimately leads to and causes the development of healthy seeds. Boron, like other nutrients are heavily impacted by the soil type and pH. B is the most available to the crops when the soil has neutral to moderately acidic soil pH levels. The deficiency impacts of B influence factors like reduced fertility, the dying off the growing tips of the roots and shoots (meristem), and reduction or the end of cell expansion. As for B toxicity, there are various symptoms which all rely on the type of plant it is impacting. The most common is yellowing or browning of the leaves, and other cases there could be some impacts on the branches or stems.

2.3.5 Molybdenum

Molybdenum (Mo) is a nutrient that is required only in small amounts for plant growth. The Mo is taken and used by enzymes to carry out redox reactions such as nitrate reductase, xanthine dehydrogenase, aldehyde oxidase and sulfite oxidase (Kaiser et al., 2005). Mo is very mobile in the phloem and xylem, and for the soil it is readily available for leaching as the soluble Mo in soil is an anion (MoO_4^{-2}). Mo deficiency causes visible ailments like pale leaves, some chlorosis and necrosis on the plant tissue between the veins. As for the toxicity of Mo, this rarely ever happens, the most likely scenario is if it was applied improperly at too high a rate. But on the off chance of it occurring, it is like its own deficiencies and other nutrient deficiencies. This is due to it restricting the intake of other nutrients. Mo becomes less available under very acidic soil pH levels.

2.3.6 Chlorine

Chlorine an essential nutrient for plant development, is absorbed and utilized by plant roots the ionic form chloride (Cl^-), not in the chlorine gas form. Chloride is often perceived as a negative soil component due to it being one of the main ions associated with some forms of saline soils. As well, high Cl^- levels, when present restrict soil microbial activity. Excess Cl^- levels it can cause microbial mortality. But, when Cl^- is present in sufficient and not excessive levels, it can be beneficial for plants, helping again with photosynthesis. Also, moisture regulation by controlling the opening and closing of the stomata, which allow for CO_2 to enter and O_2 and water vapor to exit the leaves. Too little of Cl^- results in deficiency symptoms like spotted chlorosis and necrosis. As for when a plant takes in too much Cl^- the toxicity looks more like necrosis along the leaf edges displaying on older growth first. Chloride is more available to the crop under slightly to very acidic soil pH levels.

2.3.7 Summary

Since soil acidity impacts nutrient availability for crops in various ways, understanding the effects on specific nutrients is needed. Having macronutrients and micronutrients is extremely important when evaluating and measuring soil pH. Whether it just be a nutrient deficiency, or if it is brought on by acidic conditions, a good understanding of the topic is needed to comprehend the subject. It can aid in the identification and awareness of any current or future issues. Furthermore, it improves on the overall crop evaluation and potential consideration for research in this topic.

2.4 Other Nutrient Sources

2.4.1 Soil Organic Matter

Soil organic matter (SOM) is a component of soils which consist of plant residues that could be freshly deposited onto and incorporated into soils, then there is the decomposing organic matter and lastly humus. Humus is what is left after most of the organic matter has decomposed and leaves a dark brown to black residual material. This well decomposed material contains C and N and helps form soil aggregates, making it more porous to allow for air and water to infiltrate and be stored in soils, and plant roots to grow more easily into soils. SOM percentage depends on the climate of the region, the vegetation present during soil formation. SOM is important to understand regarding soil acidity, as the decomposition process usually produces organic acids, predominantly being carbonic acid (H_2CO_3). Over time, this can cause a slow process of acidification, especially in the surface layer of the soil. In semi-arid places like southern Alberta, SOM can be extremely low in percentage, e.g., 2.5 to 4.0%; it is not one of the highest influencers for soil acidification, but it is important to understand. In this case, low SOM is a result of climatic history and the removal of organic materials during harvest. If the southern prairies are becoming warmer and drier, over time this may lead to lower levels of SOM. Agricultural practices that leave stubble/residues, do help in preserving SOM, whether it be by contributing directly or by conserving moisture in the soil. Another good example of SOM loss is when inversion tilling was a common practice in Canada. The practice exposed SOM to increased oxygen aeration causing it to breakdown faster and release carbon dioxide at a greater rate. Ensuing in the reduction of SOM percentages, and soil moisture storage amounts. The reason SOM is extremely beneficial to soil is that it provides nutrients, a place for microorganisms to live, and helps maintain a higher water holding capacity. Not only is SOM good for plants and buffers against changes in soil pH, but it influences the environment as well by being a major C sink and storage pool for global carbon.

2.5 Summary

Nutrients are an extremely crucial factor when studying acidity, as they are heavily influenced by the changing of soil pH (Figure 1.2). In some cases, low soil pH or soil acidity is often mistaken for specific nutrient deficiencies and or toxicities as they are indeed influenced by soil pH. This is occurring in areas such as this studies research sites, which were formerly neutral to alkaline in soil pH, but over time are developing sub-field areas of soil acidity. Relying on common nutrient deficiencies and toxicities brought on by soil pH changes are important to consider for observing if there are soil acidity issues and conduct soil testing to confirm. Which led to this study to be conducted for dryland, no-till farms. To see if lime treatments can ameliorate the soil without incorporation and how effectively they can treat these soils with these various treatments.

Chapter 3 – Methods

3.0 Site Selection

The sites selected were chosen using a few points of consideration to ensure the research was done well and will be beneficial to the agriculture industry. There was no monetary funding to select these specific fields that fit the criteria. However, the land use for plots was free to use and unlimited access was given. Fields that have shown symptoms of soil acidity were selected and having an impact on crop yields. Second, having the fields located in different Soil Great Group zones, i.e., Brown, Dark Brown, and Black Chernozemic. This is using the Canadian System of Soil Classification (CSSC), where there are ten soil orders with the Chernozemic soil Order being one of them. Different orders have various characteristics from their physical features to the climates they are located in.

However, in recent years there is now an eleventh Order, and that is an Anthroposolic Order, which consists of soils influenced and altered by humans. These soils are defined as highly modified or constructed by humans, with one or more of the soils naturally formed horizons removed, removed, and replaced, added to, or significantly modified (Anne Naeth et al, 2012). Anthroposols can occur in any soil order; agricultural fields do experience human disturbances. However, the top layer A horizon is followed by the suffix p, to be called an Ap horizon to signify there has been cultivation. These methods of disturbances do not significantly impact the natural horizons (Anne Naeth et al, 2012). The anthropolsolic soil term was first referenced in 1847 when Ferdinand Senft used it to describe urban soils (Lehmann & Stahr, 2007).

For each of these Orders, soils formed as a combination of the factors of parent geologic material, climate, organisms, and topography, all part of ecosystems that are unique within the Canadian landscape. Chernozemic soils developed in semi-arid to subhumid climates dominated by grass species, with some broadleaf plant species that can tolerate moisture deficits that these soils normally experience. This allowed for any differences based off soil Great Group to be compared as research results were assessed. These fields were all in regions originally considered in a pH range of neutral to alkaline, i.e., 6.5 to 8.2. These field sites had experienced natural ecosystem acidification processes, such as when organic matter decays it releases some H^+ in the soil as a carbonic acid which is very weak. Also, in drought conditions there is a moderate decrease in soil pH, which is the result of a higher concentration of H^+. However, acidification has sped up due to the use of ammonium-based nitrogen fertilizers, over the last 40 to 50 years.

3.1 Location and Description of Field Research Sites

3.1.1 Hilton Site

This site is located northeast of Strathmore, AB and is just south of the village of Nightingale, AB on a field owned and managed by Hilton Acres (16-19-25-24-W4) (Figure 3.1). The 52-hectare field showed signs of possible acidity problems, as the farmer mentioned a concern for the gradual decline of the average composite sample soil test pH value over the past decade until present. The Hilton Site is in the Foothills Fescue ecoregion. There are sandy and gravelly glacial alluvial deposits present, which agrees well with the Sandy Loam textured samples collected and observed. The area is part of the Bow River watershed with wetlands uncommon. At this study site specifically, the soil is a Orthic Black Chernozemic soil with parent material texture of Sandy Loam and Fine Sandy Loam (Alberta Agriculture and Forestry).

This region’s bedrock is made up of Tertiary and Upper Cretaceous sandstones and mudstones (Natural Regions Committee, 2006). The Tertiary is a broad term for the period of around 66 to 2.6 million years ago, which was near the Cretaceous-Paleogene extinction when

Quaternary glaciation began. Other names for this Tertiary period are the Neogene and Paleogene, however, for this site specifically it is made up of surficial geologic deposits during the Upper Cretaceous and Paleogene periods (Prior et al., 2013). The formation at the site is on the Scollard Formation, which is fine-grained, commonly cross-stratified, light grey to buff sandstone and pale to dark grey, sandy to silty mudstone; thick coal seams and carbonaceous mudstone intervals in some upper parts; nonmarine (Prior et al., 2013). Therefore, the lithology of the site is sandstone, siltstone, and shale primarily with smaller pockets of coal and bentonite.

3.1.2 Kings Lake Site

This site is located south of Grassy Lake, AB and is just north of Crow Indian Lake, AB on a farm run by Kings Lake Farming (12-07-06-13-W4) (Figure 3.1). This 129-hectare field, which was previously considered neutral or slightly alkaline in pH, now has some acidic pH areas. The King's Lake site is in the Dry-Mixed Grass Sub-Region. This Sub-Region represents topographic areas that go from level ground to gently undulating semi-arid glacial till with shallow glacial alluvial-lacustrine veneers (<1 m depth) over glacial ground moraine. It also comprises broken topographic places with coulees, valleys, badlands, and dune fields. Since this area is a dry region, adjacent natural areas have drought-tolerant plant species present. The cultivated field crops can benefit from irrigation or from moisture conserving dry-land farming techniques, e.g., no-till or direct-seeding cropping. The Soil Order that makes up this field is Orthic Brown Chernozemic with parent material textures of Loam, Silt Loam and Very Fine Sandy Loam (Alberta Agriculture and Forestry).

The bedrock geology is like the Hilton site, that is it is underlain by non-marine Upper Cretaceous sandstones, siltstones, and shale with some marine shales (Natural Regions Committee, 2006). The materials that cover the bedrock are mainly medium textured, moderately calcareous glacial till deposits (Natural Regions Committee, 2006). This can change in-depth depending on where you are in the area as some areas tend to be hummocky, which can influence the depth of this material. Since this area is a post-glacial landscape there are thin, medium, and fine textured glaciolacustrine deposits present in portions of this area (Natural Regions Committee, 2006). This is the result of small glacial lakes that resided in certain areas for a short period of time during melt and retreat of continental glaciers. Furthermore, since there was much run-off from the glaciers melting it allowed for fluvial deposits to form along ancient drainage systems (Natural Regions Committee, 2006).

3.1.3 Sierra Site

This research site is located northwest of Shaunavon, SK, it is a dry-land area farmed by the Sierra Farming (13-12-009-21-W3) (Figure 3.1). This 29.4-hectare field is also showing signs of acidity problems, when initially converted from native grassland to cultivated agriculture in the early 1900s soils in this area had either neutral or slightly alkaline pH values like the other two sites. The site is east of Cypress Hills, is on a formation called ‘The Bench’, which is an area of higher elevation northeast of the Cypress Hills. The Cypress Hills proper contain erosion resistant gravel deposits that did not erode as much over geologic time and is why it is more elevated than the surrounding lands. The Sierra Site is in a boundary area of two ecoregion zones. That is because it is located on the very northeast end of Cypress Hills and thus is a part of the Cypress Upland (CU) ecoregion. It shares in the elevation differences of the CU; however, it is more in line with the vegetation and soils of the Mixed Grassland (MG) ecoregion. This region, since it is higher elevation, experiences slightly cooler temperature and more precipitation than the low grasslands surrounding this area. The soil type matches with both CU and MG, as the samples taken of deeper horizons was a Loam textured glacial till.

Since this site is located on the boundaries of two ecoregions, it is useful to include the geology of both regions to summarize this site. Starting with CU, the Cypress Hills is a unique area in the southeast part of Alberta and southern western of Saskatchewan. To start, very coarse gravel materials were deposited by braided rivers in the Tertiary Period (44 to 35 million years ago) (Acton et al., 1998). These deposits are positioned over sands, silts and clays of older early Tertiary and Late Cretaceous formations (Acton et al., 1998). Due to this, when the last ice age occurred, the glaciers did not totally cover the area. Some locations were covered and others that had higher elevation were not glaciated. The erosion resistant gravel deposits of the Cypress Hills Uplands are made up of hard, coarse well-rounded quartzite and chert pebbles and cobbles (Acton et al., 1998). Other materials were transported from various locations and deposited there by glaciers and streams. Today, it remains a unique spot in the southern Alberta and Saskatchewan prairies not just for its geological structure, but also its unique ecosystem. The other ecoregion MG is distinct from other regions due to its varying environments. It goes from gently undulating glaciofluvial, glaciolacustrine, and glacial till plains that are disrupted by hummocky morainal uplands, sand dunes, benchlands and numerous creeks and valleys (Acton et al., 1998). This site is on a bench formation, making it higher in elevation than the surrounding agricultural areas. This region has different geological structures, primarily being marine sedimentary bedrock of the Bearpaw formation (Acton et al., 1998). This formation is made up of gray-green silty clays and shales with localized deposits of bentonite (Acton et al., 1998). It is located near the United States-Canada border, and there is a shift in geological structure near the border. That being a coal bearing Ravens crag Formation of Tertiary period over an Upper Cretaceous of clays, siltstones, and sandstones (Acton et al., 1998). Furthermore, with the change of elevation of this area, in lower eroded areas are some exposures of older bedrock formations.

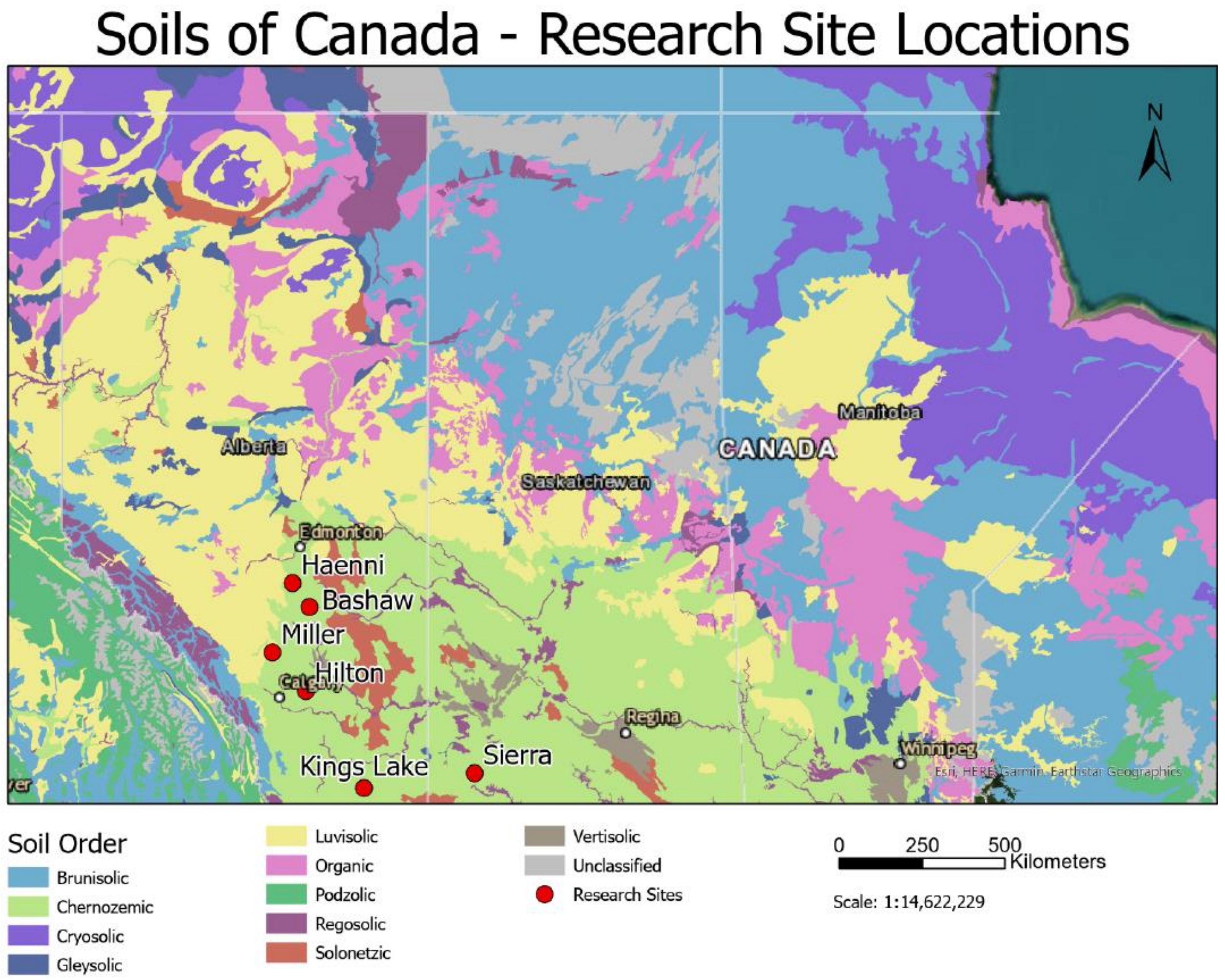


Figure 3.1: Western prairie provinces and the distribution of Soil Orders. Source: Soil Polygon Files from Government of Canada, 2021: https://www.arcgis.com/home/item.html?id=e4417190b5fc4a32b7703426c6660412. Map layout and research site locations done in ArcGIS Pro

3.1.4 Additional pH Spatial Variation Study Research Sites

The additional three fields that were established for the purpose of pH spatial variation examples were the Miller, Bashaw, and Haenni farms. These were established due to the growers’ interests in the topic of study and to expand on the current study of the efficacy of different lime and incorporation methods in dryland fields.

The Miller Farm fields are located 13 kilometers west of Olds, Alberta. The farmer has noticed and is concerned about a gradual loss in yields over the last decade, even while growing improved crop varieties, using careful nutrient management and moisture conserving reduced and no-till cropping systems. It was suspected that there are acidic soil areas and the farmer asked that grid sampling be done to determine if there were observable pockets of excessively low pH soils.

This soil is a Eluviated Black Chernozem, which is in a transition area from the prairies to forested areas further to the west. The soils consist of a Sandy Clay Loam, Clay Loam and Silty Clay Loam textures (Alberta Agriculture and Forestry).

The study site named Bashaw is located 21 kilometers west of Bashaw, Alberta, it is a field beginning to have a reduction in crop yields. The farm manager suspected soil compaction as the cause, however soil bulk density sampling indicated no soil compaction concerns. This was done by the grower and a consulting agronomist, bulk density is a test where a set soil depth sample collection is taken to be the indicator of compaction by weighing the soil, moisture, porosity, and aeration as factors to take into consideration. After this was done and ruled out, it was suggested that this field be grid sampled to assess soil pH levels.

The soil is an Orthic Dark Gray Chernozem, which exist in transition zones between grassland dominated soils and forest soils (Soils of Canadian Society of Soil Science, 2020), fitting the central Alberta location. The parent material consists of Sand Clay Loam, Clay Loam and Silty Clay Loam textured glacial till deposits (Alberta Agriculture and Forestry).

Lastly the Haenni site, which is near the hamlet of Falun, AB, about 23 kilometers west of Wetaskiwin, AB. It is in what is commonly called the “Deep Black Soils” or the Black Chernozemic Soil Zone. There are some shallow Humic Gleysolic soils present along an intermittent creek that bisects the field from the southwest to the northeast. This field is in the Prairie Parkland area. The surficial parent materials are Sandy Loam to Loamy Sand glacial-alluvial deposits.

3.2 Research Site Soils – Chernozemic Soil Order

The Chernozemic soils make up most of the cultivated lands of the three Prairie Provinces of Manitoba, Saskatchewan, and Alberta. These soils experience water deficits in most growing seasons and mean annual soil temperatures between 0 degrees Celsius to 6 degrees Celsius (Canadian Society of Soil Science, 2022). Furthermore, there are differences within this Order as it is divided into four Great Groups. The three small plot research fields that have lime application plots are located within the Brown, Dark Brown, and Black Chernozem Great groups. Considering these great groups, the difference between them all, mainly is due to do differences in temperature, and precipitation amounts that determine the dominant natural vegetation, mean annual water deficit, percentage of soil organic matter, colour chroma and colour value (Soils of Canada, 2020).

3.3 Establishment of Research Sites

To begin this study, suitable fields were found where the farmers suspected soil acidification was limiting crop yields over the past decade, as generally indicated by a lowering in the average soil pH value from regular composite soil sample analyses. To assess this grid soil sampling was done on each of the original three fields: Hilton Site (Figure 3.2), Sierra Site (Figure 3.3), and Kings Lake Site (Figure 3.4). Hilton and Sierra sites were collected by a method known as Simple Random Sampling (Figure 3.5) with a basic grid of 150 metre by 150 metre blocks overlayed on the field. This helped to ensure samples are collected in every part of the field, but with the sample(s) taken anywhere in that block to determine a spot in the field with low pH to establish the research plots. As well as this spot had to be away from the edge of the field and a spot that represented a good average of the field's topography. This method was used in conjunction with the grids to ensure the whole field was covered but also that these points could be sampled. The Kingslake site was done by normal grid sampling and the samples were taken and provided by the farm manager. Once this was completed soil pH values were measured on individual GPS tagged samples.

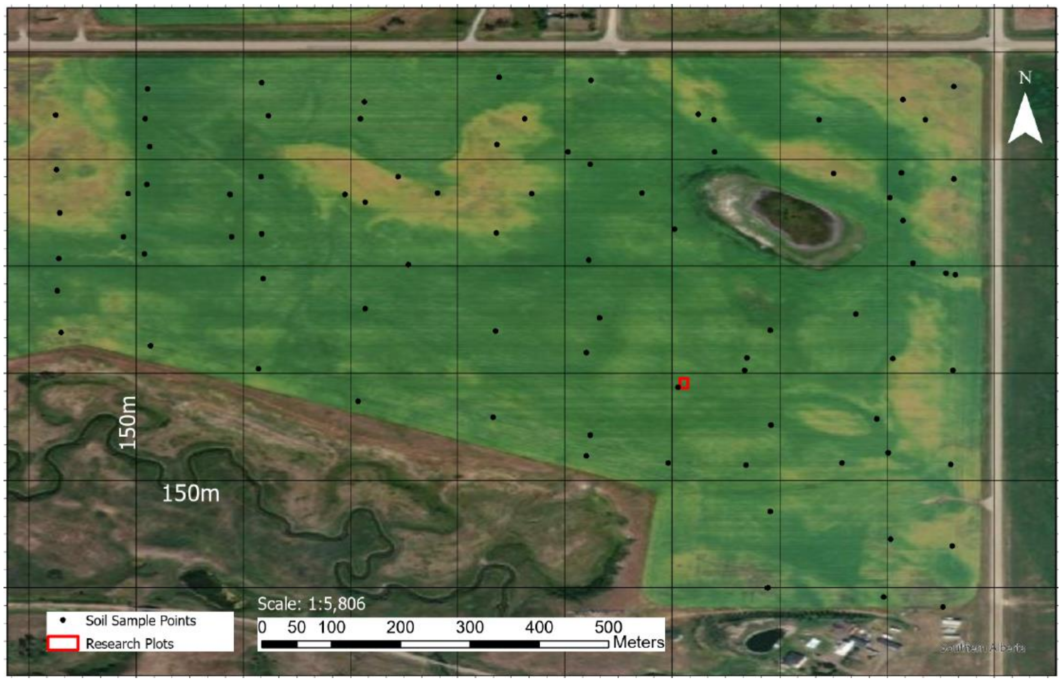


Figure 3.2: Hilton site soil sample points.

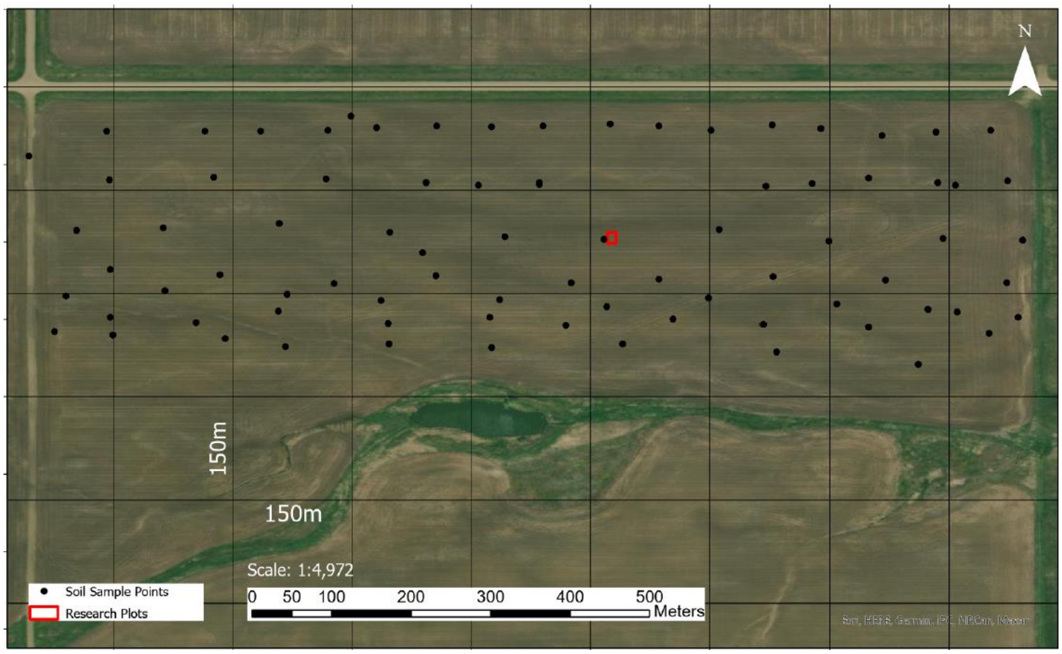


Figure 3.3: Sierra site soil sample points.

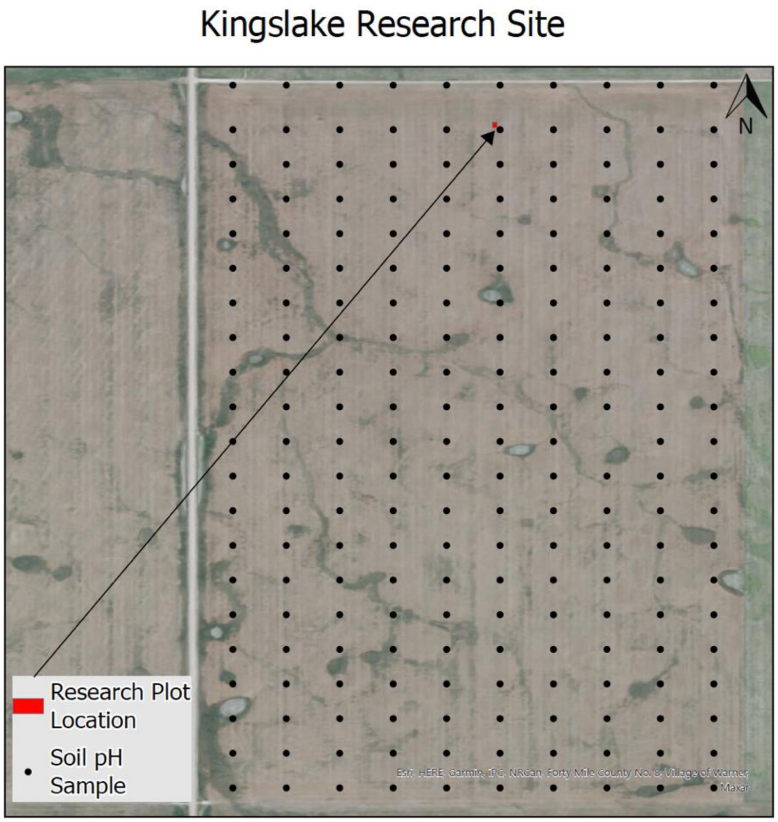


Figure 3.4: Kings Lake site soil sample points.

3.4 Soil Data Collection

3.4.1 Grid Soil Sampling

There was some deviation from a set grid pattern to be able to avoid uncultivated poorly drained depressions. The soil depth collected was 0 to 15 centimeters, due to soil acidity predominantly being present in this depth this is the depth of initial crop germination and seedling rooting. Each sample was bagged, labelled, and the GPS point recorded. Samples were air-dried in aluminum pans in a lab at the University of Lethbridge, screened to 2 mm, and stored until pH measurement was conducted. As for the third research field, Kings Lake, this was sampled by the farm crop manager with the method of systematic sampling (Figure 3.6).

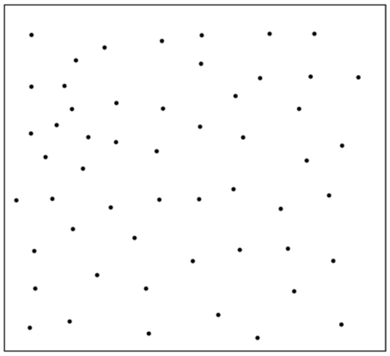


Figure 3.5: Simple Random Soil Sampling.

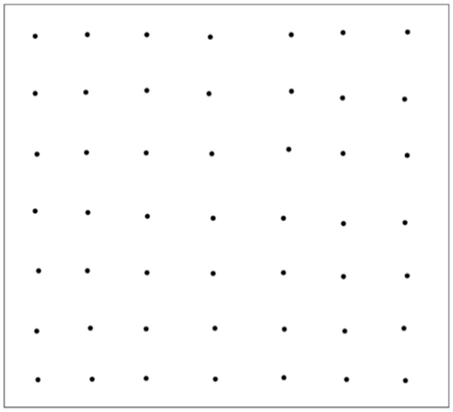


Figure 3.6: Systematic grid soil sampling.

3.4.2 Plot Establishment and Application of Lime

Once the pH values and lime requirements were determined, the data was analyzed using ArcGIS Pro and soil pH and lime requirement zones were delineated. An area with low pH was chosen, at each of the three sites, to locate lime application research plots with Hilton field location sample H75 with a pH of 4.69, Sierra Field sample S38 with a pH of 4.69 and Kings Lake field sample 103 with a pH of 4.70. The plots were mapped out and flagged with three replications of six factorial treatments and one control plot. (Figure 3.7). There were 0.5-meter alley ways between the individual plots that were 2 meters by 2 meters in size. To ensure the plots could be repeatedly located the four corners of the entire research area had metal chains buried with GPS coordinates recorded to be able to find the spots using a combination of a GPS unit and a metal detector for precision. Each lime treatment plot had a combination of a different lime form, granular or powdered; and incorporation methods, left unincorporated on the surface, or incorporated using simulated harrowing or discing. (Figure 3.8).

The lime treatments were applied in November 2020 after harvest was completed. The constant plot lime rate was calculated based off the grid sampling done earlier. This was to closely replicate what real infield lime applications would be, this takes into consideration that every square meter in an agricultural field could not be logistically sampled and analyzed. Also, pH values do vary spatially through a field. Prior to the treatment application and site preparation methods, every individual plot was sampled, and the pH measured for the 0 to 15 cm depth near the centre of each plot. This confirmed that the individual plot pH values were close to the original grid sampling spot pH value. The lime was first spread evenly on the surface of each plot individually, according to the calculated lime recommendation. Then the treatments simulating incorporation were done by hand using a rake with 10 cm tines to simulated heavy harrowing, and a heavy hoe for simulating discing.

N^					
	Tmt 1		Tmt3		Tmt 7
	Tmt 2		Tmt4		Tmt 6
	Tmt 3		Tmt 7		Tmt 5
	Tmt 4	0.5m	Tmt 6	0.5m	Tmt 4
	Tmt 5		Tmt 2		Tmt 3
	Tmt 6		Tmt 1		Tmt 2
	Tmt 7		Tmt 5		Tmt 1

Tmt 1	Powdered Surface
Tmt 2	Powdered Harrowed
Tmt 3	Powdered Tilled
Tmt 4	Granular Surface
Tmt 5	Granular Harrowed
Tmt 6	Granular Tilled
Tmt 7	Control

Figure 3.7 Example plot set up at the Sierra Site.

Figure 3.8: Plot set-up, lime treatment and site preparation, Sierra site post-treatments in Fall 2020. 3 Replications with 7 treatments, all 2 metres by 2 metres in size, as well 0.5 metre alley ways between replications. The flags indicated the corners of each plots.

3.4.3 Subsequent soil sampling and pH monitoring, Years 1 & 2

In November 2021, one year after the plot treatments were established, soil sampling was conducted in each of the plots to assess the effect of lime treatments on soil pH. The change in soil pH was evaluated in different ways to see how the lime has interacted with the soil matrix. First, was to test the average pH of each plot from 0 to 15 centimeter and compare them to the initial pH starting values. Once the first sampling was completed, then sampling of the movement down into lower soil depths, and reaction with the soils was assessed. The depths of soil sampled and tested were 0 to 5 cm, 5 to 10 cm, 10 to 15 cm, 15 to30 cm, 30 to 45 cm, and 45 to 60 cm. The effect of lime is usually in the top 15 cm of soil, and the deeper samples were taken to confirm little effect of liming below the 15 cm depth. The 0 to15 cm depth range is the crucial zone needed for a more neutral pH to have a healthy and vigorous crop. It was observed that the pH in the 15 to 60 cm deep soils had initially neutral to an alkaline pH value. This is because of the natural calcium carbonates in the soil from the more alkaline parent materials the soils formed in. This sampling method was repeated identically in 2022, however the exact sample locations in the plots were adjusted to avoid previous sample spots. The exact same soil could not be sampled as it had been removed and analyzed previously. For instance, 2021 sample locations in each plot were 75 cm from the north edge and 50 cm from the west edge. 2022 sample locations were 150 cm from the north edge and 50 cm from the west edge on all plots.

3.5 Laboratory and GIS Analysis

3.5.1 Soil pH Analysis

Soils were air dried and taken to the Down To Earth Labs, a soil test lab, and were screened using a rolling drum system with 2 mm size screens. This sped up a process that would have taken many days using hand screens. The soils were further air dried after this screening and were ready for the selected pH analyses. Each individual soil sub-sample was placed into a 100 ml beaker. After every research site was done, beakers were cleaned thoroughly to avoid any potential cross contamination. The pH was measured using a Bluetooth probe from Vernier connected to a laptop computer with Vernier LabQuest Software installed. At the start of every set of pH measurements the probe was calibrated in a pH buffer solution of 4.01 and 7.00 to ensure accuracy. One test done was the pH water test or soil mixed with distilled water pH method, which shows the current or active pH level. For all pH tests the beakers contained 20 mL of soil and 40 mL of distilled water, or a 1:2 soil to water mixture. If the soil pH was acidic a further test was done using a pH buffer test.

3.5.2 Lime Requirement Calculation

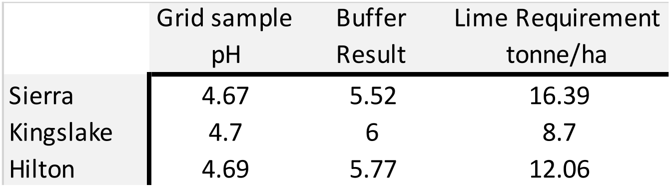
To obtain a lime requirement value, a pH Buffer (BpH) solution was applied to each pH sample having pH value less than pH 7 (Table 3.1). The buffer was P-Nitrophenol, Potassium Chromate and Calcium Chloride. The mixture was 10 mL of soil, 10mL of distilled water and the added 20 mL of the Buffer Solution. It was then stirred three times and after 30 minutes the pH measurements were taken. All the data from the two pH analysis methods were inputted into Microsoft Excel. This is solution is called the SMP buffer, which is short for The Shoemaker-McLean-Pratt buffer, this method is utilized by Down to Earth Labs in Lethbridge, Alberta and many other labs. Which is where the solution and formulas are adapted from this method to be used by labs to calculate lime requirements. To get a Lime requirement the formula used was as follows.

$$\textit{Lime Requirement (tonne/ha)} = 291.6 - 80.99\,BpH + 5.64\,BpH^{2}$$

This test is done by using the BpH, which is distilled water, pH Buffer Solution and soil. That is read with a pH probe, the research site Hilton had a result of 5.77, which is then put into the formula to give a lime requirement of 12.06 tonne/ha.

$$\textit{Lime Requirement of 12.06 (tonne/ha)} = 291.6 - 80.99(5.77) + 5.64(5.77^{2})$$

Table 3.1: Lime Requirements determined by soil and buffer solution for plot amelioration.



	Grid sample pH	Buffer Result	Lime Requirement tonne/ha
Sierra	4.67	5.52	16.39
Kingslake	4.7	6	8.7
Hilton	4.69	5.77	12.06

3.5.3 Plot Statistical Analysis of Lime and Site Preparation

Statistical analysis was completed using analysis of variance (ANOVA) for the lime application plot data to assess the changes in soil pH, and to compare lime application methods. Tests were completed to compare each field individually, and the three research sites combined, assessing the experimental factors of the form of lime used, powdered or granular, and the lime placement or incorporation method. Each analysis looks at soil depths independently to further assess how the soil profile was affected.

The following figures illustrate the previous crop residue remaining after lime application and incorporation, tilled (Figure 3.9), heavy disc equipment (Figure 3.10), harrowing (Figure 3.11), harrow equipment (Figure 3.12) or no incorporation (Figure 3.13). Each analysis looks at soil depths independently to further assess how the soil profile, to a depth of 60 cm, is being affected.

Figure 3.9: Tilled site preparation. Residue Coverage 5%

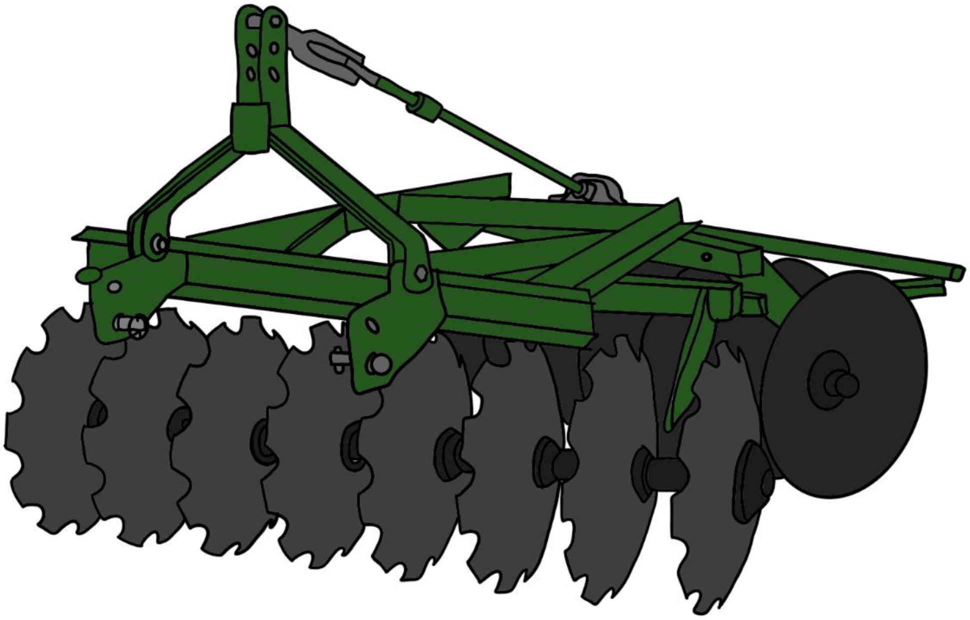


Figure 3.10: Heavy disc equipment example. Drawn by Jessica Wagner.

Figure 3.11: Harrow Site preparation. Residue Coverage 30%.

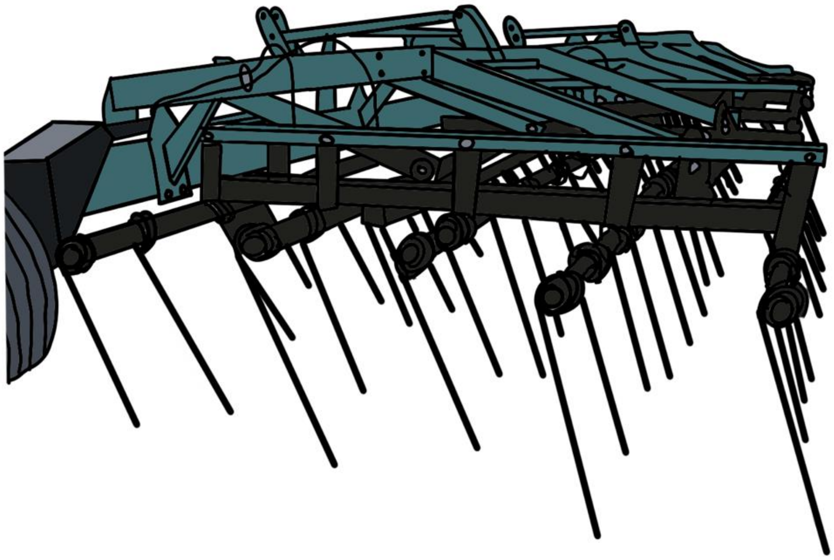


Figure 3.12: Harrow equipment example. Drawn by Jessica Wagner.

Figure 3.13: No incorporation. Residue Coverage 60%

3.6 GIS Soil Acidity Spatial Variability

Evaluating soil pH spatial variability in agriculture fields is needed for assessment and treatment of soil acidity. This results in the need for GPS tagged soil sampling, soil analysis, and GIS mapping. Soils vary in the level of pH due to differences in soil texture and organic matter content, as well as topographic position affecting water surface flow and drainage. Once all the needed information is gathered, an interpolation method called kriging can be used and is typically applied to analyze the spatial variability of the soil and display it on a map. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface and is often used in soil science and geology (Mulla & McBratney, 2002).

However, since the nature of soil pH is extremely variable Kriging proved to be an unreliable method to determine estimates of soil pH between the sample points. As such, the method known as Spline with barriers was used and produced more accurate and reliable data. Kriging and spline are both methods that can be used in soil science and the determining factor is its application. As such, studies were conducted to compare interpolation methods such as kriging and spline and proved neither was more accurate than the other, the only time one seemed to perform better was in a study more suited for that methods process (Liu et al, 2013). Spline provides continuous elevation and grade surfaces while limiting the bending of the surface produced to a minimum, producing a smoother surface (Ikechukwu et al, 2017). While in kriging, the surface that is developed trend changes from one sample point to another, so with grid sampling there will be no smoothness, but a good depiction of what the pH is in each spot. As a result, spline was the more appropriate method to go with, keeping in mind the application it would be used for when regarding treatment zones and maps for farming equipment.

Spline interpolation works to make the data smoother and minimizes the high and low end of the data, which results in maps having less small sliver areas and makes a smoother map. The default setting of 0.99 smoothing factor was used as it produces the smoothest curve, and aids in producing zones that would be well suited for treatment when accommodating the size of farming equipment. This is done by using the neighbouring data points and minimizing a drastic change in data values. The Spline with barriers interpolation is spline interpolation, but with the barrier being a mask which limits the raster to be created within the field. Due to the nature of soil pH spatial variability, it is important to locate the low pH areas where lime application is needed and beneficial, and to also know what field areas have neutral to alkaline pH soils and need no lime applied.

The map made with Kriging interpolation method for pH zones proved to be less accurate and produce less useful results (Figure 3.14). The reason this was the result is because when dealing with soil acidity there are multiple variables on why pH of a specific level is in a certain spot in a field, and it might not always be the same combination of variables in another spot in a field. Such as soil texture, electrical conductivity, soil organic matter and moisture. This results in Kriging interpolation method to not be the most useful method, as it correlates the data from the measured areas and is dependent on locations (Meng & Borders, 2013) which will not work in this case for how variable soil pH is. Whereas Spline with barriers, produces a more appropriate map for soil pH variation, when taking into consideration equipment and treatment size (Figure 3.15). There are other interpolation methods other than kriging and spline, however the spline interpolation fit this studies objective.

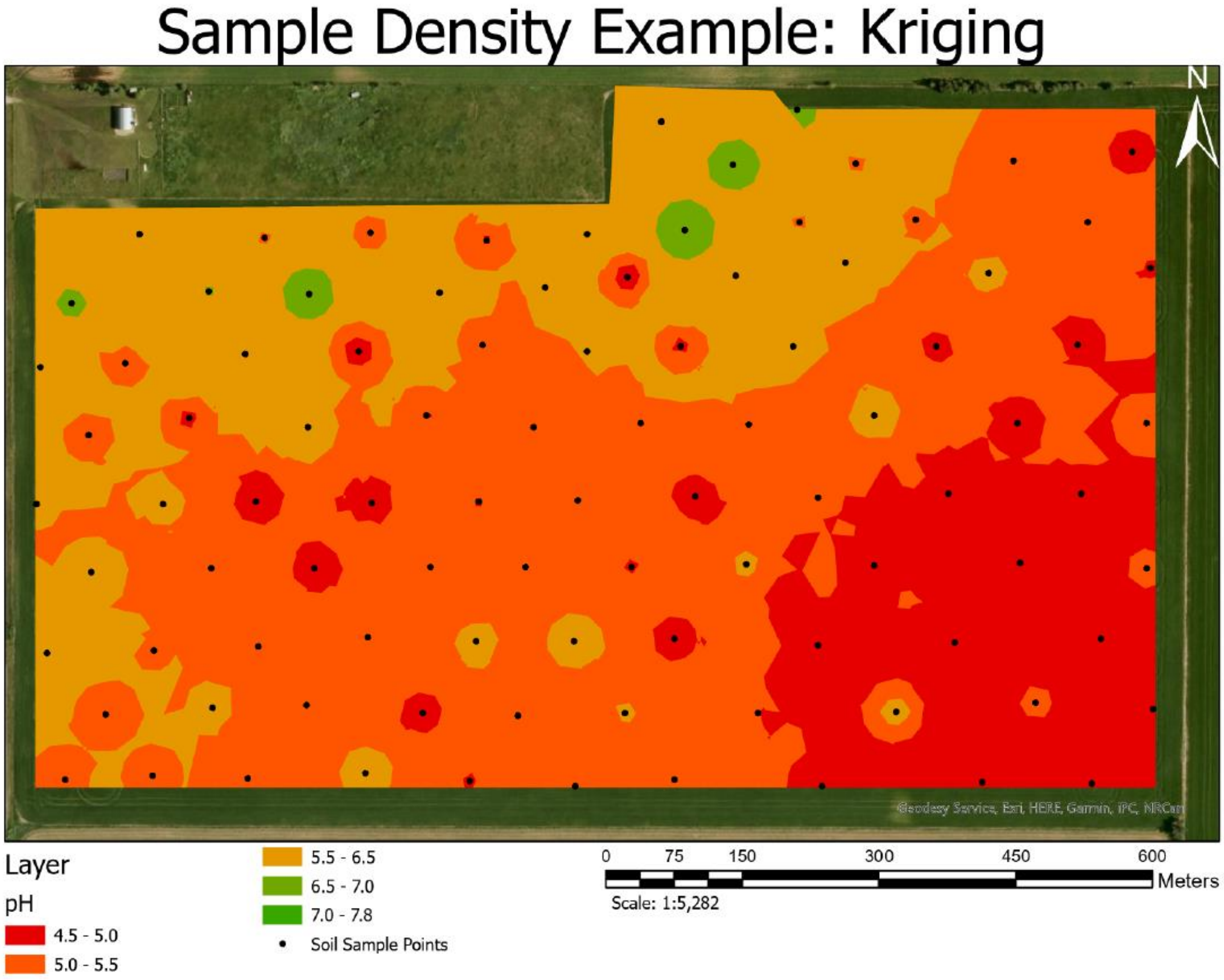


Figure 3.14: 38.4-hectare field (95 acres) tested for pH with a sample density of a sample every 0.4 hectares (1 acres). Kriging interpolation leaves noticeable spot effects, with different rings of polygons of differing pH values as a result of the steeper curve in the data from these greatly differing pH values, it creates a less smooth of a map.

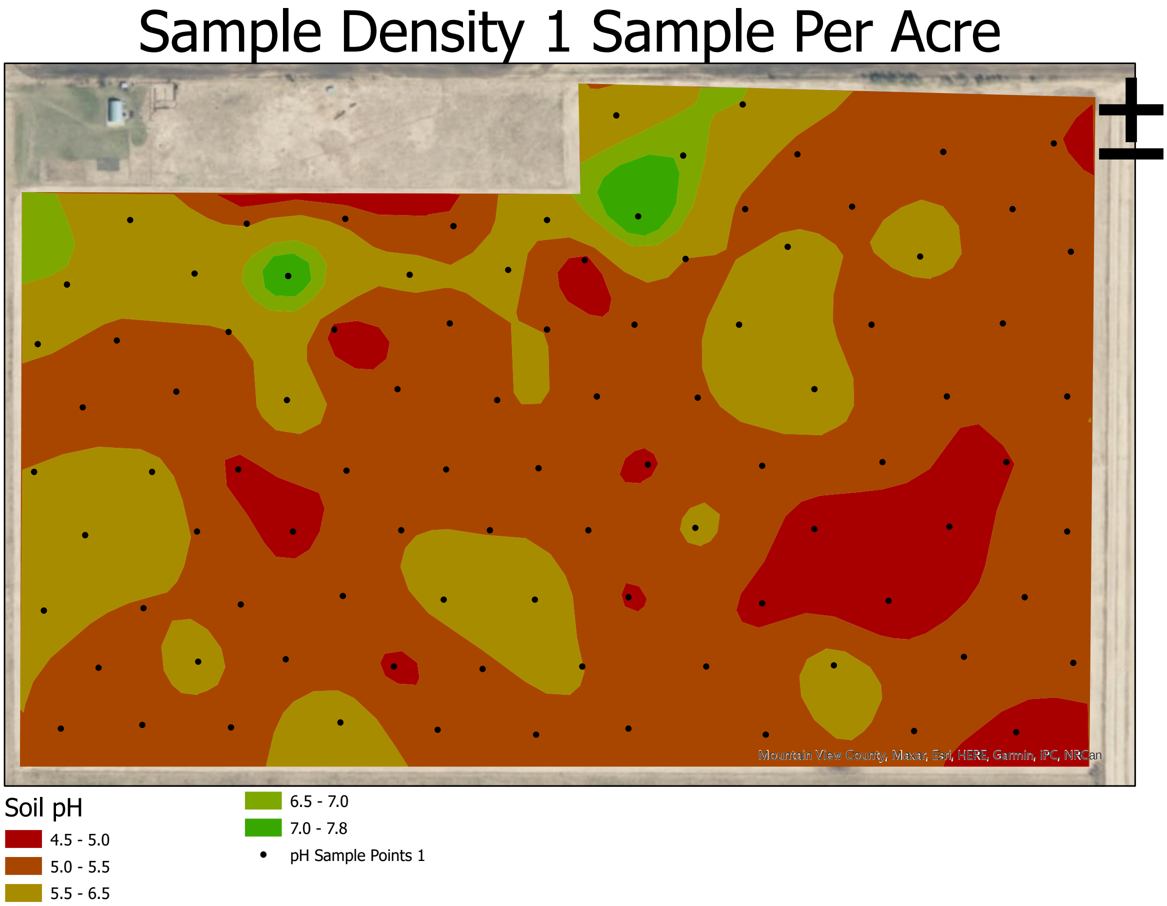


Figure 3.15: Spline with barriers method for pH field variation.

Furthermore, soil pH spatial variation being the greatest concern, goes to question how densely does sampling need to be done to have an accurate depiction of what the soils pH levels may be across the entire field (Zhang et al, 2022). On one side, there could be to many samples that provide to much detail that has no benefit on an agricultural management perspective, for example to small of zones for equipment. Then there is the other side of this and that is to little of detail that it yields no beneficial information. During this study one field near Olds was sampled initially at a density of one sample spot for every 0.4 hectare (1 acre) for this aspect of the study, sample points were set up prior to arrival. To do this, ArcGIS Pro was used with identifying the fields, creating point files, and labelling them appropriately. They were placed in a systematic soil sampling grid where each row was offset to reduce any linear discrepancies that may occur. (Figure 3.16). This offset grid sampling method is beneficial to use as it limits the potential of any linear issues that could happen in a field such as a gas line that was put in where the soil was disturbed across the field, and issue in fertilizing for example.

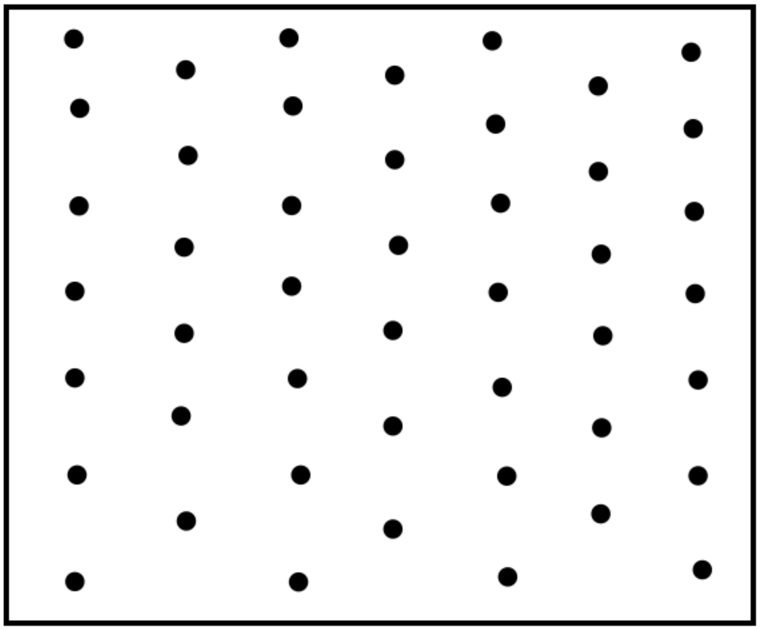
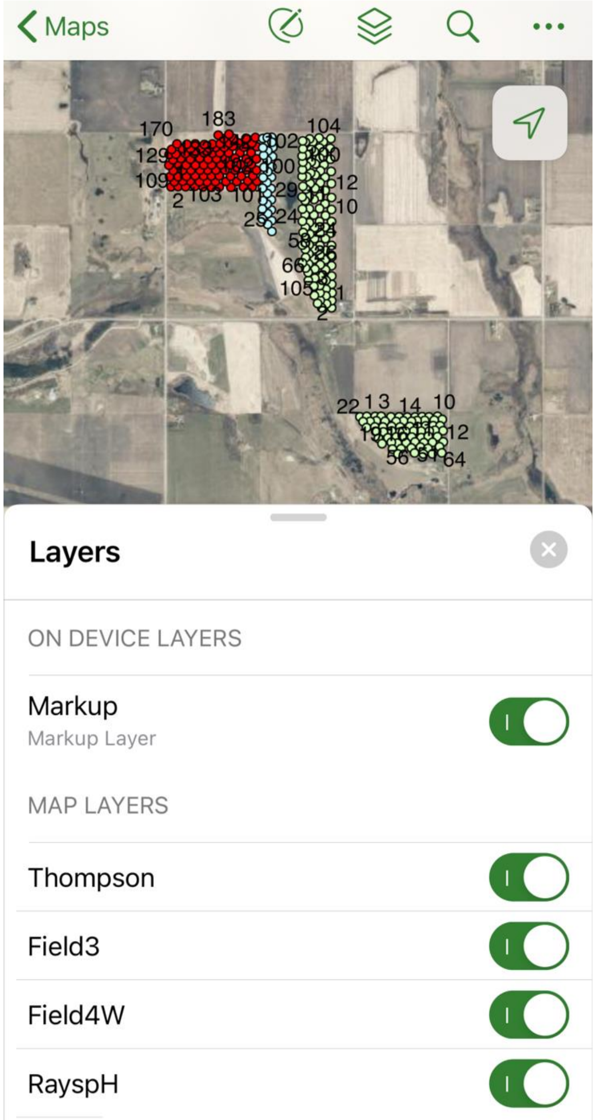


Figure 3.16: Offset Systematic Grid Sampling

Once these files were created, they were exported to ArcGIS Online, which then could easily be accessed in the field by phone GPS on the ESRI App Explorer (Figure 3.17 and Figure 3.18). This was extremely beneficial to use as the maps created on desktop is transferred easily to a mobile device to be used to sample in the correct locations in the fields. When in the field, all that was needed to be done was approach the sample point and take a soil sample from 0 to 15 cm depth and label the sample with the point number. From there, the sample would be analyzed for the pH level and the information, entered the attribute table on ArcGIS Pro and generate the pH map. Maps using different sampling densities were produced and compared on the Miller farm field but selecting every second sample point in the attribute table. Since there was a specific order in sampling, removing every second point work so that the field would then replicate how it would be if it was sampled at half the density to start with. From there a new shapefile was created with half the density of samples, this was repeated twice more.



Layers

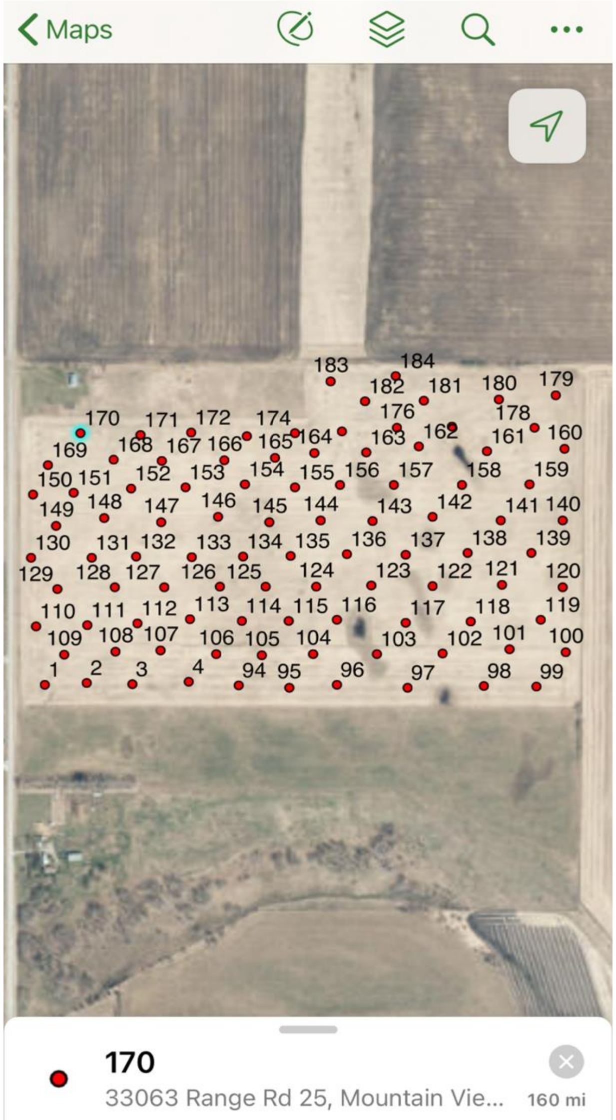
ON DEVICE LAYERS

Markup ● On
Markup Layer

MAP LAYERS

Thompson ● On
Field3 ● On
Field4W ● On
RayspH ● On

Figure 3.17: Field and soil sample locations.



170
33063 Range Rd 25, Mountain Vie... 160 mi

Figure 3.18: Soil sampling points.

3.7 Summary

In this research the fields chosen to establish the lime application plots had to be characterized by soil sampling the entire field at GPS tagged spots and testing the pH for each individual soil sample. This allowed for the identification of pockets of acidity in the fields.

From there, a position in the field was selected to locate the lime treatment plots for assessment of lime source and method of placement. The results reported were collected over a two-year period by sampling one- and two-years post lime application. This testing allowed monitoring over time as to how the lime application treatments affected soil pH. Testing the soil at various depths down the soil profile was useful to see how the lime treatments moved into and reacted with the soils. Statistical analyses were done to compare the experimental treatments. Alongside this study, it was useful to evaluate how variable soil pH in the original three research site fields, as well as seven other fields on other farms. At the one Miller Farm field, west of Olds, AB, sampling at higher to lower densities was assessed to determine what sample density is required to achieve accurate soil pH, and variable rate lime application maps.

Chapter 4 – Results and Discussion

4.0 Introduction

This research study began with the request from growers in the southern Canadian Prairies to assess the extent of soil acidification and spatial variability throughout fields. As well as what are the best ways to ameliorate the acidic soils in these rainfed Chernozemic soil fields. The amelioration research portion (Hilton, Sierra and Kings Lake sites) of the study commenced after the fields were assessed using grid sampling and a low pH area was selected to locate lime application plot treatments. It is interesting to note the extent of low pH samples throughout the fields Hilton (Table 4.1), Kings Lake (Table 4.2) and Sierra (Table 4.3). Soil pH is considered excessively acidic when it is lower than a pH of 5.5.

Table 4.1: Percentages of pH levels in the Hilton research field.

Hilton Field Soil Sample Points		
pH Zone	Number of samples	Percentage of Samples
4.66 to 5.0	13	16%
5.1 to 5.5	17	20%
5.6 to 6.5	23	28%
6.6 to 7.0	11	13%
7.1 to 8.12	19	23%

Table 4.2: Percentages of pH levels in the Kings Lake research field.

Kings Lake Field Soil Sample Points		
pH Zone	Number of samples	Percentage of Samples
456 to 5.0	21	16%
5.1 to 5.5	105	50%
5.6 to 6.5	70	33%
6.6 to 7.0	11	5%
7.1 to 7.8	3	1%

Table 4.3: Percentages of pH levels in the Sierra research field.

Sierra Field Soil Sample Points		
pH Zone	Number of samples	Percentage of Samples
4.3 to 5.0	41	51%
5.1 to 5.5	27	33%
5.6 to 6.5	12	15%
6.6 to 7.0	0	0%
7.1 to 7.3	1	1%

If the acidity of soils below pH 5.5 are considered limiting for many crop species the three initial research sites had the following crop limiting acidic soils percentages of Hilton36%, Kings Lake 60%, and Sierra 84%. This is significant soil acidification considering all three of these sites are in areas previously considered to have neutral to alkaline pH soils. Furthermore, once established, the starting pH of 0 to 15 cm of each small research plot was tested to ensure treatments would be monitored as the lime reacted with the soils. The most important question the growers wanted to know is what form of agricultural lime to use, powdered or granular, and whether incorporation using harrowing or discing was needed compared to just surface applications (Figure 4.1). Experimental treatments were replicated three times to allow statistical comparison of experimental treatment means. In plot research there is typically 3 to 4 replications done, 3 was chosen for this research due to limited materials and time limitations for the number of samples that would need to be take and tested. In research it is a good practice to have at least three replications to have precision in data, it can be verified and to reduce any spatial issues that could arise, e.g., a plot is damaged.

The data was analyzed using two types of Analysis of Variance (ANOVA), specifically One-Way Analysis of the separate experimental treatments, and Factorial Analysis (FA) to see if there were overall differences between lime form, and placement method, and if there was an interaction between lime form and placement. ANOVA was used as it is a very reliable and accurate method to see if there is statistically any different within a group—three replications at a field—and effective at comparing different groups to each other—the three different sites. The treatment means were compared using the Least Significant Difference (LSD) test method. This set the standard for testing if the P value in ANOVA is greater, then it is not significantly different. Which in the case of this study, is very good to see, as it means the treatments performed similar across different sites and different treatments within a site. The results are presented for each research site, and a combined three-site average. These analyses were for the 0 to 15 cm depth, as well as separately for the depths of 0-5, 5-10, 10-15, 15-30, 30-45 and 45-60 cm for year 1 and year 2. The soil pH test results of the 0 to 15 cm are a valuable indicator of how treatment pH levels began and how they were raised or improved. The initial soil grid sampling data gathered and used for making the pH maps, and in the variable rate lime requirement maps were 0-15 cm depth samples. The progression depth samples were useful to see how the applied lime treatments were moving down into and reacting with the soils. Furthermore, it allows for a good understanding how even when samples are gathered more densely in a smaller area, the pH change does vary slightly, along with the natural soil cantena effects on the soils.

The last portion of this study was done on other farm fields, concentrated on the one Miller Farm west of Olds, AB, initial sampling was done at a density of one sample location per 0.4 ha (1 acre) to answer the question “When soil pH grid samples are taken in a field, what density of samples are required to provide reasonable and accurate data?”.

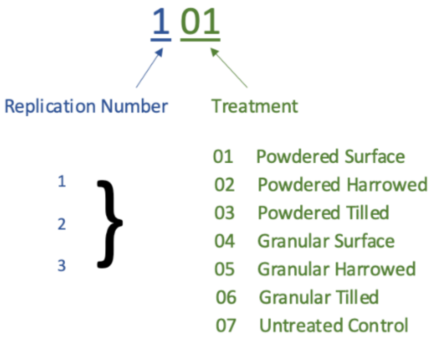


Figure 4.1: Nomenclature of Plots and treatment identifiers.

4.1 Hilton Site – Black Chernozem Soil

4.1.1 Hilton Site, starting soil pH 0 to 15 cm compared to Year 1 & 2, ANOVA Factorial Analysis

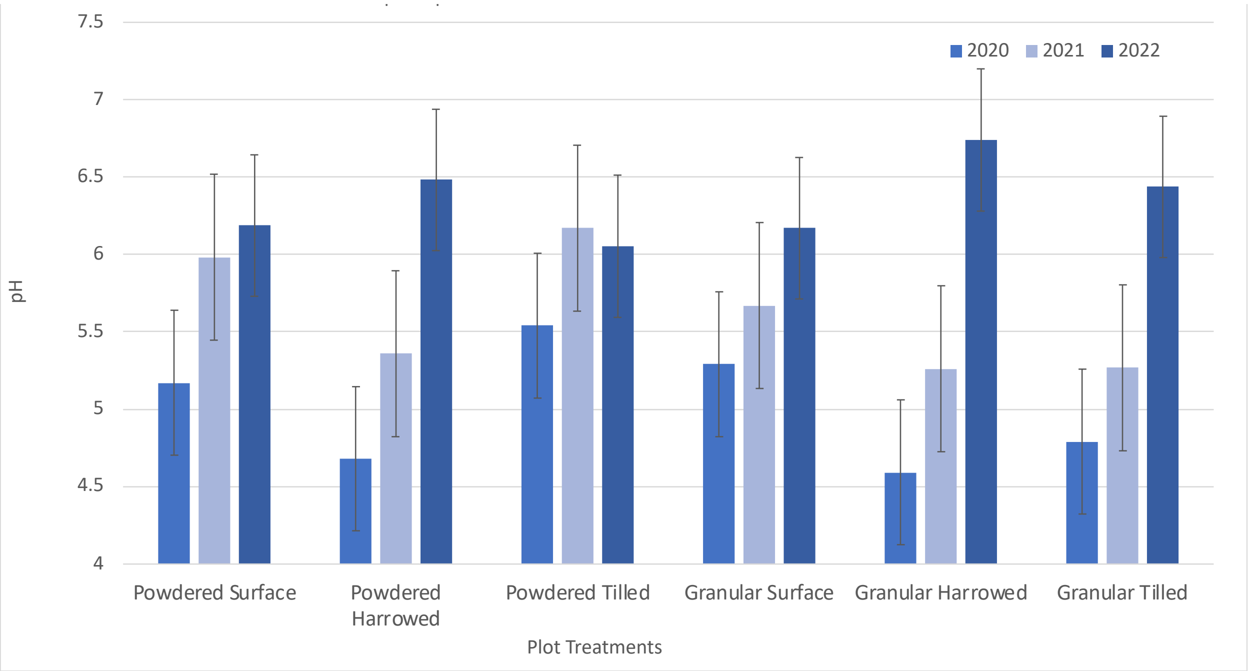


Figure 4.2: Displays the initial statistical comparison of the natural variation amongst the plots, Hilton site. Then it carries into how this variations pH slowly returns to a neutral pH, changing due to the treatments applied to the soil and how the 0 to 15 cm growing zone of the soil is changing.

Sample size of n=21 for each individual year, with comparing the years n=42. Least significant difference (LSD) 0.05 = 0.53 is the uncertainty determine for 2021 and LSD 0.05 = 0.43 for 2022. The data for the soil depth of 0 - 15 cm shows there is a significant difference in the rise of soil pH. The Hilton site in 2020 had an average pH across all plots 4.97 soil pH level, in 2021 this increased to a pH of 5.57 and then in 2022 this increased to 6.28. When analyzing the data for the 0-to-15-centimeter depth (Figure 4.2) there was a slight improvement on all plots and a significant improvement in 2022. For the granular harrowed and tilled, this is attributed to the granular taking longer to disperse and react with the soil There is some natural spatial variability throughout the 7 by 14 m small plot areas, however, when looking at the overall pH change, soil pH increased close to the target level of pH 6.5.

4.1.2 Hilton Site, Year 1 & 2 soil layer pH treatments ANOVA Factorial Analysis 0-5 5-10, 10-15 cm.

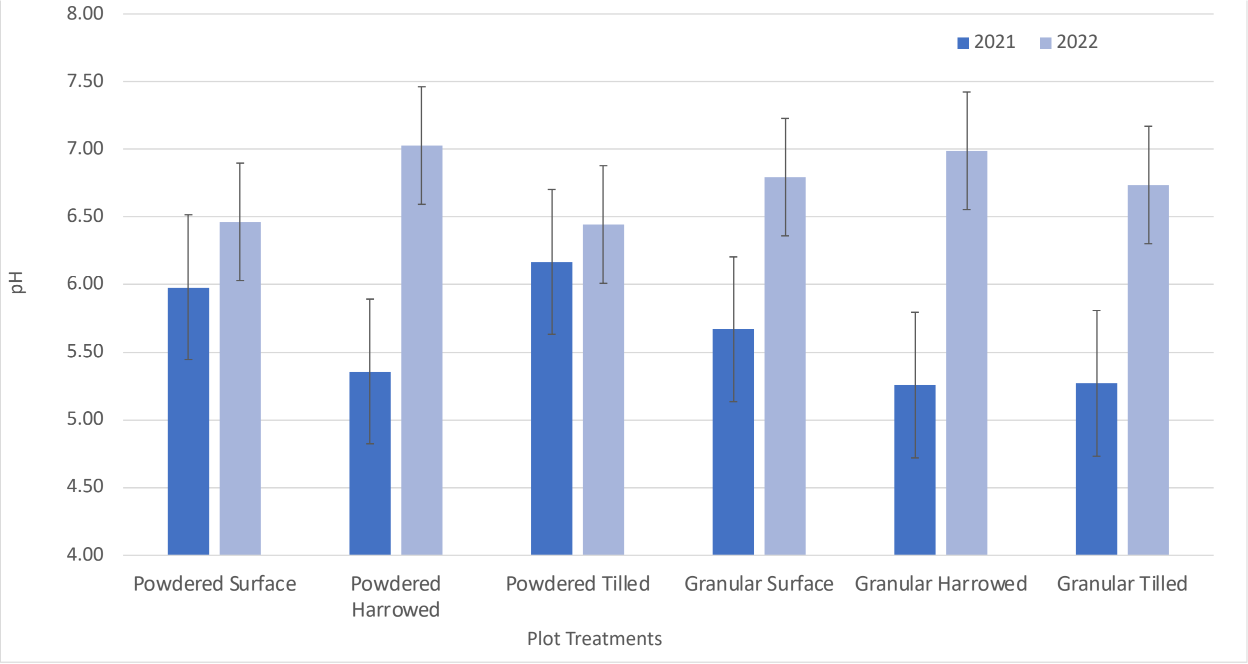


Figure 4.3: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 0 to 5 cm growing zone of the soil pH levels vary, Hilton site. In 2021, the treatments stayed low, averaging around 5.5 pH, with the powdered tilled, increasing the soil pH the highest. Whereas in 2022, all treatments increase to around 6.5 soil pH, with the granular treatments and powdered harrowed, increasing the pH the greatest after two years.

Sample size of n=21 for each individual year, with comparing the years n=42. LSD 0.05 = 0.53 is the uncertainty determine for 2021 and LSD 0.05 = 0.43 for 2022. The data is for the soil depth of 0 - 5 cm if there is a significant difference in the rise of soil pH. This is determined in all the data by comparing one of the treatments pH change amongst the same other three replication treatments by testing it against a 0.05. Below this value means it is statistically significantly and if it is higher then it is not. This is only the case if, it is higher than the 0.05, if it is lower, then there is difference in the effects of a treatment and would then be unreliable for claiming a specific treatment would work.

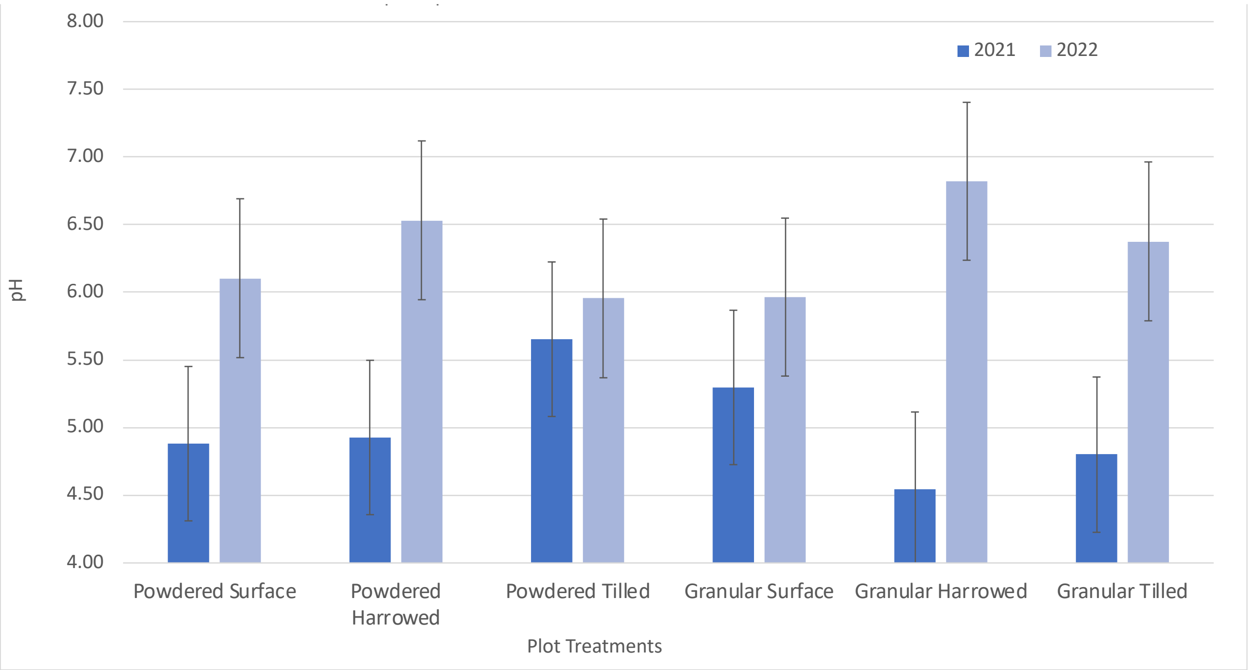


Figure 4.4: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 5 to 10 cm growing zone of the soil pH levels vary, Hilton site. At this depth, all treatments in 2021 averaged a pH of 5, but in 2022, all pH's gradually increased with the powdered harrowed, granular harrowed and granular tilled increase significantly to the 6.5 range.

Sample size of n=21 for each individual year, comparing the years n=42. LSD 0.05 = 0.57 is the uncertainty determine for 2021 and LSD 0.05 = 0.59 for 2022. The data is for the soil depth of 5 - 10 cm if there is a significant difference in the rise of soil pH.

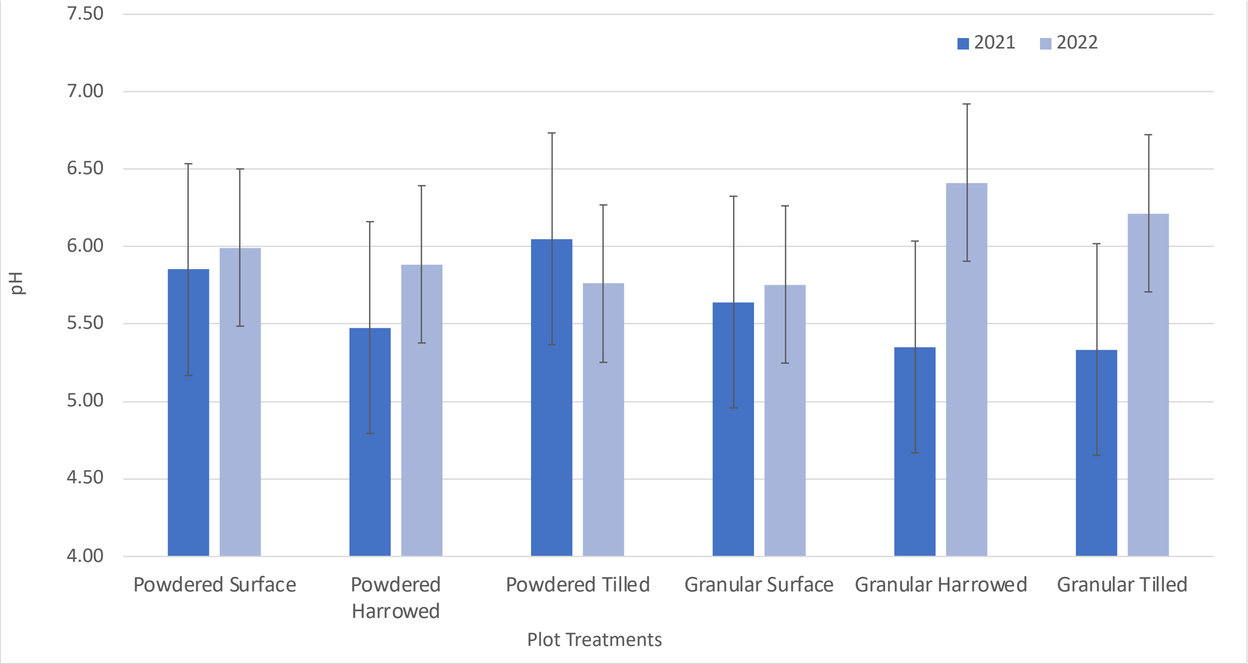


Figure 4.5: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 10 to 15 cm growing zone of the soil pH levels vary, Hilton site. At this depth, the pH does not increase significantly from 2021 to 2022, except for granular harrowed and tilled treatments, these showed an increase of the year.

Sample size of n=21 for each individual year, comparing the years n=42. LSD 0.05 = 0.68 is the uncertainty determine for 2021 and LSD 0.05 = 0.50 for 2022. The data is for the soil depth of 10 – 15 cm if there is a significant difference in the rise of soil pH.

Assessing this information, the 0-to-5-centimeter range (Figure 4.3) has brought the pH up to an average of 5.57 pH which is still lower than the target soil pH of 6.5, but more tolerable for crops. Between 2021 and 2022 the data from powdered surface, harrowed, tilled and granular surface, remain around the same pH level not seeing any significant change in the pH data. However, the granular harrowed does show a significant difference in pH change from 2021 to 2022. This is attributed to the granular taking longer to dissolve, disperse and react with the soils.

Whereas the granular tilled treatment saw an improvement in pH, but it was not statistically significant and that is likely due to a portion of the lime being worked deeper into the soil.

The 5-to-10-centimeter soil depth analysis (Figure 4.4) proved to be stable from 2021 to 2022 with no significant changes noted when analysing the data. The average pH is 5.02 in 2021 and in 2022 it is 6.29, this rise in pH is associated with the surface powdered application leaching into deeper soil layers and the granular lime also dispersing and leaching deeper into the soils. However, the granular harrowed and granular tilled treatments did see the most improvement with the harrowed powdered lime changing from a pH of 4.54 to 6.82 and granular tilled a change of 5.33 to 6.21. This is due to the granular form of lime dissolving and into the soils.

Lastly, within the 10-to-15-centimeter soil depth analysis (Figure 4.5) there was little difference between lime treatments regarding the level of pH each one was raised to. In this depth the average soil pH was originally 5.62 and rose to pH 6.00. At this depth the lime treatments are not influencing soil pH much due to the closer to natural alkaline parent materials not being affected as much by acidification processes compared to the 0-5 and 5-10 cm depths. The reason is that one, it is not as acidic there, so the pH does not have to increase as much as the soils closer to the surface and that the lime takes for time to react at these lower levels. This is a result of lime being not to soluble and mobile in the soil, preventing it from migrating down deeper and quicker.

4.2 Kings Lake Site – Brown Chernozem Soil

4.2.1 Starting soil pH 0 to 15 cm to Year 1 & 2 ANOVA Factorial Analysis

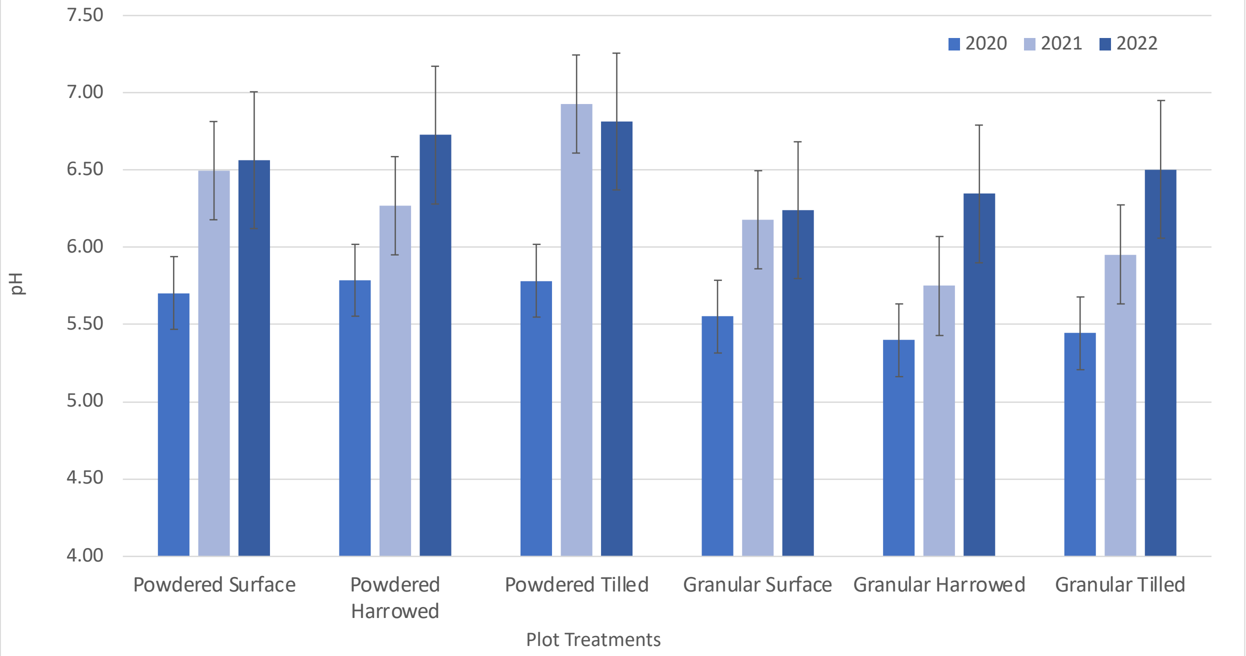


Figure 4.6: Displays the initial statistical comparison of the natural variation amongst the plots, Kings Lake site. Then it carries into how these variations of pH slowly returns to a neutral pH, changing due to the treatments applied to the soil and how the 0 to 15 cm growing zone.

The sample size n=21 for each individual year, with comparing the years n=63. LSD 0.05 = 0.23 is the uncertainty determine for 2020, LSD 0.05 = 0.31 for 2021 and LSD 0.05 = 0.44 for 2022. Data for the soil depth of 0 - 15 cm assessing if there is a significant difference in the rise of soil pH. The Kings Lake research field did not have as low of a pH value as the Hilton field or particularly the Sierra field, which will be discussed in section 5.3. Nevertheless, there was still an observable rise in soil pH in the 0-15 cm soil depth to lime applications (Figure 4.6). Prior to treatment in 2020 the pH ranged from 5.40 to 5.79 amongst the small plot averages. In 2021, one year after treatment this range improved to the lowest being 5.75 to 6.93 pH. Again, the most effective treatment was powdered lime that was tilled into the soil. While year 2 post-treatment in 2022 the lowest pH is 6.38 and the highest is 6.97. However, like the other two research sites by the second year after lime applications the differences between lime form and incorporation combinations were small.

4.2.2 Year 1 & 2 soil layer pH treatments ANOVA Factorial Analysis 0-5, 5-10, 10-15 cm

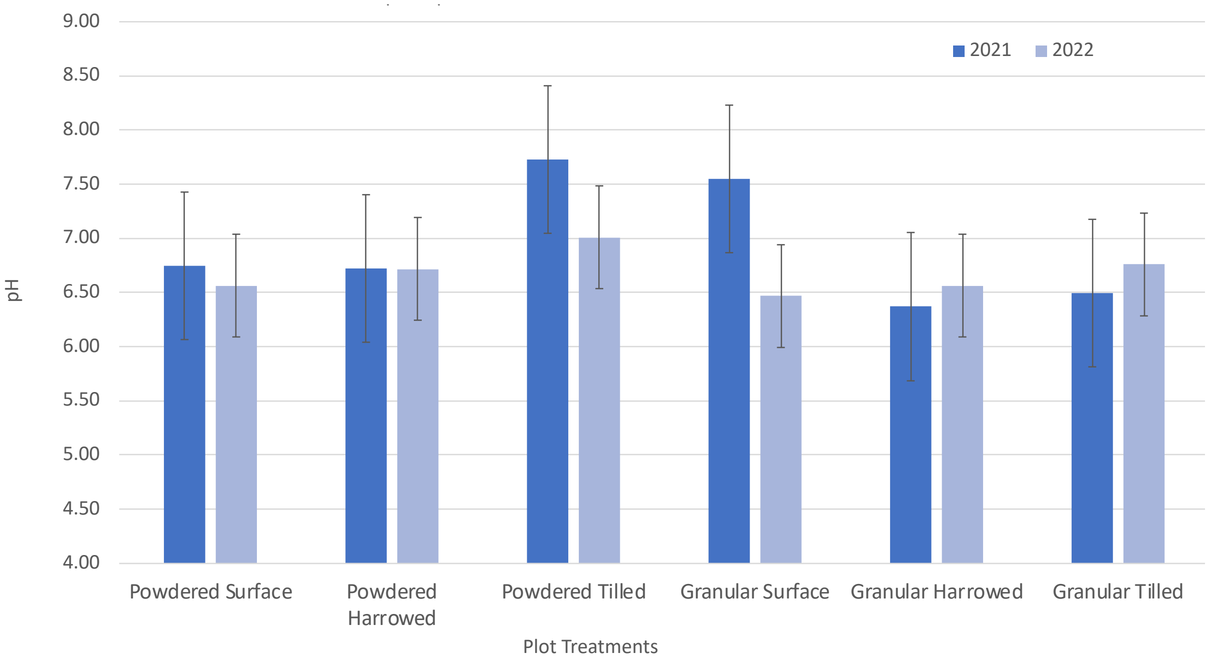


Figure 4.7: Displays the statistical comparison of the variation amongst the plots the treatments applied to the soil and how the 0 to 5 cm growing zone of the soil pH levels vary, Kings Lake Site. At this site and depth, the was no significant changes between the years.

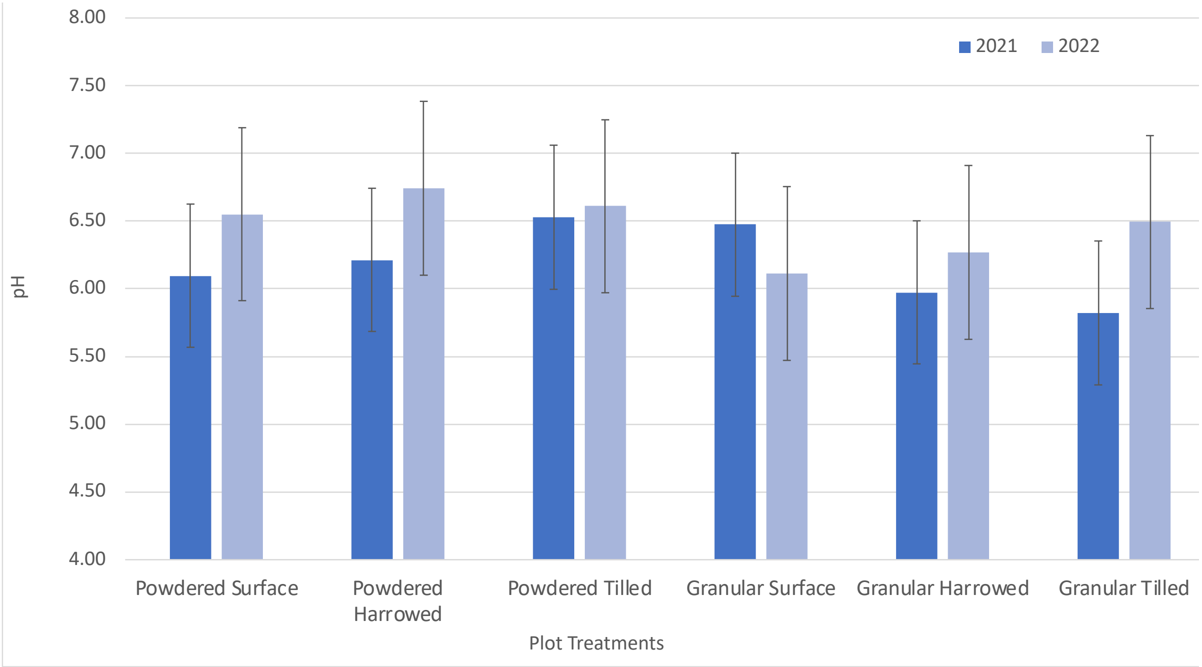


Figure 4.8: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 5 to 10 cm growing zone of the soil pH levels vary, Kings Lake site.

The sample size of n=21 for each individual year, with comparing the years n=42. LSD 0.05 = 0.53 is the uncertainty determine for 2021 and LSD 0.05 = 0.64 for 2022. The data is for the soil depth of 5 - 10 cm if there is a significant difference in the rise of soil pH.

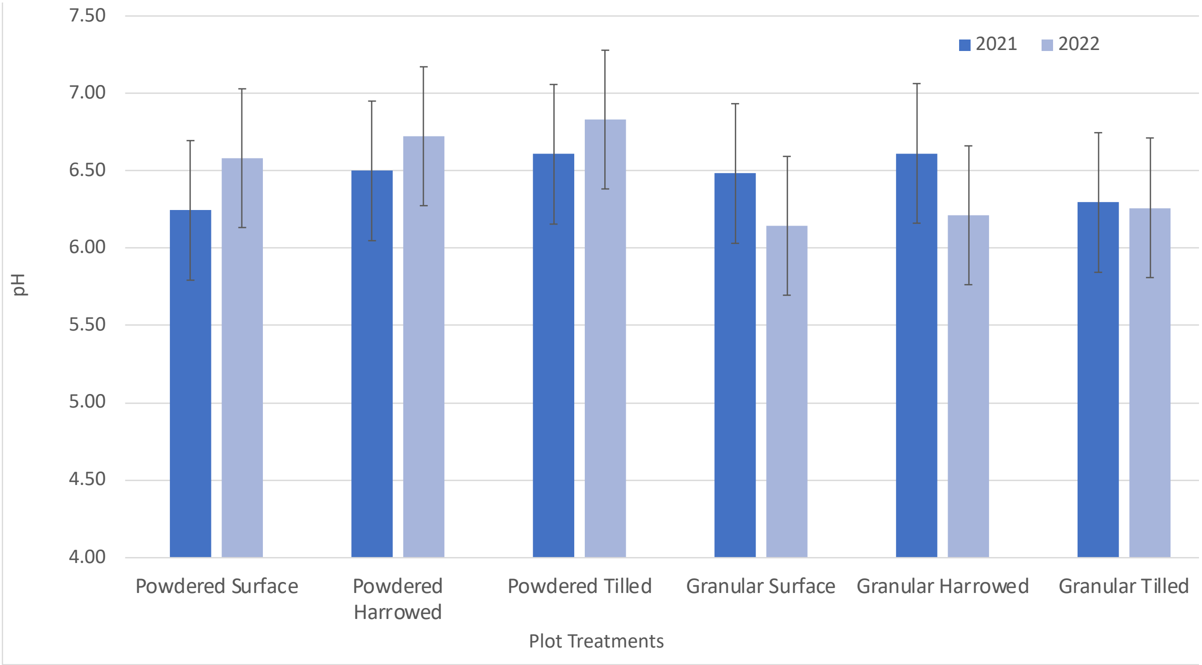


Figure 4.9: Displays the statistical comparison of the variation amongst the plots, with the treatments applied to the soil and how the 10 to 15 cm growing zone of the soil pH levels vary, Kings Lake site.

The sample size of n=21 for each individual year, with comparing the years n=42. LSD 0.05 = 0.45 is the uncertainty determine for 2021 and LSD 0.05 = 0.44 for 2022. The data is for the soil depth of 10 - 15 cm if there is a significant difference in the rise of soil pH.

The sample size n=21 for each individual year, with comparing the years n=42. LSD 0.05 = 0.68 is the uncertainty determine for 2021 and LSD 0.05 = 0.48 for 2022. The data is for the soil depth of 0 - 5 cm if there is a significant difference in the rise of soil pH. In the 0-to-5-cm depth (Figure 4.7) analysis, there was no significant difference shown in the treatments from year 2021 and 2022. This is the same said for the depths 5 to 10 (Figure 4.8) and 10 to 15 centimeters (Figure 4.9). However, like the Hilton Site and all the depths sampled in the Kingslake site, it is interesting to note that the greatest rise in soil pH from Year 1 to year 2 was observed in the granular harrowed and granular tilled treatments. However, these had the least improvements in pH initially in 2021.

4.3 Sierra Site – Dark Brown Chernozem Soil

4.3.1 Starting soil pH 0 to 15 cm to Year 1 & 2 ANOVA Factorial Analysis

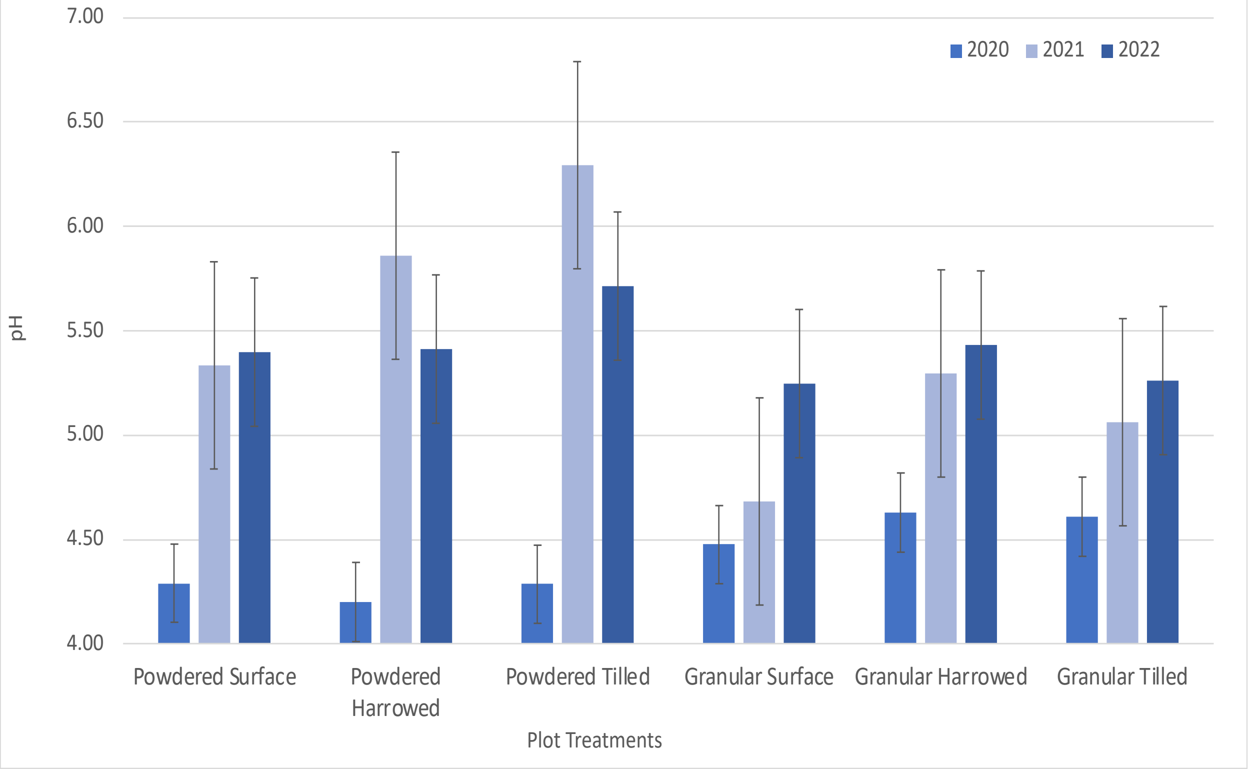


Figure 4.10: Displays the initial statistical comparison of the natural variation amongst the plots, Sierra site. Then it carries into how this variations pH slowly returns to a neutral pH, changing due to the treatments applied to the soil and how the 0 to 15 cm growing zone of the soil is changing.

The sample size of n=21 for each individual year, comparing the years n=63. LSD 0.05 = 0.18 is the uncertainty determine for 2020, LSD 0.05 = 0.50 for 2021 and LSD 0.05 = 0.35 for 2022. Data for the soil depth of 0 - 15 cm if there is a significant difference in the rise of soil pH. The Sierra research site had the lowest pH levels out of the three research sites with an average pH of 4.42 across the plots for the depth of 0 – 15 centimeters. The comparisons of the change in soil pH in the 0 to 15 cm soil depths are shown (Figure 4.10). In 2020 pre-treatment the plots averages ranged from a 4.2 to 4.63 pH. In the Fall of 2021, or one year after lime application, the control still had a low pH of 4.5 and the most effective treatment at a pH of 6.29 was the powdered lime and tilled treatment. Many of the other lime form and incorporation treatments had pH values in between the control and the powdered lime and tilled treatment. This however changes going into year 2 in Fall 2022 with the control being 4.87 and the highest treatments pH of 6.14. Here the differences between the lime form and incorporation treatments have narrowed and there is fewer treatment mean differences observed. This shows the treatments did not have as much of an effect on soil pH during the first year. But it did perform as good as the others by the second year after lime application. This is the result of a few factors, one being the granular lime takes longer to break down and treat the soil, compared to the powdered lime. As well as the drought conditions the prairies faced during these years, would have influenced the break down of the lime into the soil layers.

4.3.2 Year 1 & 2 soil layer pH treatments ANOVA Factorial Analysis 0-5, 5-10, 10-15 centimeters

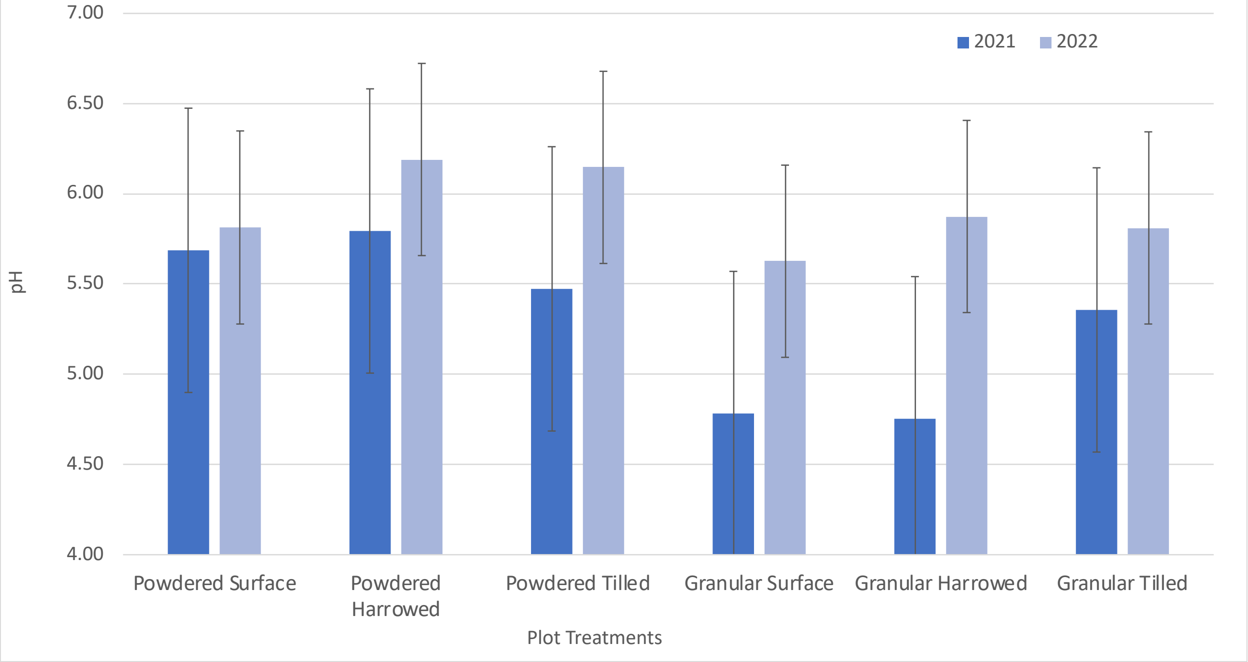


Figure 4.11: Displays the statistical comparison of the variation amongst the plots, with the treatments applied to the soil and how the 0 to 5 cm growing zone of the soil pH levels vary, Sierra site. At this depth, the treatments that showed improvement from 2021 to 2022 was the granular surface and harrowed. However, they also performed less than the other treatments for increasing the soils pH in 2021.

The sample size of n=21 for each individual year, with comparing the years n=42. LSD 0.05 = 0.79 is the uncertainty determine for 2021 and LSD 0.05 = 0.53 for 2022. The data is for the soil depth of 0 - 5 cm if there is a significant difference in the rise of soil pH.

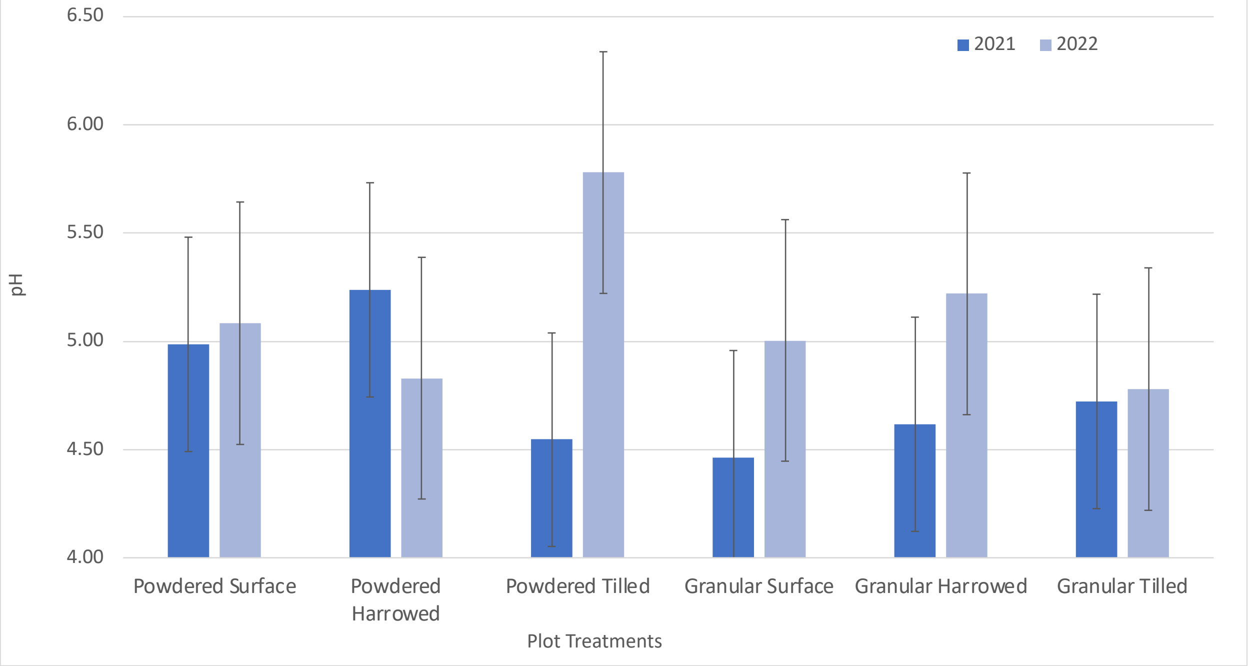


Figure 4.12: Displays the statistical comparison of the variation amongst the plots with the treatments applied to the soil and how the 5 to 10 cm growing zone of the soil pH levels vary, Sierra site. All treatments performed similarly from 2021 to 2022, however the powdered tilled treatment significantly increased from 2021 to 2022.

The sample size of n=21 for each individual year, with comparing the years n=42. LSD 0.05 = 0.49 is the uncertainty determine for 2021 and LSD 0.05 = 0.56 for 2022. The data is for the soil depth of 5 – 10 cm if there is a significant difference in the rise of soil pH.

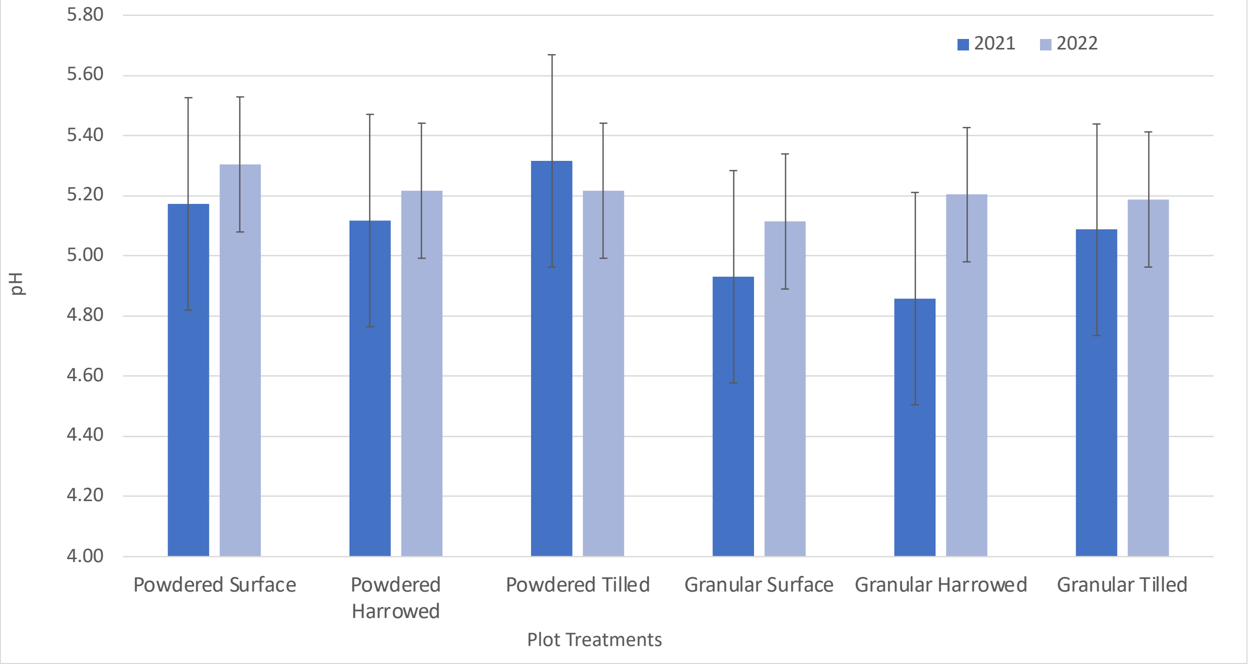


Figure 4.13: Displays the statistical comparison of the variation amongst the plot with the treatments applied to the soil and how the 10 to 15 cm growing zone of the soil pH levels vary, Sierra site.

The sample size of n=21 for each individual year, with comparing the years n=42. LSD 0.05 = 035 is the uncertainty determine for 2021 and LSD 0.05 = 0.22 for 2022. The data is for the soil depth of 10 - 15 cm if there is a significant difference in the rise of soil pH.

Unlike the Hilton and Kings Lake site, the Sierra site data does differ more for how the treatments behave in the soil as affecting soil pH. This could be due to various reason, one being that this site was lower in pH than Hilton and Kings Lake sites, and that the effects of the treatments can be seen in the results much more clearly. In the 0-to-5-centimeter depth (Figure 4.11), the average of all plots this depth in 2021 is 5.31 and in 2022 5.91, with no significant differences between the years. However, there is a rise in pH in all the treatments, the highest being the three granular-incorporation treatments and the powdered lime and tilled treatment. The 5-to-10-cm depth (Figure 4.12) showed that all plots had no significant difference between years 1 and 2 except for the granular harrowed which had a greater rise in soil pH. Changing from a pH of 4.62 to a pH of 5.22. Lastly, the 10-to-15-centimeter depth (Figure 4.13) had two significant changes from 2021 to 2022 in treatments and they were the granular harrowed and granular tilled. This is similar the observations made at the Hilton and Kingslake sites depths of 10 to 15 cm. But, at the Sierra site, the data shows they did in fact change the deeper soil depths greatly two years post treatment (Figure 4.13).

4.4 Three Site and Two Year Combined Factorial Analysis

In Sections 4.1 through to 4.3, the research results for each of the three lime application research sites was shown and discussed separately. In Table 4.4 is a summarized look into the data by combining the three sites from two years of data and running the data in a four-way ANOVA Factorial Analysis. The statistical significance of the combined sites along with the graphs earlier, from each individual site, allow for insight into which factors are influencing the change in soil pH. Graphs are also included below showing the overall three-site analysis and the differences between experimental treatments.

Table 4.4: ANOVA four-way factorial analysis.

Experimental Factors and Interactions	F probability values for factors and factor interactions			
	0-15 cm	0-5 cm	5-10 cm	10-15 cm
Form	0.0018	ns	ns	ns
Placement ns ns ns ns	ns	ns	ns	ns
Form + Placement ns ns ns ns	ns	ns	ns	ns
Year	0.0086	0.0121	0	ns
Form + Year	0.0002	ns	ns	ns
Placement + Year	ns	ns	ns	ns
Form + Placement + Year	ns	ns	ns	0.0438
Site	ns	ns	ns	ns
Form + Site	ns	ns	ns	ns
Placement + Site	ns	ns	ns	ns
Form + Placement + Site	ns	ns	ns	ns
Year + Site	0.0051	0.0035	0.0002	ns
Form + Year+ Site	ns	ns	ns	0.003
Placement+ Year + Site	ns	ns	ns	ns
Form + Placement + Year + Site	ns	ns	0.0095	ns

* Not Significant (ns)

Starting with the 0-15cm soil depth, **form** was statistically significant, this was seen in each field assessed individually based on the lime being powdered or granular. It was noted that the pH did rise the most with the powdered lime the first year after lime application as it more quickly moved into and reacted with the soils. The **year** also was noted to be significant, with all lime treatments raising soil pH by the second year, but not in the first year. As well the **form + year** interaction was significant. **The Year + site interaction** is significant as there were differences between sites between the two years. It is a positive research result to observe changes happening within the 0-15cm depth, as it shows this main soil growing layer is successfully being ameliorated from an acidic to a neutral pH.

Next for the 0-5cm soil depth, **year** was noted to be significant. This is likely a result of it being the first depth of soil in contact with the applied lime treatment, especially for the lime applications applied and not incorporated with harrowing or tillage._**Year + site interaction**, was significant, specifically for the 0-5 cm depth.

The 5-10 cm soil depth, **year** is significant likely because of lime in most treatments were measured and showed in the data that the lime moved down into the second depth by the second year. The slightly different soil properties of soil texture and organic matter content between the three field research sites resulted in a Year + site interaction. Lastly, the four-way interaction of **Form + Placement + Year + Site**, is significant for the 5-10 cm depth, however even though these four factors together are significantly different when combined, it makes it difficult to interpret. With the four-way comparisons, with the site included. This adds in other variables which does change the dynamic of the data. The treatments all behave similarly in each field, but the rate at which they change between the sites is different. This has to do with different textures, SOM and climate. All of which will affect the time it will take to change and the degree of which the pH will change.

For the 10-15cm soil depth, **form + placement + year** interaction had significant results, which is due to all these influences of the powdered and granular, the tilling, harrowing or surface and the time between samplings. The change in pH at this depth, is useful to show how all the lime treatments are successfully raising soil pH down to this depth. Lastly, **form + year + site** proved to be significant and is important to note that even in the deeper soil layers there is still a variability from field to field of pH. The lime form has notable impacts on the deeper soil pH test and over time the pH has changed from these treatments and the natural variability in the plots.

Sampling in the depths 15-30, 30-45, and 45-60 cm was done at both years one and two years after lime applications, and the pH values measured. There did not appear to be any effect of lime application treatments on these lower depths. As a result of the pH naturally increasing to more neutral or alkaline at this depth and increasingly so, the deeper the sample was taken. As well, the lime has little to no affect at this depth, as most of the carbonates would tie up in the shallower layers to raise the pH, leaving little to be leeched down, if any at all would be leached since lime is not highly mobile in the soil. As well with the high soil pH at this depth, there would be no way to measure if the lime did change the soil. As well, the limiting low pH is in the 0 to 15 cm depth, where acidity is having an effect, but lower, these pH values are more neutral.

4.4.1 Starting soil pH 0 to 15 cm compared to Years 1 & 2, ANOVA Factorial Analysis – three fields combined.

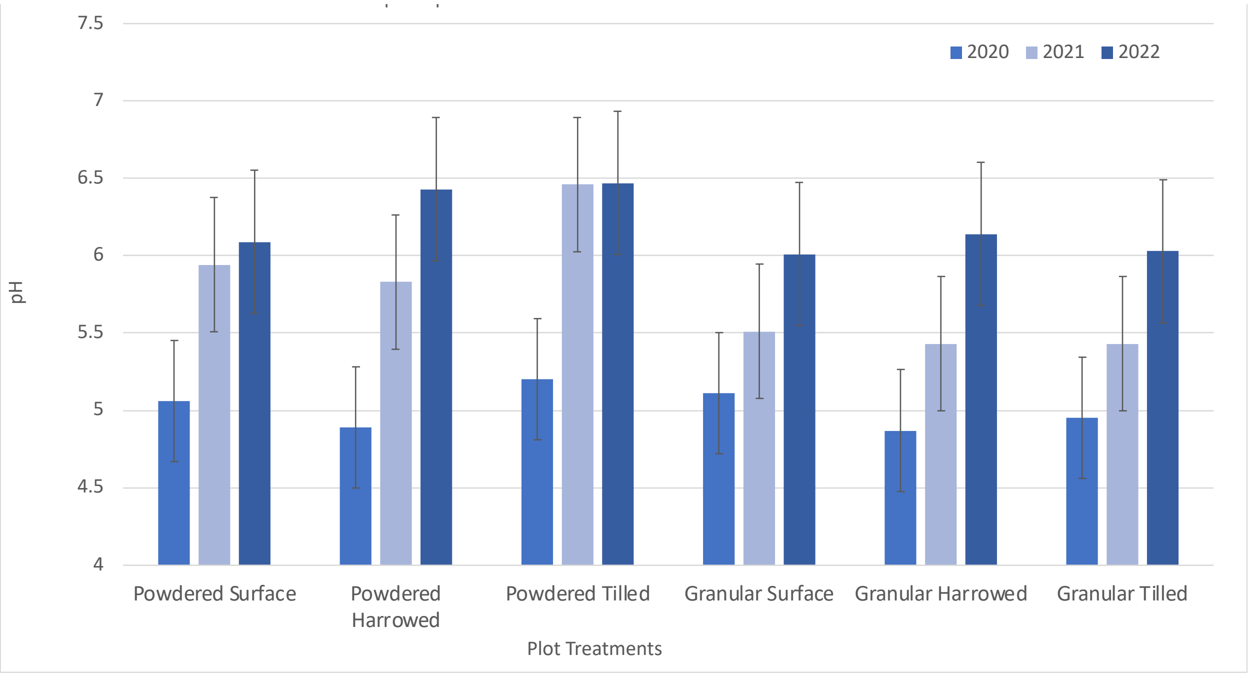


Figure 4.14: Displays the three-site combination statistical comparison of the six-lime form-incorporation treatments, before lime application to years 1 and 2.

The sample size n=63 for each individual year, with comparing the years n=126. LSD 0.05 = 0.39 is the significant difference for 2020, LSD 0.05 = 0.43 for 2021, and LSD 0.05 = 0.46 for

2022, for the soil depth of 0 - 15 cm. This is valuable data showing the combined three research fields have similar trends to each other, indicating that the treatments are behaving the same.

4.4.2 Year 1 & 2 soil layer pH treatments ANOVA Factorial Analysis 0-5, 5-10, 10-15 centimeters – three sites combined.

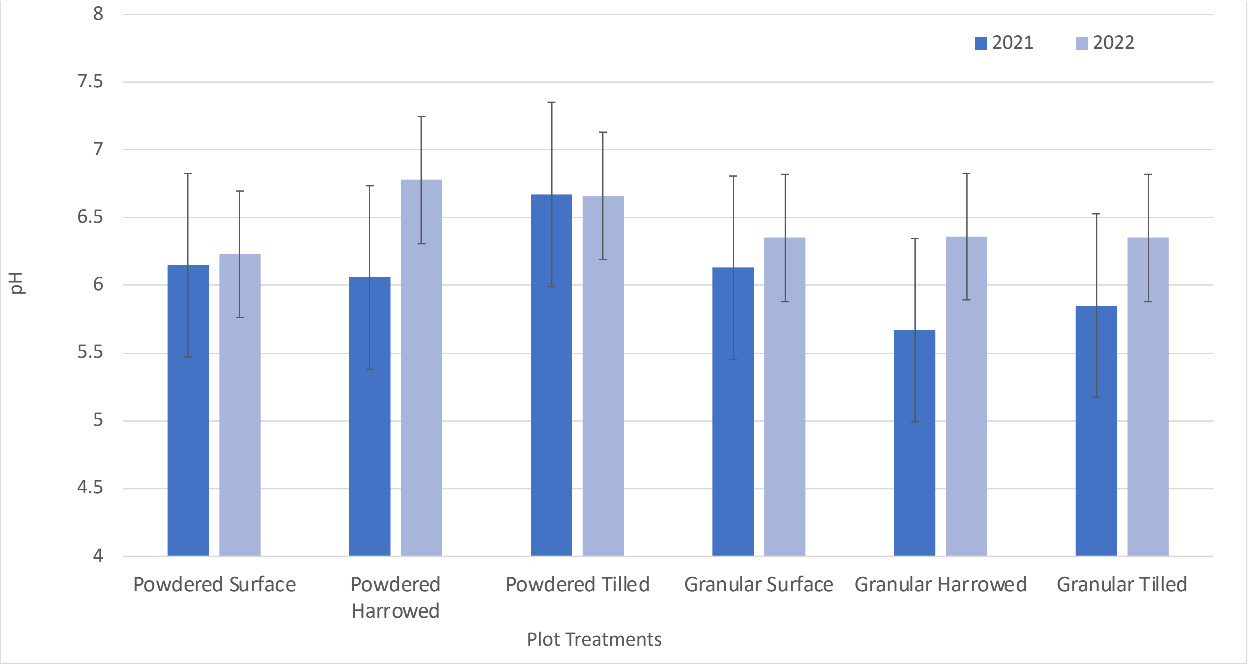


Figure 4.15: Displays the three-site combined statistical comparison of the variation amongst the treatments applied to the soil and how the 0 to 5 cm layer of the soil pH was affected.

The sample size of n=63 for each individual year, with comparing the years n=126. LSD 0.05 = 0.68 is the uncertainty determine for 2021 and LSD 0.05 = 0.47 for 2022. The data is for the soil depth of 0 - 5 cm if there is a significant difference in the rise of soil pH.

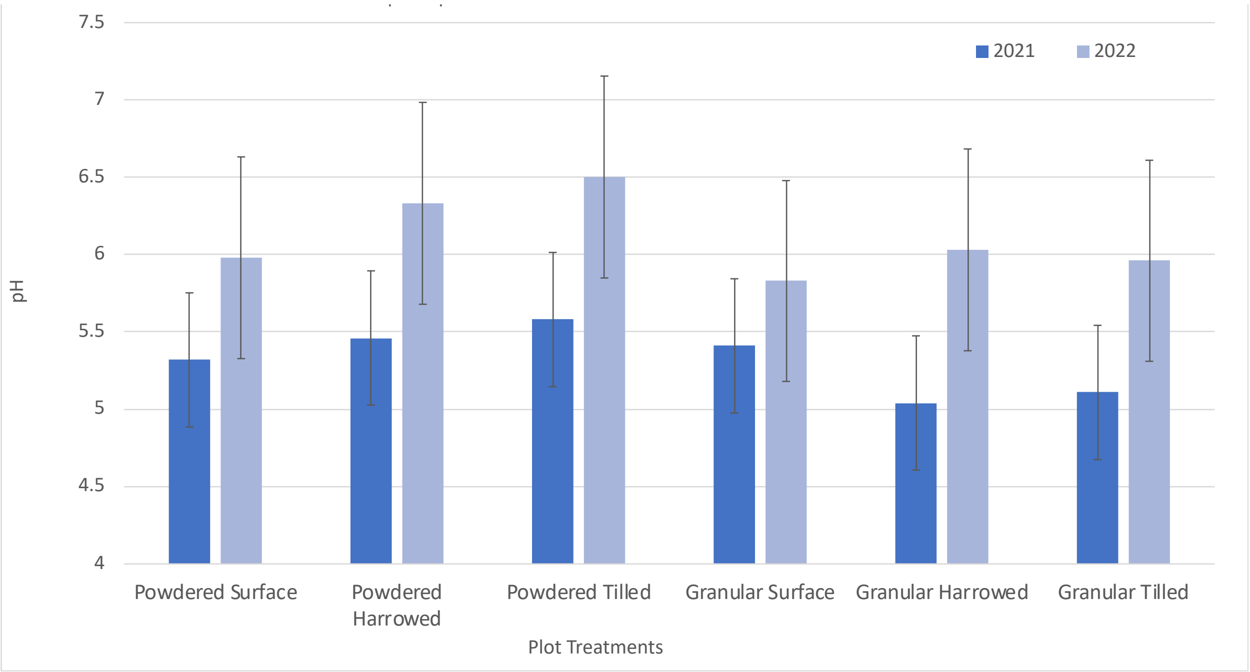


Figure 4.16: Displays the statistical comparison three-site combined of the variation amongst the treatments applied to the soil and how the 5 to 10 cm growing zone of the soil pH levels was affected.

The sample size of n=63 for each individual year, with comparing the years n=126. LSD 0.05 = 0.43 is the uncertainty determine for 2021 and LSD 0.05 = 0.65 for 2022. The data is for the soil depth of 5 – 10 cm if there is a significant difference in the rise of soil pH.

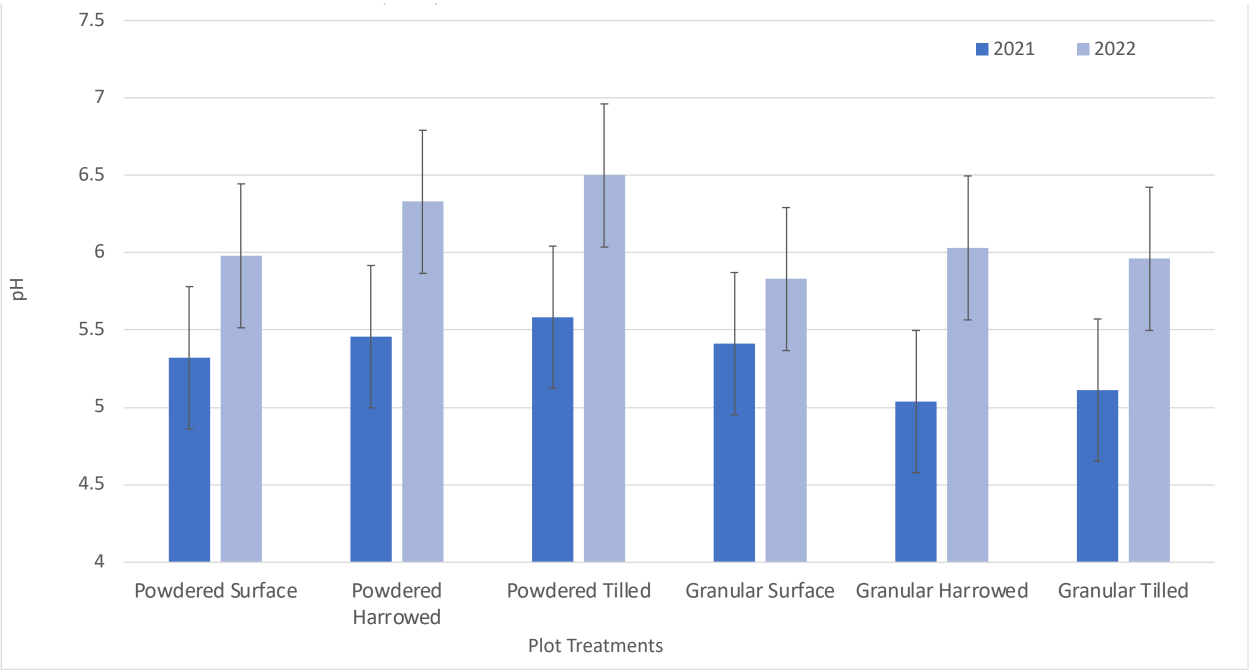


Figure 4.17: Displays the statistical comparison three-site combined of the variation amongst the treatments applied to the soil and how the 10 to 15 cm growing zone of the soil pH levels was affected.

The sample size of n=63 for each individual year, with comparing the years n=126. LSD 0.05 = 0.45 is the uncertainty determine for 2021 and LSD 0.05 = 0.46 for 2022. The data is for the soil depth of 10 - 15 cm if there is a significant difference in the rise of soil pH. Besides the treatment comparisons, it is beneficial as well to see how the soil pH average across all three sites changes through the soil depths. As well, from each treatment and also going past the 15 cm depth to show how after this soil depth, the soils pH increases steadily (Figures 4.18 to 4.23).

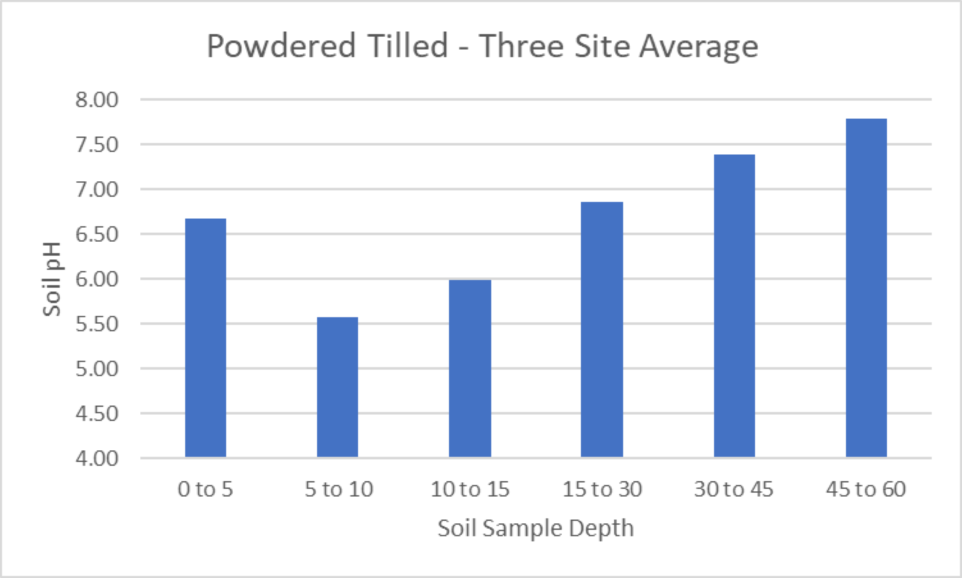


Figure 4.18: Soil depth profile of pH change, the pH change influence from the lime treatment and incorporation to the natural increase of pH.

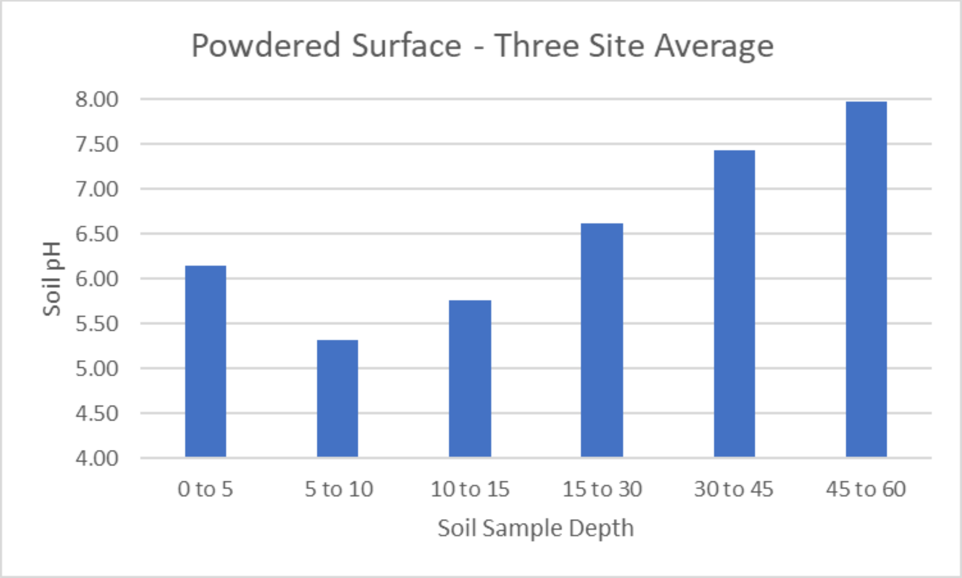


Figure 4.19: Soil depth profile of pH change, the pH change influence from the lime treatment and incorporation to the natural increase of pH.

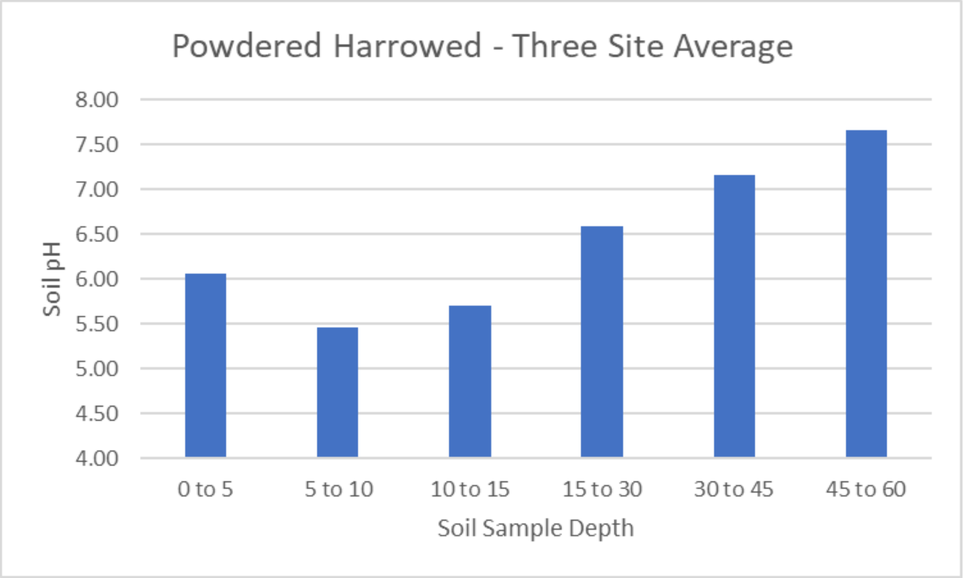


Figure 4.20: Soil depth profile of pH change, the pH change influence from the lime treatment and incorporation to the natural increase of pH.

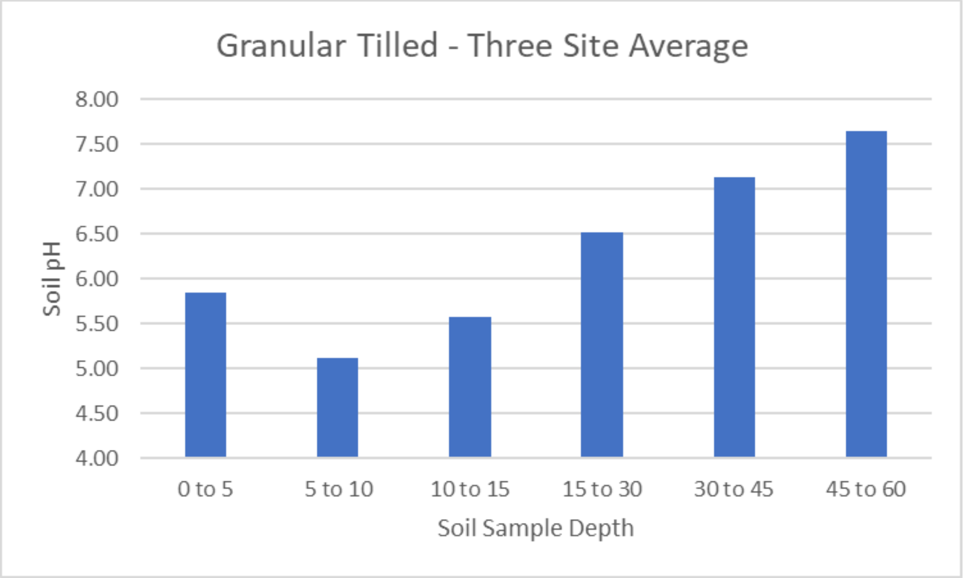


Figure 4.21: Soil depth profile of pH change, the pH change influence from the lime treatment and incorporation to the natural increase of pH.

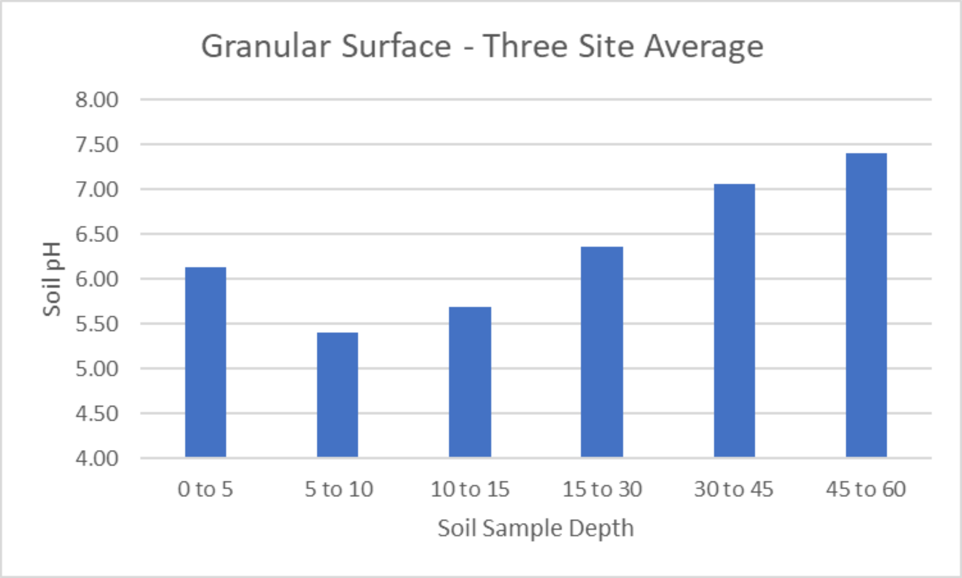


Figure 4.22: Soil depth profile of pH change, the pH change influence from the lime treatment and incorporation to the natural increase of pH.

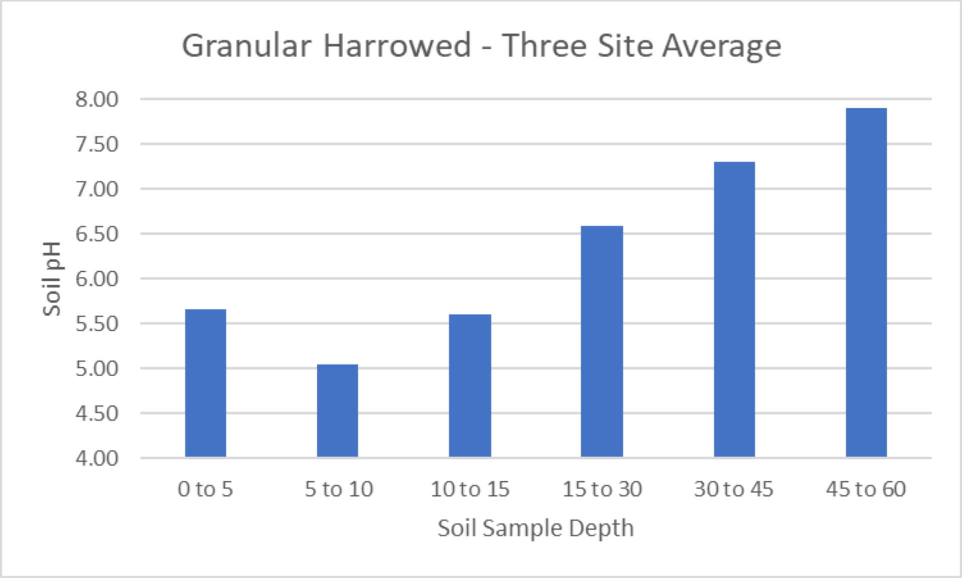


Figure 4.23: Soil depth profile of pH change, the pH change influence from the lime treatment and incorporation to the natural increase of pH.

The data gathered from the three research sites showed that the lime application treatments are in fact working, even with some pH variability occurring throughout the relatively small plot area, i.e., 7 m x 14 m area, which was determine by the initial 0 to 15 cm soil collection and pH testing of each plot. The overall, results are promising that soil pH levels have been raised to a more suitable level for crop growth, e.g., close to a pH of 6.5. There will still always be variability in the soil, but a more suitable soil pH variability to allow the growth of healthier crops. As for comparing types of lime and incorporation methods, the research has shown that there are noticeable differences between treatments the first year, but less differences between lime treatments in the second year.

The top layer of soil (0 – 15 centimeters) in agricultural fields is a key area for influencing crop growth. Once the crop has been planted the roots may have trouble establishing due to soil hardness, compaction, pore sizes, loose soil, and erosion (Passioura, 2002). The results found in this study, shows that pH could be a potential factor that may also impact crop germination and growth. This is because soil pH has a great influence on root health, root growth, and nutrient availability. The research shows that all lime treatments were effective; however, some do still perform more effectively in a shorter time.

Furthermore, it was observed with the pH test results that there was some natural pH variability of the soil within the small plot research areas, i.e., Hilton ranging from 4.59 to 5.54, Kingslake ranging from 5.40 to 5.79 being the least acidic site, and Sierra ranging from 4.20 to 4.63 having the lowest pH values out of the three small research plot areas.

4.5 Soil pH Spatial Variability

4.5.1 Sampling Density

One of the questions asked by farmers with patches of acidic pH soils is how many samples are required to be able to accurately show the different soil pH zones in a field and ultimately produce a reliable variable lime treatment map. This led to the results of making pH variation maps with different sampling densities using one of the Miller Farm fields west of Olds, AB. Figure 4.18 demonstrates a sample density of one sample every 0.4 hectares (1 acre), this produced a useful map showing spatial change of soil pH in a single field. With this pH areas were detected as low as 4.5 – 5.2, with others being 5.2 – 5.5, 5.5 – 6.2 and 6.2 – 7.5. This dynamic change enforces why taking a sample for every 0.4 hectares (1 acre) (Figure 4.24) will produce the most spatially accurate results. It even allows to see how a field can be broken up by these different lower versus higher pH areas or zones, as well as indicate smaller pockets of different pH levels amongst contrasting values. From there this was halved to one sample for every 0.8 hectares (2 acres) (Figure 4.25). This sampling density produced a reasonably accurate map with similar pH range zones as produced using the denser sampling. However, the pH zones are changed slightly and less detailed. Further changing to a sample density of everyone sample for every 1.2 hectares (3 acres) (Figure 4.26), there begins to be a loss in the accuracy of pH variation in a field. With less density, kriging does not perform as well as it is seen at this number of samples. Lastly at a sample density of one sample for 1.6 hectares (4 acres) (Figure 4.27), this sample density greatly underperforms and is not effective for producing a useful pH variation map, let alone a lime prescription map.

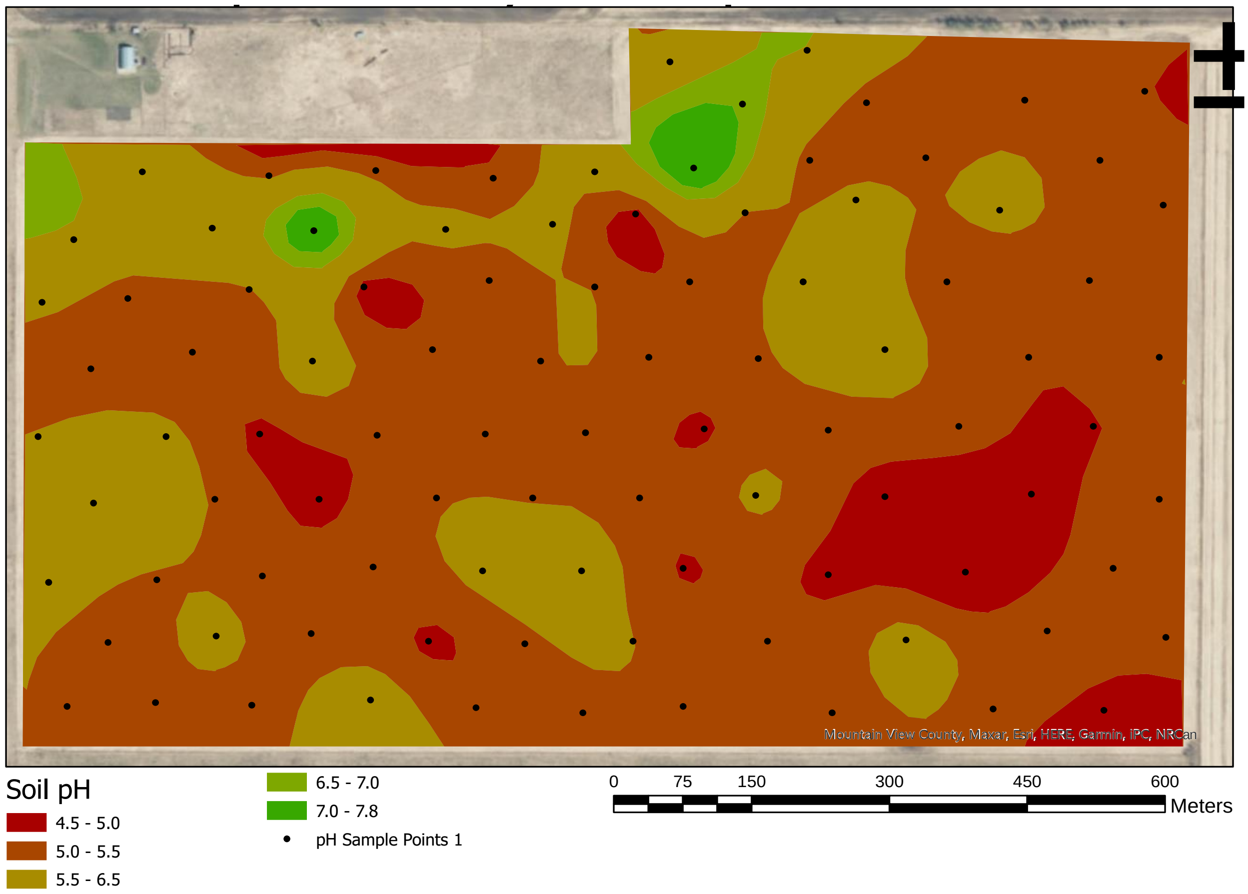
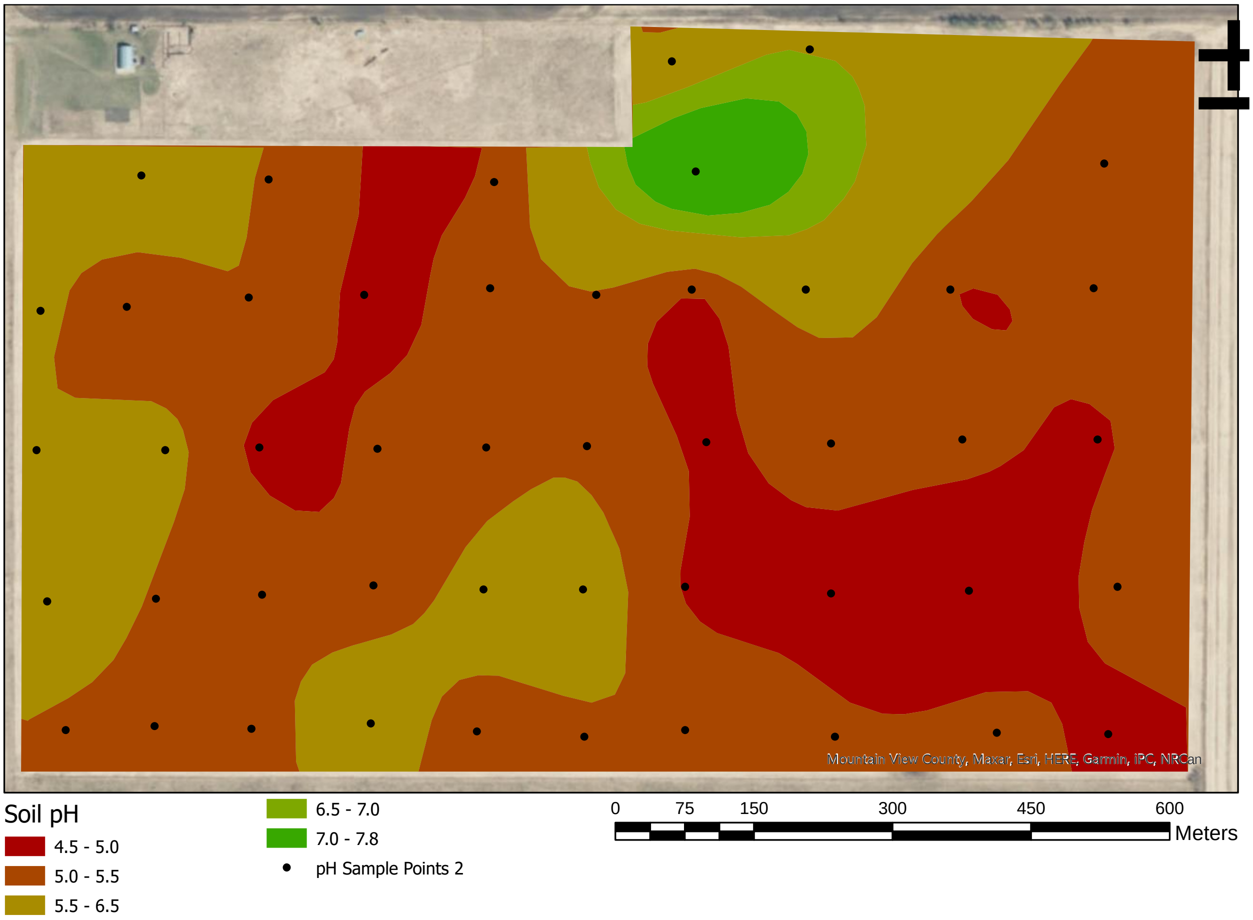


Figure 4.24: 1 sample per 0.4 hectares (1 acre), Miller Farm.

In figure 4.24 this sample density is a higher standard to sample at and takes a considerable amount of time, but the results are a more accurate representation of what the fields pH is across the area. Based on the physical data gathered in the field and spread across the spaces between the data points, this pulls the values from the physical data points and spreads them out over the field. Which is why it is important to have spaced out sample points to even out the weighting of the map to be made. But, due to soils high variability, there could values higher or lower than predicted from the interpolation. However, keeping in mind the end results need for this data, these smaller areas would be irrelevant when treating the field in an agricultural management perspective.



Mountain View County, Maxar, Esri, HERE, Garmin, IPC, NRCan

Figure 4.25: 1 sample per 0.8 hectares (2 acres), Miller Farm.

In figure 4.25 sample density is acceptable in terms of precision agriculture for variation maps, and in some cases, growers may only want this density sampled due to cost. It provides an accurate representation of what pH’s average is across the area, based on the physical data gathered, pair with the interpolation method best fit for the end results. This should be the lowest standard of grid sampling to ensure a precise map.

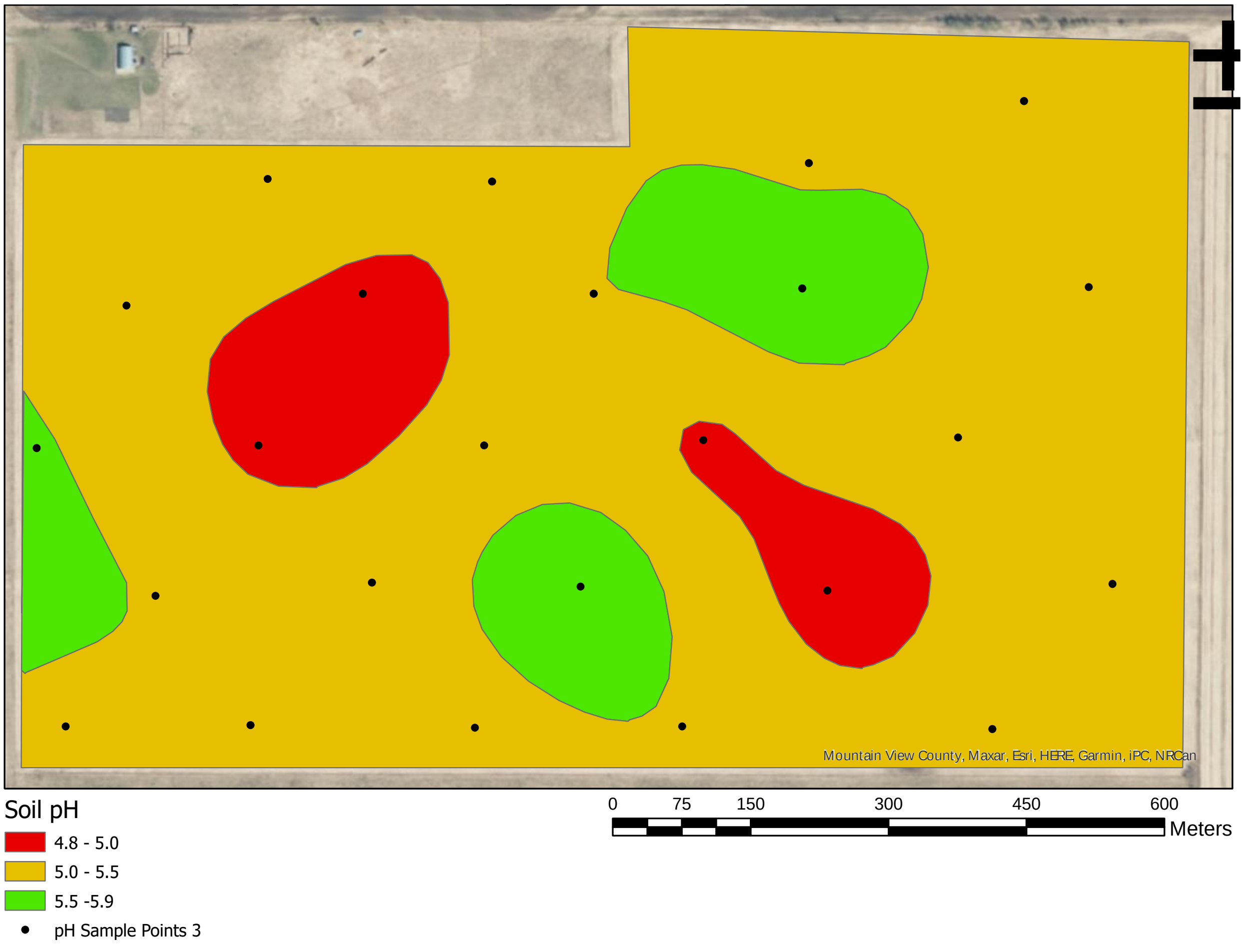


Figure 4.26: 1 sample per 1.2 hectares (3 acres), Miller Farm.

In figure 4.26 this sample density is beginning to lose accuracy; it generalizes the field to be closer to the fields average pH and could thus result in errors for an accurate lime variation map. This can be observed by the spots of extreme changes, as well as the average pH of the field starts to become the dominate zone of the map.

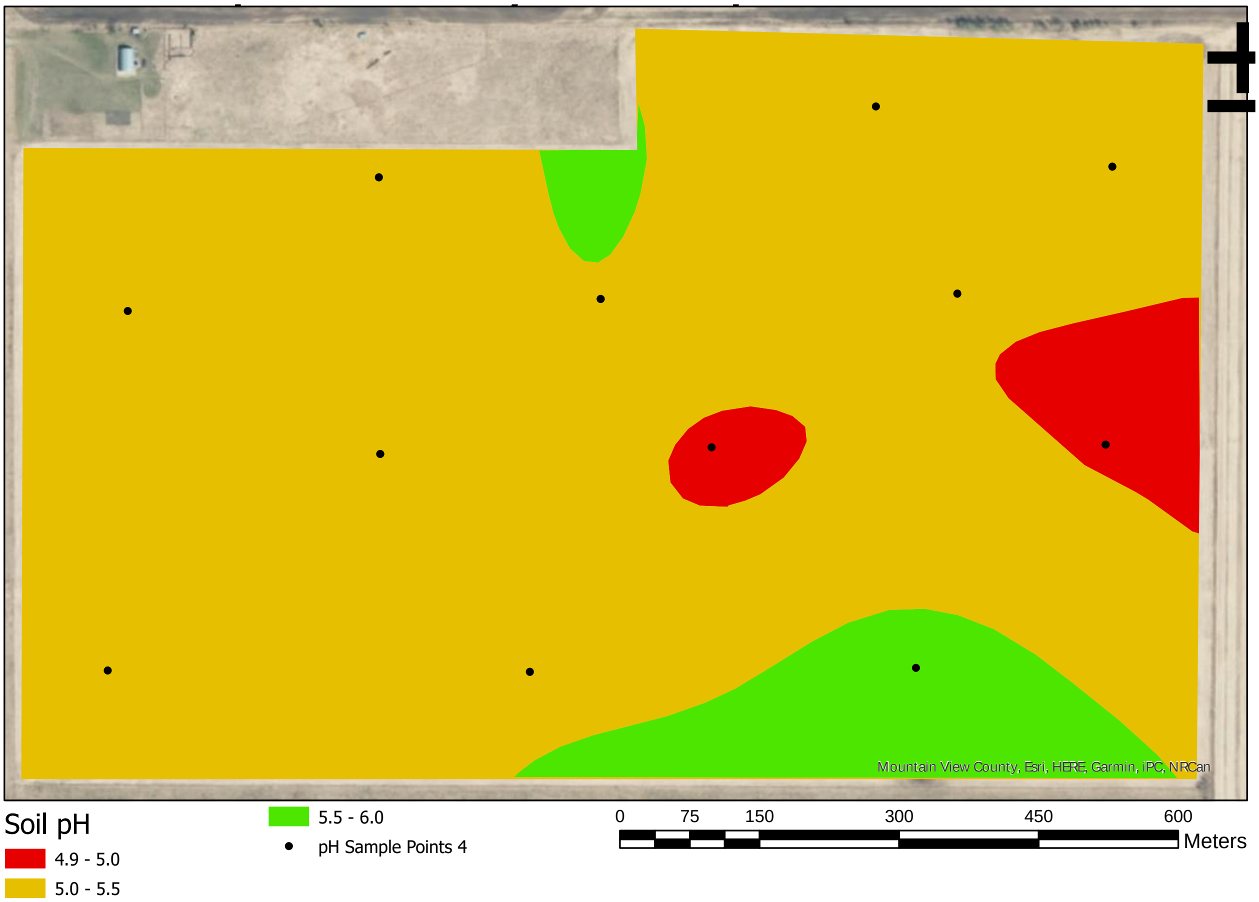


Figure 4.27: 1 sample per 1.6 hectares (4 acres), Miller Farm.

In figure 4.27 sample density is encroaching on conventional composite sampling, which is when 15 random soil sample spots are taken, then combined. This entails taking soil samples spread out over a field evenly, mix the sample and take the average of that soil result. Which when you compare this sample density, the results would be very similar to conventional composite soil sampling and the treatment would be treated the same, from an agricultural management perspective. This density resulted in very little differences in pH, and this could vary per field as you could get very different results if the samples are taken in different spots. Making this an unreliable density for applying a variable rate of lime to raise the soil pH.

4.5.2 Soil pH Variation

In soil, there can be a wide range of variability in a field, not just in pH but other factors as well, e.g., texture, SOM, nutrient levels and so forth. This is a result of natural forming factors of the area, the climate and management practices. This study was on pH, understanding the most effect amelioration methods on these dryland no-till farms, how sampling densities can have a significant impact on understanding the complexity of a field and how variable they can be within a field. This is why the Bashaw Site (Figure 4.28) and Haenni Site (Figure 4.29), were done to assess these extreme changes.

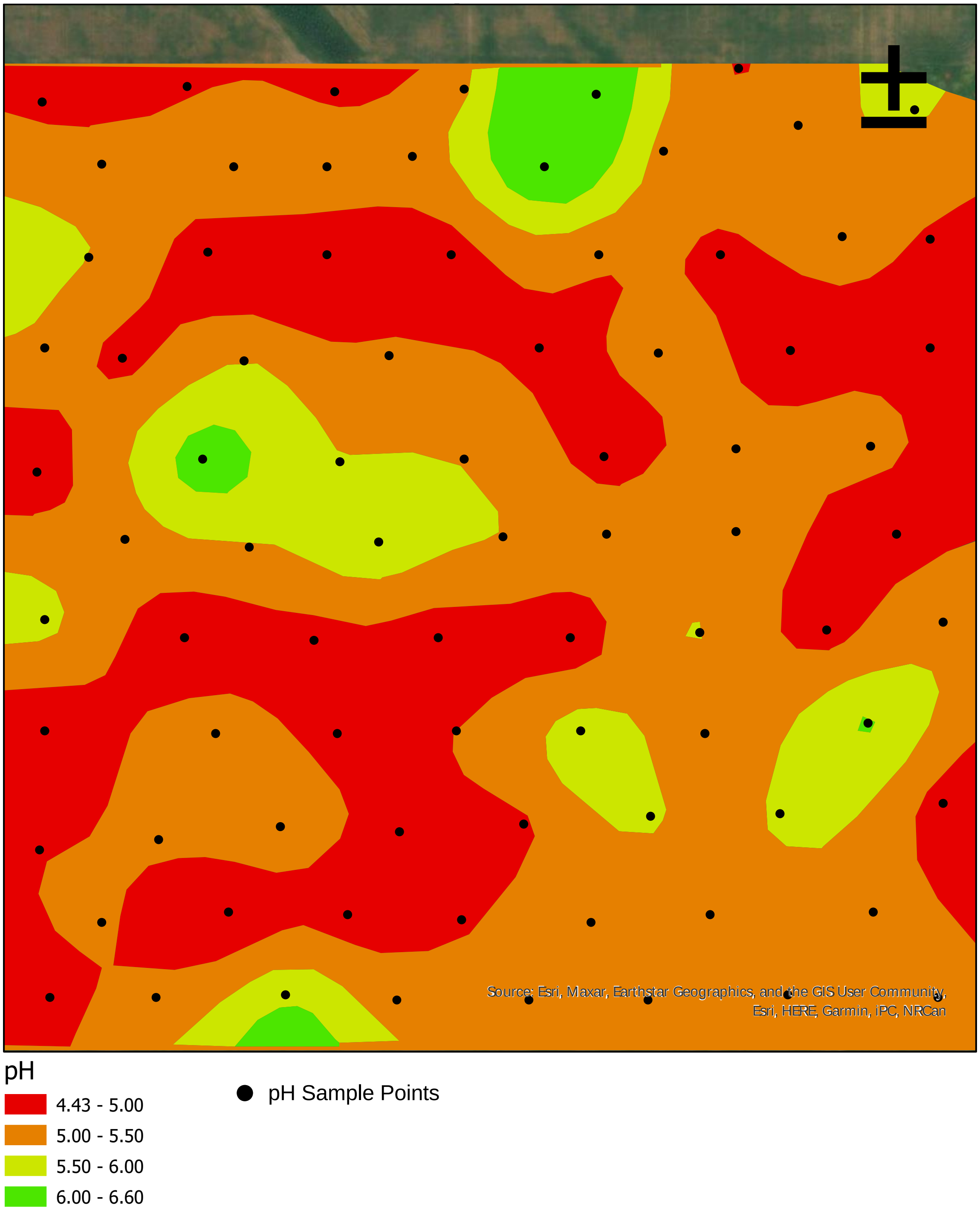


Figure 4.28: Bashaw Site Spline map with the pH field tested and mapped out to show the pH variation throughout the field.

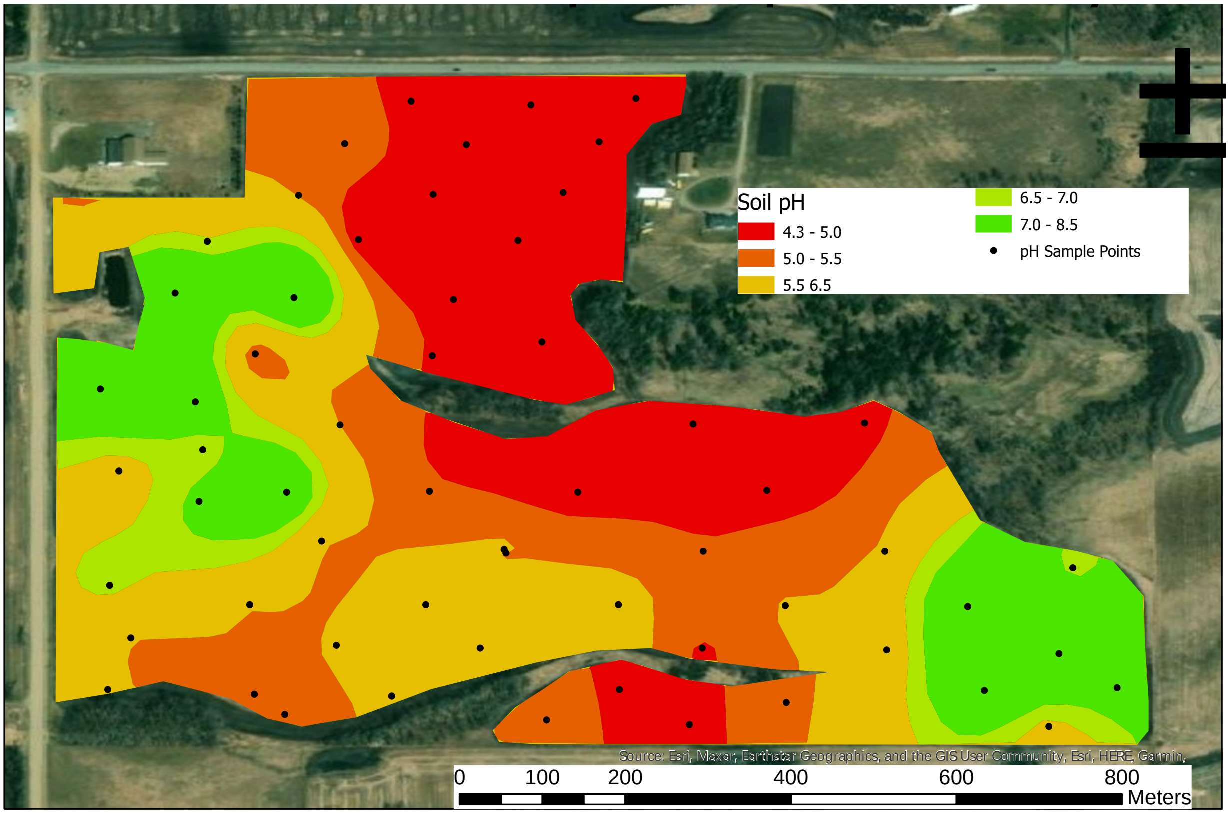


Figure 4.29: Haenni Site Spline map with the pH field tested and mapped out to show the pH variation throughout the field.

Due to anthropogenic influences, primarily ammonium-based nitrogen fertilizer applications, soil pH values have decreased on average and excessively acidic in portions of fields. The Miller, Bashaw and Haenni fields are examples of how much difference there is from the lower pH values to the high. These maps show how N-fertilizer applications, environmental factors, topography, and other soil influencing factors affect soil pH variability, over a period of about four to five decades of cropped agriculture. The pH in the Millers field is generally lower throughout, but even within these fields there are still observable areas of more neutral soil pH. This is the same for the Bashaw (Figure 4.28) and Haenni (Figure 4.29) fields. Research in this study show that soil pH values cannot be assumed to be uniform across the fields. If a blanket application of single lime rate were to be applied this would raise the pH too high in some areas that were already neutral in pH. Resulting in possible excessively alkaline pH values, resulting in nutrient deficiencies for some nutrients, e.g., P and Zn, in parts of the fields and thus likely resulting in lower crop yields in previously neutral to mildly alkaline soil pH areas.

Chapter 5 – Conclusions

5.0 Summary

The purpose of this study was to conduct trials to assess if lime could increase a soils pH just as effectively with little to no incorporation, since all these sites were on no-till dryland farms. Typically, lime is incorporated into the soil to get it to react in the soil and change the pH more efficiently, however, if this could be avoided, and still increase the soils pH, then that would be extremely beneficial knowledge to these growers.

As a result, this study was done in fields in the dark brown, black, and brown chernozemic groups, which were selected to be apart of the research. The reason for this was to have the studies conducted on the dominate agricultural soils, to know it would work in most, if not all similar areas. Once it was proven to be acidic by testing the soil, the samples were collected, pH and lime requirement tested and mapped out. From there a location was selected with specific criteria, noted earlier in this thesis, to place the research plots. The plots were set up, tested before any treatment, then all treatments were applied and then one year past. After this time past, the soil sampling of the soils was conducted, as well as two-year post treatment as well. All analysis was completed to assess how the treatments were ameliorating the soils pH.

The soil pH variability aspect of the study was also done on chernozemic soils, with growers suspecting significant pH changes. This portion was set up, to be able to truly understand how variably a pH could change in a single field, and why it was important to conduct detailed sampling. As well as how many samples would be needed in a field to accurately map these acidic areas out.

From these results it can be concluded that if a fast rise, i.e., one year, in soil pH is needed using powdered lime tilled into the soil will be effective. The granular lime-harrowed and granular-lime tilled treatments in the data suggests it has effectiveness within two years, and to a greater depth, i.e., 10 to 15 centimeters. The small plot research results show that using granular or powdered and any incorporation method would see an improvement in soil pH within two years. The grid soil sampling at three additional fields to the original three field sites shows how grid soil sampling can be used for accurately representing a fields pH spatial variation. Furthermore, it is imperative to understand the pH will likely remain variable throughout each field individually because of a fields own natural heterogeneity of such soil characteristics as soil texture and organic matter content.

5.1 Conclusions

There are different perspectives this research could have on agricultural management for farms assessing and treating their fields for soil acidity. The first objective of this research to identify soil acidity locations to host research plots on comparing lime treatments amelioration effects. This started with the lime type itself, the results show how powdered lime does in fact improve the soils pH faster than the granular, and this is likely due to the granular lime not mixing and reacting with the soil as quickly. This is due to the lime being not an extremely soluble material, so the powdered source is smaller and would react with the soil faster than the granular. However, both forms of lime, powdered or granular do show signs of ameliorating the soil, which is promising and beneficial to not limit lime types used. This can assist with deciding which kind of equipment can be used and will be needed according to the lime type that is decided upon. The next aspect is the lime incorporation, as per the results tilling came out to be the most effective treatment after one year of application, and then second was harrowing. With the lime type and incorporation methods, this can give a grower a time frame of when desired results will likely be achieved to raise the soil pH from acidic to neutral. So, farmers have some options to consider. Most of the farmers I worked with in this research would prefer to continue using no-till or direct seeding cropping and not to use tillage operations. This is because direct seeding conserves moisture, controls soil erosion, and helps to maintain soil organic matter in the southern Prairie soils. There are many other factors to consider but looking at these results and other management strategies, these are solutions that can be applied to help control soil acidity problems and raise the soil pH to a more neutral level, i.e., close to a pH 6.5. These results help growers in making management decisions when the issue of soil acidity arises.

The second objective was showing the occurrence of soil acidity in fields can be highly spatially variable and should not be treated using a blanket application of one lime treatment rate. This can have negative impacts on areas that need no improvement. As such an adequate grid-sampling density needs to be used to accurately depict spatially variable soil pH levels. Too low of a sampling density cannot accurately represent the field.

5.2 Future Recommendations

This research documented the concern that once neutral-alkaline soil pH agricultural field soils are now beginning to exhibit changes to a more acidic nature. These fields would gradually turn acidic naturally due to Ca and Mg leaching, and the H+ would be being increased due to the decomposition of various organic matter, this natural process takes long periods of time to occur. Compared to being altered by agricultural practices, which has sped up this process. Which will result in decreased crop yields caused by lower soil pH levels. Originally work was planned to compare the lime treatment areas pH values to remotely sensed data using a Field Spectroradiometer, and then compare this data with remotely sensed multispectral satellite data. This would allow assessment to see if remote sensing could be used to reduce the amount of grid soil samples needed. However, the outbreak of the COVID-19 pandemic resulted in the remote sensing portions to be cut from the study. Other potential future research topics could include:

- Assessment of the extent of soil acidity on irrigated land There is a generally accepted opinion that the slight alkaline pH value of irrigation surface waters originating out of the limestone mountains on the west side of Alberta are maintaining irrigated soils at neutral pH values. This has not been studied or documented.
- Using a Field Spectroradiometer for assessing the different lime application treatments might show the potential use of remote sensed satellite data in the future for large scale pH assessment of field soils and require less grid soil sampling. This would be done ideally with a Field Spectroradiometer to see if there are wavelengths at which these pH changes could be correlated with the data. If there were wavelengths that did pick up these changes, then this could be made into a sensor that is paired with a Remotely Piloted Aircraft System. Allowing for maps to be made of pH zones much more efficiently and accurate.
- Conduct lab test analyses on the crops and soils of lime treated areas to see if soil acidity amelioration has a positive impact on nutrient availability to crops.
- Further study on applying variable rate test strips across entire fields, e.g., a whole quarter section (160 acres) in size and correlating them with accurate yield data from properly calibrated and operated combine harvesters. This would determine if there were significant increases in yields of crops in low pH acidic soil zones, and whether lime applications are economically beneficial.

References

Acton, D. F., Padbury, G. A., Stushnoff, C. T., University of Regina. Canadian Plains Research Center, & Saskatchewan. Saskatchewan Environment and Resource Management. (1998). *The ecoregions of saskatchewan*. University of Regina, Canadian Plains Research Center.

Alberta Agriculture and Forestry. (n.d). Alberta Soil Information Viewer. (Last Accessed 2021) https://soil.agric.gov.ab.ca/agrasidviewer/

Alejandro, S., Höller, S., Meier, B., & Peiter, E. (2020). Manganese in plants: from acquisition to subcellular allocation. *Frontiers in Plant Science*, *11*. (Last Accessed 2021). https://www.frontiersin.org/articles/10.3389/fpls.2020.00300/full

Anderson, C., Peterson, M., Frampton, R., Bulman, S., Keenan, S., & Curtin, D. (2018). Rapid increases in soil pH solubilise organic matter, dramatically increase denitrification potential and strongly stimulate microorganisms from the firmicutes phylum. *Peerj*, *6*, e6090. doi:10.7717/peerj.6090

Anne Naeth, M., Archibald, H. A., Nemirsky, C. L., Leskiw, L. A., Anthony Brierley, J., Bock, M. D.& Chanasyk, D. S. (2012). Proposed classification for human modified soils in Canada:.Anthroposolic order. *Canadian Journal of Soil Science*, *92*(1), 7-18. (Last Accessed 2024). https://cdnsciencepub.com/doi/full/10.4141/cjss2011-028

Appl, M. (1997, September). The Haber-Bosch heritage: The ammonia production technology. In *50th Anniversary of the IFA Technical Conference* (Vol. 25). Spain: Seville. (Last Accessed 2024). chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.fertilizer.org/wp-content/uploads/2023/01/HABER.pdf

APPLEBY, C. A. (1984). Leghemoglobin and rhizobium respiration. *Annual Review of Plant Physiology*, *35*(1), 443-478. (Last Accessed 2021). https://doi.org/10.1146/annurev.pp.35.060184.002303

Bala, G., Devaraju, N., Chaturvedi, R.K., Caldeira, K., and Nemani, R. (2013). Nitrogen deposition: how important is it for global terrestrial carbon uptake? Biogeosciences Discuss.net, 10, 11077-11109. (Last Accessed 2021).

https://www.researchgate.net/publication/307804291_Nitrogen_deposition_how_important_is_it_for_global_terrestrial_carbon_uptake/link/57ceb09f08aed6789700f7b5/download

Balemi, T., & Negisho, K. (2012). Management of soil phosphorus and plant adaptation mechanisms to phosphorus stress for sustainable crop production: a review. *Journal of soil science and plant nutrition*, *12*(3), 547-562.

Bojórquez-Quintal, E., Escalante-Magaña, C., Echevarría-Machado, I., & Martínez-Estévez, M. (2017). Aluminum, a friend or foe of higher plants in acid soils. *Frontiers in plant science*, *8,* 1767. https://www.frontiersin.org/articles/10.3389/fpls.2017.01767/fullBolin, B., & Arrhenius, E. (.). (1977). Nitrogen - an essential life factor and a growing environmental hazard [nitrogen cycle, human intervention, toxic effects, economic-ecological interactions]. report from nobel symposium no. 38. Ambio, 6(2-3), 96-105.

Brady, N. C., & Weil, R. R. (2008). *The nature and properties of soils* (Vol. 14th). Upper Saddle River, N.J: Pearson Education.

Bridges, E. M., & Van Baren, J. H. V. (1997). Soil: an overlooked, undervalued and vital part of the human environment. *Environmentalist, 17*(1), 15-20. (Last Accessed 2020). https://link.springer.com/article/10.1023/A:1018575211129

Canadian Society of Soil Science. 2020. Soils of Canada. [Online] Available: soilsofcanada.ca [2022].

Canola Encyclopedia. (2020). Canola Council of Canada: Field Characteristics. (Last Accessed 2021). https://www.canolacouncil.org/canola-encyclopedia/

Cheng, Y., Wang, J., Mary, B., Zhang, J., Cai, Z., & Chang, S. X. (2013). Soil pH has contrasting effects on gross and net nitrogen mineralizations in adjacent forest and grassland soils in central Alberta, Canada. *Soil Biology and Biochemistry, 57,* 848-857. (Last Accessed 2021).doi: 10.1016/j.soilbio.2012.08.021

Contributions to Canada and the world Canadian fertilizer industry. (Last Accessed 2023). https://fertilizercanada.ca/wp-content/uploads/2018/09/fc_fact-infographic2018_vf4-pages-en.pdf

Dmitriev, A. A., Krasnov, G. S., Rozhmina, T. A., Zyablitsin, A. V., Snezhkina, A. V., Fedorova, M. S., . . . Melnikova, N. V. (2019). Flax (linum usitatissimum L.). Response to non-optimal soil acidity and zinc deficiency. *BMC Plant Biology, 19*(Suppl 1), 54-54. (Last Accessed 2021). doi:10.1186/s12870-019-1641-1

Dolling, P J. and Porter, W. M. (1984) "Barley production and soil acidity," Journal of the Department of Agriculture, Western Australia, Series 4: Vol. 25: No. 4, Article 8. (Last Accessed 2022). Available at: https://researchlibrary.agric.wa.gov.au/journal_agriculture4/vol25/iss4/8

Donald, C., & Porter, I. (2009). Integrated control of clubroot. *Journal of Plant Growth Regulation*, *28*, 289-303. (Last Accessed 2022). https://idp.springer.com/authorize/casa?redirect_uri=https://link.springer.com/article/10.1007/s00344-009-9094-7&casa_token=krEBf_aIsGwAAAAA: S38yskr7Bkb5sBx9mROQhqZCFxNxhDbeHb9wBHe_lKK5VhdbSVLShhEyFc6MW4nFLzBNgP0XnUUtew5

Earth Institute. (2019). Columbia University Agriculture & Earth Sciences: *Phosphorus: Essential to Life—Are We Running Out? (Last Accessed 2022).* https://blogs.ei.columbia.edu/2013/04/01/phosphorus-essential-to-life-are-we-running- out/

ESRI. (2021). ArcGIS Desktop: How Kriging works. (Last Accessed 2024). https://desktop.arcgis.com/en/arcmap/latest/tools/3d-analyst-toolbox/how-kriging-works.htm

Fertilizer Canada. (2021). Canadian Natural Fertilizer Industry. (Last Accessed 2024). chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://fertilizercanada.ca/wp-content/uploads/2021/08/Fertilizer-Canada-Nitrogen-101.pdf

Fu, X., Zhao, C., Ma, S., Tian, H., Dong, D., & Li, G. (2020). Determining available potassium in soil by laser-induced breakdown spectroscopy combined with cation exchange membrane adsorption. *Journal of Analytical Atomic Spectrometry, 35*(11), 2697-273. (Last Accessed 2022). doi:10.1039/d0ja00394h

Geisseler, D., & Scow, K. M. (2014). Long-term effects of mineral fertilizers on soil microorganisms – A review. *Soil Biology and Biochemistry, 75*, 54-63. (Last Accessed 2021). doi: 10.1016/j.soilbio.2014.03.023

Ghimire, R., & Bista, P. (2016). Crop diversification improves pH in acidic soils. *Journal of Crop Improvement, 30*(6), 657-667. (Last Accessed 2021). doi:10.1080/15427528.2016.1219894

Government of Canada. (2021). Soils of Canada. (Last Accessed 2024). https://agriculture.canada.ca/atlas/apps/aef/main/index_en.html?AGRIAPP=3&APPID=e87af05bd35848598994b13f45a24a25&WEBMAP-EN=c225cc78d5b142d58eacefae91cc535b&WEBMAP-FR=ad0b6822a33e411683f99979a1167efa&mapdescription=true&print=true&breadcrumb=can,agr,b10,b3&adjust_to_viewport=true

Government of Saskatchewan. (n.d.) Nitrogen Fertilization in Crop Production. (Last Accessed 2024). https://publications.saskatchewan.ca/api/v1/products/75197/formats/84107/download

Hochmuth, G. (2011). Iron (Fe) nutrition of plants. *EDIS, 2011*(8). (Last Accessed 2022). https://edis.ifas.ufl.edu/pdffiles/SS/SS55500.pdf

Ikechukwu, M. N., Ebinne, E., Idorenyin, U., & Raphael, N. I. (2017). Accuracy assessment and comparative analysis of IDW, spline and kriging in spatial interpolation of landform (topography): an experimental study. *Journal of Geographic Information System*, *9*(3), 354-371.

Inverse. (2019). Melting Glaciers are Having an Unxpectedly Positive Effect on Carbon Dioxide. (Last Accessed 2023). https://www.inverse.com/article/58594-glaciers-are-melting-but-theyre-still-trying-to-help-whats-your-excuse

Jensen, T. (2018). Geography 3080 – Soils. (Lecture)

Kaiser, B. N., Gridley, K. L., Ngaire Brady, J., Phillips, T., & Tyerman, S. D. (2005). The role of molybdenum in agricultural plant production. *Annals of botany*, *96*(5), 745-754.

Kaiser, D, E. & Rosen, C, J. (2018). University of Minnesota Extension: Potassium for crop production. (Last Accessed 2022). https://extension.umn.edu/phosphorus-and-potassium/potassium-crop-production

Kalayu, G. (2019). Phosphate solubilizing microorganisms: Promising approach as biofertilizers. *International Journal of Agronomy, 2019*, 1-7. (Last Accessed 2022). doi:10.1155/2019/4917256

Kertesz, M. A. (2004). The role of soil microbes in plant sulphur nutrition. *Journal of Experimental Botany*, *55*(404), 1939-1945. (Last Accessed 2022). doi:10.1093/jxb/erh176

Lal, R., & Stewart, B. A. (2018). *Soil nitrogen uses and environmental impacts* (First ed.). Boca Raton, FL: CRC Press, Taylor & Francis Group.

Lehmann, A., & Stahr, K. (2007). Nature and significance of anthropogenic urban soils. *Journal of Soils and Sediments, 7*, 247-260.

Liaghat, S., & Balasundram, S. K. (2010). A review: The role of remote sensing in precision agriculture. *American journal of agricultural and biological sciences*, *5*(1), 50-55.Liu, Z. P., Shao, M. A., & Wang, Y. Q. (2013). Large-scale spatial interpolation of soil pH across the loess plateau, china. *Environmental Earth Sciences, 69*(8), 2731-2741. (Last Accessed 2022). https://doi.org/10.1007/s12665-012-2095-z

Mahler, R. L., Wilson, S., Shafii, B., & Price, W. (2016;2015;). Long-term trends of nitrogen and phosphorus use and soil pH change in northern Idaho and eastern Washington.*Communications in Soil Science and Plant Analysis, 47*(4), 414-424. (Last Accessed 2020).doi:10.1080/00103624.2015.1118119

McKenzie, R, H. & Middleton, A. (2013). Agri-Facts: *Phosphorus FertilizerApplication in Crops.* (Last Accessed 2022). https://open.alberta.ca/dataset/c04d2746-3a48-4562-b9b0-ecdef835fb72/resource/8c3b7543-f9e6-4332-bdd0-9313fcdc0527/download/2013-542-3.pdf

McLaughlin, S. B., & Wimmer, R. (1999). Tansley review no. 104: calcium physiology and terrestrial ecosystem processes. *New Phytologist*, *142*(3), 373-417. (Last Accessed 2022). https://doi.org/10.1046/j.1469-8137.1999.00420.x

Meng, Q., Liu, Z., & Borders, B. E. (2013). Assessment of regression kriging for spatial interpolation - comparisons of seven GIS interpolation methods. *Cartography and Geographic Information Science*, *40*(1), 28- 39. (Last Accessed 2024). https://doi.org/10.1080/15230406.2013.762138

Michigan State University. (2015). Facts about Soil Acidity and Lime. (Last Accessed 2020). https://www.canr.msu.edu/resources/facts_about_soil_acidity_and_lime_e1566Mosaic

Fertilizer Technology Research Centre. (2013) Fertilizers and Soil Acidity. (Last Accessed 2021). https://www.cropnutrition.com/fertilizers-and-soil-acidity

Mosaic. (2020). Nitrogen: Nitrogen in Plants. (Last Accessed 2021). https://www.cropnutrition.com/nutrient-management/nitrogen

Mosaic. (2020). Nutrient Management: Phosphorus. (Last Accessed 2021). https://www.cropnutrition.com/nutrient-management/phosphorus

Mulla, D. J., & McBratney, A. B. (2002). Soil spatial variability. *Soil physics companion*, *343373*.(Last Accessed 2023). https://books.google.ca/books?hl=en&lr=&id=kYPLBQAAQBAJ&oi=fnd&pg=PA343&dq=soil+spatial+variability&ots=Uz6wYODR4d&sig=_ZAtqZ1DCEEhnP_gUxLwVdGFlF8#v=onepage&q=soil%20spatial%20variability&f=false

Natural Regions Committee 2006. Natural Regions and Subregions of Alberta. Compiled by D.J. Downing and W.W. Pettapiece. Government of Alberta. Pub. No. T/852. (Last Accessed 2021). https://albertaparks.ca/media/2942026/nrsrcomplete_may_06.pdf

Negusse, H., Cook, D. R., Haileselassie, T., & Tesfaye, K. (2022). Identification of Aluminum Tolerance in Ethiopian Chickpea (Cicer arietinum L.) Germplasm. *Agronomy*, *12*(4), 948. (Last Access 2023). https://www.mdpi.com/2073-4395/12/4/948

Passioura, J. B. (2002). Soil conditions and plant growth. *Plant, Cell & Environment*, *25*(2), 311-318. https://onlinelibrary.wiley.com/doi/epdf/10.1046/j.0016-8025.2001.00802.x

Peringe, G., Engleryd, A., Forius, M., Hov, Ø, Rodhe, H., and Cowling, E. (2020). Acidrain and air pollution: 50 years of progress in environmental science and policy. Ambio 49, 849-864. (Last Accessed 2022). https://doi.org/10.1007/s13280-019-01244-4

Pierce, F. J., & Nowak, P. (1999). Aspects of precision agriculture. *Advances in agronomy*, *67*, 1-85. (Last Accessed 2024). https://www.sciencedirect.com/science/article/abs/pii/S0065211308605131

Porter, W. M., Cox, W. J. & Wilson, I. (1980). Soil acidity: is it a problem in Western Australia? *Journal of the Department of Agriculture, Western Australia, Series 4*, *21*(4), 126-133.

Prasad, R., & Shivay, Y. S. (2016;2018;). Sulphur in soil, plant and human nutrition. Proceedings of the National Academy of Sciences, India. Section B: Biological Sciences, 88(2), 429-434. (Last Accessed 2022). doi:10.1007/s40011-016-0769-0

Prior, G.J., Hathway, B., Glombick, P.M., Pană, D.I., Banks, C.J., Hay, D.C., Schneider, C.L., Grobe, M., Elgr, R. and Weiss, J.A. (2013): Bedrock geology of Alberta; Alberta Energy Regulator, AER/AGS Map 600, scale 1:1 000 000.

Rahman, M., Lee, S. H., Ji, H. C., Kabir, A. H., Jones, C. S., & Lee, K. W. (2018). Importance of mineral nutrition for mitigating aluminum toxicity in plants on acidic soils: current status and opportunities. *International journal of molecular sciences*, *19*(10), 3073. (Lasted Accessed 2022). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6213855/

Reid, K., Schneider, K., & McConkey, B. (2018). Components of phosphorus loss from agricultural landscapes, and how to incorporate them into risk assessment tools. *Frontiers in Earth Science*, *6*, 135.

Ritchie, H. (2017) How many people does synthetic fertilizer feed? https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feedRuttenberg, K. C. (2003). The global phosphorus cycles. *TrGeo*, *8*, 682. (Last Accessed 2022). https://ui.adsabs.harvard.edu/abs/2003TrGeo...8..585R/abstract

Ruttenberg, K. C. (2003). The global phosphorus cycles. *Treatise on geochemistry*, *8*, 682.

Rütting, T., Aronsson, H., Delin, S., Naturvetenskapliga fakulteten, Faculty of Sciences, Göteborgs universitet, . . . Department of Earth Sciences. (2018). Efficient use of nitrogen in agriculture. *Nutrient Cycling in Agroecosystems, 110*(1), 1-5. (Last Accessed 2022 doi:10.1007/s10705-017-9900-8

RX Green Technologies. (n.d.). Essential Plant Nutrients. (Last Accessed 2023) https://www.rxgreentechnologies.com/rxgt_papers/plant-nutrition-and-deficiencies/#:~:text=Macronutrients%20are%20defined%20as%20being,calcium%2C%20magnesium%2C%20and%20sulfur.

Samreen, S., & Kausar, S. (2019). Phosphorus Fertilizer: The Original and Commercial Sources. In *Phosphorus-Recovery and Recycling*. IntechOpen.

Sattar, A., Naveed, M., Ali, M., Zahir, Z. A., Nadeem, S. M., Yaseen, M., . . . Meena, H. N. (2019). Perspectives of potassium solubilizing microbes in sustainable food production system: (Last Accessed 2022). A review. *Applied Soil Ecology: A Section of Agriculture, Ecosystems & Environment, 133*, 146-159. doi: 10.1016/j.apsoil.2018.09.012

SKSIS Working Group. 2018. Saskatchewan Soil Information System – SKSIS. A. Bedard-Haughn, M. Bentham, P. Krug, K. Walters, U. Jamsrandorj, and J. Kiss, eds. [Online] Available: sksis.usask.ca [September 2022].

Soils of Canadian Society of Soil Science. (2020). Soils of Canada. [Online] Available: soilsofcanada.ca [October 2021].

The Fertilizer Institute. (2023). Soil Test Summary, Soil Test Levels in North America. (Last Access 2023). https://soiltest.tfi.org/

Statistics Canada. (2023) Table 32-10-0037-01 Canadian fertilizer production, by product type and fertilizer year, cumulative data (x 1,000). (Last Accessed 2023) DOI: https://doi.org/10.25318/3210003701- eng

Thor, K. (2019). Calcium—nutrient and messenger. *Frontiers in plant science*, *10*, 440. (Last Accessed 2022). https://www.frontiersin.org/articles/10.3389/fpls.2019.00440/full

University of Missouri Extension. (2022). Nitrogen in the Environment: The Nitrogen Cycle. (Last Accessed 2023). Https://extension.missouri.edu/publications/wq252

University of Saskatchewan (n.d) Ecoregions of Saskatchewan. (Last Accessed 2021 https://www.usask.ca/ biology/rareplants_sk/root/htm/en/researcher/4_ecoreg.php

Wagner, S. C.. (2011) Biological Nitrogen Fixation. *Nature Education Knowledge* 3(10):15. (Last Accessed 2024). https://www.nature.com/scitable/knowledge/library/biological-nitrogen-fixation-23570419/

Wang, J., Wang, J., He, J. Z., Zhu, Y. G., Qiao, N. H., & Ge, Y. (2021). Arbuscular mycorrhizal fungi and plant diversity drive restoration of nitrogen-cycling microbial communities. *Molecular Ecology*, *30*(16), 4133-4146. (Last Accessed 2022) https://onlinelibrary.wiley.com/doi/abs/10.1111/mec.16030?casa_token=QIJi5ulC9BkAAAAA:evRG6_hKWtMtEHuYE4D9Fum8UgY88a7dC_NUrWs4_7mHgm2rLwmilmSdC5us2O02Scwbl3ocuzT0xQ

Washington State Department of Natural Resources. (2024). Washingtons Glacial Geology. (Last Accessed: April 21st, 2024). https://www.dnr.wa.gov/programs-and-services/geology/glaciers

White, P. J., & Broadley, M. R. (2003). Calcium in plants. *Annals of botany*, *92*(4), 487-511.(Last Accessed 2022) https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4243668/

Zhang, H., Edwards, J., Carver, B., & Raun, B. (n.d.). Oklahoma State University: Managing Acid Soils for Wheat Production. (Last accessed 2022) http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Rendition-5075/F-2240web%20color.pdf

Zhang, X., Xiang, D. Q., Yang, C., Wu, W., & Liu, H. B. (2022). The spatial variability of temporal changes in soil pH affected by topography and fertilization. (Last Accessed 2023). *Catena*, *218*, 106586. https://www.sciencedirect.com/science/article/pii/S0341816222005720

Zheng, S. J. (2010). Crop production on acidic soils: overcoming aluminium toxicity and phosphorus deficiency. *Annals of botany*, *106*(1), 183-184. (Last Accessed 2024). https://academic.oup.com/aob/article/106/1/183/96425?login=false

Zinc: Nutri-Facts. (n.d.) International Plant Nutrition Institute. (Last Accessed 2023) http://www.ipni.net/publication/nutrifacts-na.nsf/catalog?ReadForm&cat=Z