Evaluating the Impact of Soil pH on Root and Crown Diseases of Wheat and Using Agricultural Limestone to Manage Soil Acidification in northern Idaho

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Authorization to Submit Thesis

This thesis of Andrew D. Leggett, submitted for the degree of Master of Science with a Major in Plant Sciences and titled " Evaluating the Impact of Soil pH on Root and Crown Diseases of Wheat and Using Agricultural Limestone to Manage Soil Acidification in northern Idaho" has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Soil pH has been declining in northern Idaho, primarily due to the consistent use of ammonium-based nitrogen fertilizers. The major yield reducing factor in low pH soils is increased aluminum (Al) toxicity. Research is needed to determine the rates of lime needed to ameliorate the acidic soil and the economic rate of return for those rates. Studies were conducted in the greenhouse and field to explore the response of *Rhizoctonia oryzae, R. solani* AG-8, and *Fusarium culmorum* to increases in soil pH with liming. Results indicate that incidence and severity of Rhizoctonia root rot and Fusarium crown rot is likely to increase when soil pH increases with liming and that a soil pH value of 6 is optimal for these pathogens. A second component of the research was to establish long-term field studies in northern Idaho to explore the effect of three liming rates (2,242; 4,484; and 6726 kg ha^{-1}) on ameliorating soil pH and examine the economic feasibility of these treatments. Trials were conducted at five locations for 2 years and all three lime rates significantly increased soil pH in the top 7.5 cm at all sites, with some sites experiencing increases in the 7.5 to 15 cm range. The increased pH was associated with significantly increased base saturation and reduced Al concentrations at all sites as well. Yields were increased with increasing rates of lime at many of the sites. Net present value was used to amortize the cost of liming over multiple years. Based on the data from this study, there was an economic benefit to liming in five of the seven site-years, with an average of $21, $26 and $39 ha-1 net returns for the 2,242; 4,484 and 6,726 kg ha-1 lime rates, respectively. Preliminary data suggests that lime application in soils with documented acidification may be economically beneficial for growers in northern Idaho.

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Dedication

Most importantly, I express my deepest appreciation to my parents, Deryl and Carolyn Leggett, who have loved, guided, supported, and counseled me through the ups and downs in my life. Without their selfless sacrifices, I could not be where I am today. No two people deserve more credit for helping me reach this point than my beloved parents.

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Chapter 1: Introduction and Literature Review

Cropping systems of northern Idaho

Northern Idaho is geographically located in the inland Pacific Northwest (PNW). This area is rainfed and has a typical semiarid Mediterranean climate, with winters being cool and moist and summers being warm and dry. According to Schillinger and Papendick (Schillinger and Papendick 2008), average annual precipitation ranges from 15.2 cm in the driest parts of the inland PNW (south-central) to 86.4 cm in the wettest parts (most easterly), with about two-thirds of the precipitation occurring during October to March, and about one-third of that being snow. For northern Idaho, average rainfall varies from as low as 30.5 cm near Lewiston to as high as 86.4 cm near Sandpoint. Rainfall is generally low intensity and low volume. Average annual high temperature in Lewiston, ID is 17.5°C, with an average annual low temperature of 5.8°C. Average annual high temperature in Sandpoint, ID is 14°C, with an average annual low temperature of 1.5°C (Climatemps 2012). Frost free days range from 135 to 180 days in the Lewiston area, and 60 to 120 days in the Sandpoint area (Soil Survey Staff 2019)

Crop choices for growers are limited in this region due to the lack of irrigation, climate and steep, hilly terrain. Historically agricultural production in the area was cereal grains, and predominately soft white wheat (*Triticum aestivum*). Marcus Whitman made the first introduction of wheat to the area in 1837 at his mission near the present-day town of Walla Walla, Washington (Shepherd 1975). Early settlers began to discover that the native bunch grass was a good indicator of fertile ground for growing wheat. Most of the arable soils in the area are classified as fine aeolian loam deposits, formed from decomposed basaltic lava rock. The high natural fertility of the soil, as well as a compatible climate for cereal production, made wheat production possible for early settlers. Gold rushes in the PNW and British Columbia, as well as the presence of military units, provided the first need for commercial agriculture in the region (Shepherd 1975; Schillinger and Papendick 2008). With

favorable growing conditions and a local market, commercial wheat production was able to begin and has continued to the present.

The suitability of the region to grow wheat is as impressive today as it was then. From 1879 to 1972, wheat yields in the PNW were 147% of the Unites States (U.S.) average for the same time period (Shepherd 1975). Today, the 4-year average (2013-2016) for U.S. wheat production was 3134 kg ha-1 (USDA ARS 2016). For the same 4-year period, production in northern Idaho was 4512 kg ha-1 (USDA ARS 2016, 2017), or about 144% of the national average.

Increased wheat yields in the region can largely be attributed to advances in technologies for wheat production and in wheat genetics. The inventions of the self-propelled hillside combine and diesel powered tracked, or "caterpillar" tractors, greatly reduced per acre production costs by significantly reducing labor inputs and increasing harvesting efficiency (Shepherd 1975). In his book, World Food Unlimited, author and farmer Jack DeWitt recalls from his childhood memories of growing up on a farm just northeast of Moscow, ID that before self-propelled combine harvesters, stationary thrashers were used that required 15 or more people to operate (DeWitt 2017). Shepherd reports the first hillside combines, developed by Benjamin Holt in Stockton, California in 1891, reduced the number of men needed to 5 or 6. However, the machine was very heavy and cumbersome, requiring up to 32 horses or mules to pull them. The addition of a hopper to tractor-pulled combines in the 1930s and 1940s, reduced the number of men needed to 3. The first self-propelled combine marketed by the Harris Manufacturing Company made it possible for 1 man to operate the combine.

After decades of cereal production, yield was mainly limited by the decreasing native nitrogen in the soil. By 1950, advances in chemistry during the previous decades led to the ability to synthesize inorganic fertilizers such as nitrogen (N). One of these new fertilizers, anhydrous ammonia, was now readily available, inexpensive, easy to apply, and provided farmers yet another powerful tool to directly increase yields. However, the full potential of inorganic N fertilizers to increase wheat yields was not fully realized until the release of the semi-dwarf wheat Gaines, developed by USDA-ARS

wheat breeder Orville Vogel, in 1961 (Schillinger and Papendick 2008). Previous wheat varieties were much taller and would lodge under high levels of N fertilizer. The introduction of semi-dwarf wheat, which would not lodge under high levels of N fertilizer, significantly increased the average yield of wheat. Average yields in the PNW increased from 1,311 kg ha-1 in 1879-1882 to 2,784 kg ha-1 in 1965-1972 (Shepherd 1975).

In addition to cereal grains such as barley (*Hordeum vulgare*) and spring and fall planted wheat, grain legumes, such as peas (*Pisum sativum*), chickpeas (*Cicer arietinum*) and lentils (*Lens culinaris*), are commonly grown throughout the mid to high rainfall areas of the region as vital rotation crops. These crops are commonly grown in 2 to 3-year rotations with cereal grains. The addition of legumes into the crop rotation has many benefits, including disease suppression, weed control, and nitrogen fixation. Legumes can provide much of the N they need from the atmosphere by forming associations with N fixing bacteria in the soil called rhizobia. Rhizobium species are host specific. *Rhizobium leguminosarum* forms associations with peas and lentils, while *Mesorhizobium* spp. form associations with chickpeas. Although there can be native populations of these rhizobia in the soil, it is always advised that growers in northern Idaho use *Mesorhizobium* inoculant if it has been more than 2 years since chickpeas were grown to insure there are sufficient populations and adequate nodule formation (Mahler 2005). For lentils and spring peas, Mahler (2015) reports that *R. leguminosarum* is present in adequate amounts in soils with a history of lentil production in the last 20 years, and thus do not need additional inoculation, unless soil pH is below 5.2.

Tillage has changed significantly in northern Idaho over the last 100 years. Traditionally, a moldboard plow was used to invert the soil to begin seedbed preparation. Extensive subsequent tillage is then required to “farm-down” and smooth the soil to prepare a good seedbed (Schillinger and Papendick 2008). The benefits of inverting the soil can include elimination of crop residue, reducing disease and pest pressures, and weed control (DeWitt 2017). However, one very important disadvantage with moldboard plowing is exposing bare soil to erosion factors such as wind and rain.

In the rolling hills of northern Idaho, gravitational erosion becomes an important factor as well. For this reason, many growers have moved to less intense forms of tillage, and some have even adopted no-till practices to reduce soil erosion, as well as lower input costs (Paulitz et al. 2003).

Soil Acidity and Its Impact on Plant Growth

Soil acidity is a major problem in many agricultural soils around the world, affecting approximately 30-40% of the arable land (Hede et al. 2001). Crop health and yields can be suppressed in acidic soils by a combination of mineral toxicities and deficiencies in critical plant nutrients. Aluminum toxicity is the most common cause of reduced crop production in soils with a pH below 5.5 (Aniol 1984) and has been documented in the PNW (Koenig et al. 2011; Schroeder and Pumphrey 2013) Soil acidity is expressed by pH which is a measure of the hydrogen ions (H^+) present in a solution. It is measured on a negative logarithmic scale from 1 to 14, with 7 being neutral. A pH measurement below 7 is acidic and above 7 is alkaline. Thus, acidic soils are soils with a pH below 7 and have higher concentrations of H+ ions in the soil solution.

Soils can acidify naturally or by human interaction. Natural acidification is largely influenced by the parent material of the soil, climate and biological factors. The process of natural acidification is slow, often occurring over millennia in climates where precipitation exceeds evapotranspiration (Hede et al. 2001; Fujii et al. 2012; Hart et al. 2013). As the rain falls through the atmosphere, it reacts with carbon dioxide, forming dilute carbonic acid (H_2CO_3) with a pH of 5.5 that adds H^+ ions to the soil solution. These H^+ ions replace calcium, magnesium, and potassium at the exchange sites. The combination of leaching of exchangeable bases and the addition of H^+ to the exchange sites, results in a natural acidification of soil over time.

Additionally, areas of high rainfall produce higher quantities of vegetation which results in large amounts of organic matter in the soil. As this organic matter decomposes, both organic and inorganic acids are formed. The Inorganic acids sulfuric acid (H_2SO_4) and nitric acid (HNO_3), along

with strong organic acids, supply significant amounts of hydrogen to the soil and are the driving force in the development of moderately and strongly acid soils (Brady 1984).

Soil texture is also important to the rate of natural acidification (Hart et al. 2013). Sandier soils usually acidify faster than soils with higher amounts of clay and organic matter due to lower cation exchange capacity (CEC). Low CEC soils have lower buffering capacity and greater leaching potential than high CEC soils. The higher the CEC, the more exchange sites are present, and therefore more H^+ are needed to affect a change in soil pH. This was exemplified by Deorge and Gardner (1985) in Oregon by comparing a Nekia silty clay loam from western Oregon where soil pH is low, to a Madras sandy loam in eastern Oregon where soil pH is higher. Even though soils in western Oregon are usually lower in pH due to a high rainfall climate, the acidification rate of the eastern Oregon soil was twice that of the western Oregon soil (0.2 pH unit/year vs 0.1 pH units/year).

Soil acidification through human interaction can occur within a few years to a few decades, with the main cause of acidification in agricultural soils being the use of ammonium-based nitrogen (N) fertilizers (Sullivan et al. 2013; Hart et al. 2013). Ammonium-N fertilizers acidify soil when soil microbes oxidize ammonium to nitrate via nitrification. During this process the ammonium is combined with two oxygen molecules, producing nitrate, water, and two hydrogen ions. The increase in hydrogen ions in the soil solution results in lower soil pH.

The acidifying of agricultural soils with ammonium-based fertilizers is the product of two significant events in modern agriculture. The first event was the development of the Haber-Bosch process to produce ammonium fertilizer on an industrial scale early in the 20th century (Baber 1904). Before the development of the Haber-Bosch process, combining nitrogen gas with hydrogen to produce ammonia was very slow and low yielding. To produce meaningful amounts of ammonia gas quickly, Haber and Bosch determined that a combination of high temperatures, very high pressures, and iron oxides as catalysts was needed. By 1913, the first chemical plant producing ammonia was operating in Germany. The first ammonia producing plants were built in the United States in the

1920s. However, it was not until the development of the shank applicator at Mississippi Agricultural Experiment Station in 1930 (Nelson 1990) that anhydrous ammonia became easily applied to the soil and a viable option for agriculture.

The availability of an inexpensive, highly effective inorganic N fertilizer led to greater increases in crop yields. As discussed earlier, however, the potential yield increases from inorganic N fertilizer was not fully realized until the development and release of the semi-dwarf wheat variety "Gaines" by USDA-ARS wheat breeder Orville Vogel, in 1961 (Morrison and Vogel 1962). Thus, it was this combination of inexpensive inorganic N fertilizers and new cultivars of wheat capable of handling high N applications which lead to a dramatic increase in ammonia-based N fertilizer use, and the associated increase in the acidification rate of agricultural soils.

Unfortunately, decreasing soil acidity is rarely noticed until crops are severely impacted. This is because symptoms associated with decreasing soil acidity are not always obvious until a crop's pH threshold is met (Hart et al. 2013). The pH threshold for a crop is defined as the minimum pH before crop damage and yield loss occurs. Once the pH threshold is reached, the difference in crop performance is so dramatic, Hart and others (2013) likened it to a stream going over a waterfall. Prior to reaching the threshold, decreases in crop vigor and yield are minor, such as the decreases in elevation over the length of a stream. Once the threshold is reached, however, a very small change in soil pH can result in a substantial crop vigor and yield decrease, just like going over a waterfall dramatically changes elevation in a short horizontal distance.

Soil Acidity and Its Impact on Plant Growth: Toxic Elements

Soil acidity affects crops in many ways. Due to changes in soil chemistry, low soil pH can reduce crop vigor, yield, and quality (Mahler and McDole 1987). The two major effects of acidic soils are increased toxic elements in the soil solution (aluminum, manganese, and iron) and reducing the availability of critical plant nutrients. Additionally, decreased crop vigor due to a lack of vital nutrients

and/or aluminum toxicity can make the crop more vulnerable to plant diseases (Paulitz and Schroeder 2016).

Aluminum toxicity is the greatest yield-limiting factor for soils with a pH below 5.5. As soil pH drops below 5.5, materials in the soil that contain Al dissolve, allowing Al to become plant soluble (Johnson 1992). The most easily observed symptom of aluminum toxicity is significant changes to the root architecture, including reduced root growth and root deformation. Toxic quantities of soluble Al causes plant roots to become thickened, stubby, swollen, have no fine branching, and turn brown (Koenig et al. 2011; Foy 1984).

Aluminum is accumulated in the root apex, the site of meristematic activity. Work done by Sivaguru and Horst (1998) revealed the site most sensitive to Al toxicity within the root apex to be an area between the zone of active cell development and fast cell elongation, known as the distal transition zone, where cells prepare for rapid elongation. In Al sensitive corn (*Zea mays*), Doncheva and others (2005) reported the interaction with Al and this transition zone causes rapid inhibition of cell elongation and inhibits root cell division in the apical meristem within a few minutes of exposure. This inhibition of growth on the main root, stimulates the formation of new lateral roots. However, in highly acidic soils where Al is in high concentration, these laterals are quickly inhibited and often stubbed off, producing the characteristic visual symptoms of Al toxicity (Poschenrieder et al. 2008).

Sasaki and others (1997) showed similar findings in wheat. They found that cells in the elongation zone of roots exposed to an aluminum treatment were significantly affected in several ways including, (1) an increase in cell diameter and decrease in cell length, (2) decrease in cell viability after 3 hours of exposure, (3) lignin deposition in the cell walls of the second and third layers of the cortex, and (4) a disruption of microtubules in elongating cells. They concluded that the reduction of root growth is strongly related to these effects. Ultimately the result of Al toxicity is reduced root mass, deformation of existing roots, and inefficient absorption of nutrients and water, all of which negatively impacts crop vigor.

Manganese (Mn) toxicity is secondary to Al toxicity in most soils. Manganese is an important plant nutrient within the right quantities. Manganese is critically important to the water-oxidizing process in photosynthesis. Additionally Mn specifically activates the enzymes decarboxylases and dehydrogenases involved in the Kreb cycle (Taiz et al. 2015). However, when in excess, Mn is also damaging to the photosynthetic process (Millaleo et al. 2010). As soil pH decreases, H^+ ions displace exchangeable Mn^{2+} at the exchange sites, increasing Mn^{2+} in the soil solution, which is readily taken up by plants and translocated to the shoots. As a result, Mn toxicity appears to affect the tops of plants as opposed to the roots. Visual symptoms include black necrotic spots or streaks on leaves of cereals. On canola and legumes, chlorosis of leaf margins and leaf cupping is observed with Mn toxicity (Johnson 2011).

Soil Acidity and Its Impact on Plant Growth: Reduced Plant Nutrients

Soil acidity affects the availability of many critical plant nutrients (Ahmad and Tan 1986). Calcium (Ca), Mg, and potassium (K) are readily displaced at the cation exchange sites by H^+ and Al^{3+} ions in acidic soils. As these cations are displaced from the exchange sites, they can be quickly leached from the soil and no longer available to the plant. This is especially true of K, which is less competitive than Ca and Mg with Al at the exchange sites. While Ca can be displaced in acidic soils, Ca deficiencies can be mitigated by soil texture. Silty clay loam soils have a higher CEC than loam soils, and thus can hold more cations such as Ca, even in acid soils (Hart et al. 2013; Fernández and Hoeft 2009).

The availability of phosphorus (P) can be reduced at both high and low soil pH. In acidic soils, P precipitates with Al and iron (Fe) to form insoluble minerals (Miller 2016). Higher concentrations of Al in acid soils also affects the plants ability to assimilate P. This principle is well exemplified in the case study of a silage corn field in western Oregon that experienced uneven growth. The shorter plants (about half the size of the healthier plants) were exhibiting typical P deficiency symptoms (purple coloration of older leaves). Soil testing revealed that P levels in areas of both shorter and taller plants

was above 30 ppm, which was sufficient for the crop. However, the pH of the surface soil where the plants were shorter and purple was 4.8. The pH in the area where pants were taller and green was 5.2. Tissue testing confirmed the plants with purple leaves were deficient in P. It was determined that the stunting and P deficiency of the plants in the lower pH soil was due to Al toxicity, restricting the plants ability to take up P (Hart et al. 2013).

The effect of soil acidity on N is varied. In neutral to alkaline soils, the enzyme urease converts the plant available ammonium (NH_4^+) to ammonia (NH_3), which is easily volatilized. However, in acid soils the high concentrations of H^+ maintains the NH_4^+ concentrations. The positive charge of NH_4^+ means it can be adsorbed to the exchange sites, becoming less available to the plant (Miller 2016). For this reason, the other plant available form, nitrate (NO_3^-) is more readily taken up by plants at a lower pH as it has a negative charge. However, nitrification generally decreases as soil pH decreases due to the effects of soil acidity on nitrification enzyme activity (Zebarth et al. 2015). Therefore, less NO_3^- is being produced, while NH_4^+ is simultaneously adhering to the exchange sites. It is important to note that while enzyme activity is decreased as pH decreases, Zebarth and others (2015) reported that nitrification was still rapid within a pH range of 4.5 to 5.2. Therefore, the net effect is a gradual, not sharp, decline in plant available N as soil pH decreases.

Soil Acidity and Its Impact on Plant Growth: Nitrogen Fixation

In pulse crops, such as pea, lentil and chickpea, the nitrogen fixing rhizobia bacteria that normally associates with the roots of these crops are also negatively affected by soil acidity, thus reducing crop vigor and yield (Slattery and Coventry 1995; Khosro Mohammadi 2012; Rice et al. 2000). Long-term field, greenhouse, and laboratory experiments conducted by Lapinskas (2007) in Lithuania, concluded that soil acidity significantly affected the symbiotic efficiency of *R. leguminosarum* bv. *trifolii*, *Sinorhizobium meliloti*, *R. galegae*, and *R. leguminosarum* bv. *viciae*. Mahler and McDole reported a twenty percent increase in spring pea after liming, which they attributed in part to an increased population of *R. leguminosarum* (Mahler and McDole 1985).

The reduced availability of Ca and molybdenum (Mo) in acidic soils is a primary contributor to the reduction of symbiotic efficiency. Calcium is well known to be critically important for the adhesion of rhizobia bacteria to legume roots (Weisany et al. 2013). Studies have shown a Ca-spiking phenomenon initiated in root hairs at the site of infection by nodulation factors and rhizobia (Khosro Mohammadi 2012). In alfalfa, nodulation has been seen to increase from 35 to 70% when soil pH is increased from 5.3 to 5.8 and soil Ca increased in greenhouse studies (Hart et al. 2013). After nodulation, Mo is needed in ample supply for the synthesis of nitrogenase, the enzyme responsible for N fixation in the rhizobia. Studies by Doerge and Gardner (1985) showed a significant increase in alfalfa growth after application of lime. Their studies also revealed a significant increase in Mo in the tissue of alfalfa as pH increased, indicating an increase in Mo availability.

Managing Soil Acidity

Two methods of managing soil acidity are readily available to growers. Methods include selecting aluminum tolerant cultivars and liming. Aluminum tolerant cultivars can be a viable choice for growers who need mediation of aluminum toxicity but cannot afford to lime. However, aluminum tolerance limits cultivar choice and does not correct the underlying problem. Thus, liming to raise soil pH and ameliorate aluminum toxicity is typically the preferred method.

Managing Soil Acidity: Aluminum Tolerant Cultivars

As previously mentioned, one method growers can use to manage soil acidity is by planting cultivars that are aluminum tolerant. Some plants can protect themselves from the harmful effects of Al by producing organic anions such as malate and citrate (Sasaki et al. 2014). These organic anions are excreted by the roots and chelate Al in the soil solution, preventing absorption by the plant. In working with near-isogenic lines of wheat, Delhaize and others (1993a; 1993b) showed that Al-sensitive genotypes accumulated 5 to 10 times more Al in the root apices than tolerant genotypes. Al tolerance was linked to a single locus, *Alt1* (aluminum tolerance 1) and the excretion of malate.

Studying the physiology of this aluminum tolerance mechanism further, Sasaki and others (2004) later identified *TaALMT1* (aluminum-activated malate transporter 1) as the specific gene responsible for Al tolerance in wheat. From this research, we now know that wheat responds to Al ions in the soil by releasing malate from the root apices via an Al-activated malate transporter (Sasaki et al. 2014). Many cultivars of spring and winter wheat have been identified (Schroeder and Pumphrey 2013) and new cultivars are continuing to be screened in the PNW. Citrate is responsible for the aluminum tolerance of barley, sorghum, wheat and rice bean and is controlled by genes from the multidrug and toxic compound extrusion (MATE) family (Sasaki et al. 2014). It is important to note that these Al tolerance mechanisms can be overcome if high enough concentrations of plant available Al exist in the soil.

Managing Soil Acidity: Liming

While using Al tolerant cultivars can help overcome the adverse effects of soil acidity, it does nothing to correct the underlying problem. It is like using morphine to treat a broken leg. The pain can be masked, but the leg is still broken. The key to managing soil acidity is raising the soil pH. Soil acidity can be ameliorated most effectively by using liming materials. The practice of using lime on agricultural soils is not new. Cato and Varro (1979) referenced the use of lime dating back to the first and second centuries B.C. In Roman times, soils were tested for acidity by tasting water that had percolated through a basket of soil. In the U.S. the use of liming products was studied by Ruffin who wrote extensively about his research on his own farm using marl to improve crop yields. Such research sparked interest in liming research at several state agriculture experiment stations in the late 19th century and early 20th century using burned lime, gas lime, or marl as liming agents (Barber 1984).

Today, liming is still a necessary component of crop production for many areas in the U.S. Scarf (2000) reports that liming a soil from a pH of 4.5 to 6.0 can increase soybean yields by 15 percent in Missouri. According to Mamo and others (2009), the cost of liming the top 15 to 20 cm of soil should be considered a capital investment of five to ten years. In a Washington County, Nebraska study looking at liming a corn and soybean rotation, average annual income was greater than the

average annual expense by year 4 after a lime application that cost \$108 ha^{-1} , with a five percent interest rate.

The previous example illustrates the difficulty in liming leased land. It does not make economic sense for a tenant operator to pay for a liming application if their lease is less than 5 years. According to Warmann (1995), in Kansas, lime dealers advise tenant operators to secure long-term leases for this reason. These dealers have reported many 5-year leases, and even some ten-year leases in cases where liming is required. Even with a long-term lease, it is often still necessary for the landlord and tenant operator to cost share the cost of liming. According to Scarf (2000), in Nebraska, some leases stipulate that a landowner must repay the tenant operator's share of the lime expense should the producer lose the lease. A survey of lime dealers in Kansas (Warmann 1995) showed that the most common arrangement for sharing lime cost were the landlord paying one-third, tenant paying two-thirds, and second most common arrangement was the landlord paying the full expense.

Liming materials are defined as materials that contain either calcium or magnesium and can neutralize soil acidity (Mahler 1994). Liming materials used for agriculture are commonly found in three formulations, (1) ground limestone, (2) granule/prill, or (3) fluid. Differences among formulations include reaction time, ease of application, and cost. Finely ground limestone is known as agricultural lime, or aglime for short. The limestone may contain calcite (calcium carbonate [$CaCO_3$]) dolomite ($CaCO_3$ & magnesium carbonate [$MgCO_3$]), or a mixture of both. Aglime is the most commonly used liming material due to its relatively low cost. However, due to its powdery nature, it can be difficult to apply uniformly. Granule and prilled limes can be applied with dry fertilizer spreaders, making the application easier than aglime and more uniform. Their largest drawback is cost, being on average more than twice the cost of aglime. Fluid lime is ultra-micronized lime suspended in water, and therefore reacts quicker than granule or aglime. It is however also the most expensive of the three formulations. Due to its high cost, fluid lime is best used in maintenance applications where lime rates are lower (Anderson et al. 2013) and in high value crops.

Regardless of formulation, lime is generally applied to the soil surface and incorporated by tillage to a depth of about 7 to 15 cm. The carbonate reacts with the H^+ ions in the soil solution to form water and carbon dioxide, thus neutralizing the soil acidity. This chemical reaction continues until allof the lime has reacted (Sullivan et al. 2013).

Measuring the effectiveness of liming materials can differ by state, but is classified by its lime score, also referred to as effective calcium carbonate equivalent (ECCE). The ECCE is the product of a liming materials' CaCO3 equivalence (CCE), moisture, and fineness, expressed as a percent of pure $CaCO_3$. CCE is defined as the acid-neutralizing capacity of the material by weight in relation to pure $CaCO_3$ ($CaCO_3$ is assigned a value of 100) and is determined in a lab. Moisture is simply the difference in weight between a dry sample and a fresh sample of the liming material. In Idaho, guaranteed analysis of finesses is defined as the minimum percentage of material that will pass a 100 mesh, 60 mesh, and 10 mesh sieves (ID. Stat. Title 22, Chapter 6, 22-603 2017). These percentages are then multiplied by an efficiency factor, the products are summed and divided by 100. Efficiency factors are based on reaction of the various particle sizes over a certain time. In Oregon, efficiency factors are based on a reaction time of 4 to 5 years (Thompson et al. 2016). Mahler (1994) determined efficiency factors based on a 1-year reaction time. The length of the reaction time is important because particle size is intrinsically tied to reaction time. Larger particles will react slower than smaller particles. Therefore, it is important to characterize the particle sizes of a liming material for evaluation, as it will help determine how quickly soil acidity will be neutralized.

The amount of lime needed to adjust a soil's pH to a level suitable for crop production (lime requirement) is determined by soil testing (Anderson et al. 2013). Lab analysis is performed to measure the pH of the soil solution (active acidity), the buffer pH (reserve acidity) and the cation exchange capacity (CEC). The higher the CEC of a soil, the more H^+ ions it can hold in reserve—therefore more lime will be needed to neutralize all the H^+ ions in the soil (United States Department of Agriculture 1993). Active acidity refers to the presence of H^+ ions in the soil solution (Mamo et al.

2009). Measuring active acidity determines the soil pH and indicates if lime is needed. Buffer pH is a measurement of the amount of H^+ ions adsorbed on the cation exchange sites. As lime neutralizes the H^+ ions in the soil solution, these reserve H^+ ions (known as reserve acidity) are released into solution to replace the H^+ ions that were neutralized. This is known as the buffering capacity of the soil, or the ability of the soil to resist change in pH (Sullivan et al. 2013). Thus, the quantity of lime applied needs to be large enough to neutralize the H^+ ions in solution, as well as the H^+ ions on the exchange sites. Buffer pH is determined with a buffer test by mixing a buffering solution of known pH with a soil sample of known pH. The difference between the original soil pH and the ending pH determines how much lime is needed. A large difference indicates little buffering capacity, and thus smaller amounts of lime needed to neutralize the reserve acidity. A small difference in pH indicates a greater buffering capacity, and greater amounts of lime will be needed to neutralize the reserve acidity (Camberato 2014). Common buffer tests are Adams-Evans, Mehlich, and Woodruff (Hill et al 2009).

Depth of tillage is an important consideration in calculating a liming rate. Most soil testing laboratories base lime recommendations on a 12-inch acre-furrow slice. However, in the field, depth of incorporation or the depth to be managed may not equal the reference depth used by the lab. Consequently, tillage depth must be factored into the final application rate calculation. Thompson and others (2016) refer to this a T-Factor calculation. It is calculated by dividing the actual depth of incorporation by the laboratory reference depth. Liming application rate can then be determined by multiplying the ECCE of a liming material by the T-Factor.

Liming in northern Idaho was studied by Mahler in the 1980s. Field studies were conducted between 1982 and 1984 using locally-sourced ground limestone in rates of 0; 2,200; and 4,400 kg ha^{-1} applied to the soil surface and then incorporated to a depth of 15 cm (Mahler 1986). Significant increases in soil pH were seen. They observed that lime rates of 2,200 and 4,000 kg ha^{-1} resulted in positive net pH changes of 0.48 and 0.79, respectfully. In this same study, lentil yields in the 2,200 and 4,000 kg ha^{-1} treatments were 23.7 and 22.4% higher than the controls. Mahler concluded that yields

of spring pea, winter wheat, and spring barley in northern Idaho would respond to applications of lime when soil pH was sufficiently low.

Effect of Soil pH on Soilborne Pathogens of Root Diseases of Cereal Grains

Soil acidity can impact the incidence and severity of fungal diseases. The best examples in wheat include *Cephalosporium gramineum*, the causal agent of Cephalosporium stripe, and *Gaeumannomyces graminis* var. *tritici*, the causal agent of take-all. Cephalosporium stripe was first described in Japan in the 1930s. By 1955, it was occurring frequently in the U.S. Cephalosporium stripe can be a serious disease, causing as much as 80% yield loss in winter wheat (Mundt 2010). *Cephalosporium gramineum* is the only vascular wilt disease of small grain cereals such as wheat and inhabits xylem vessels, impeding the transport of water and nutrients (Quincke et al. 2016). Bockus and Claassen (1985) were the first to provide evidence suggesting a relationship between soil pH and incidence of Cephalosporium stripe in field conditions. The results of their studies showed that incidence of Cephalosporium stripe was significantly reduced when lime was used to raise soil pH. These results were confirmed by Love and Bruehl (1987). Results of their work showed higher disease incidence of Cephalosporium stripe in spring wheat at pH levels of 4.5 and 5.0, few diseased tillers at 6.0 to 7.0, and no disease at pH 8.0.

The response of take-all to soil pH is opposite that of Cephalosporium stripe. Cook (2003) characterized take-all of wheat as possibly the most studied root disease of any crop, and one of the most important root diseases of wheat around the world, particularly in temperate climates. It can affect not only the roots, but also the crown and basal stem, disrupting the flow of water up the plant (Cook 2003; Paulitz 2010b). Liming and alkaline soils generally favor take-all, particularly at soil pH levels above 6.0.

Ammonium-N fertilizers have also been shown to suppress take-all, compared to nitrate-N fertilizers, probably due to the lowering of the soil pH over-time, as was shown by MacNish (1988) in

field plots in Australia. Results of those studies showed that the incidence of take-all increased when soil was treated with lime to raise soil pH. Plots fertilized with ammonium sulfate had less take-all than sites fertilized with sodium nitrate or no N at all. Additionally, yields with ammonium sulfate were higher than those with sodium nitrate, which MacNish attributes to the control of take-all by ammonium sulfate. According to Cook (2003), while the severity of take-all is well known to increase with liming, the reason for this phenomenon is still not known.

Fusarium Crown Rot

Fusarium crown rot (FCR) is a widespread soil-borne root and crown disease of wheat and barley in the Pacific Northwest, particularly in dryland production. It may be simply referred to as crown rot (CR) when *Fusarium* spp. are the dominant pathogens (Smiley et al. 2005). Dryland foot rot is another name given to this disease, owing to the fact the disease is favored by drought conditions (Cook 2010). *Fusarium pseudograminearum* and *F. culmorum* are the most common species found in dryland, rainfed areas of the PNW. *Fusarium pseudograminearum* is favored by lower elevations, higher temperatures and lower moisture, while *F. culmorum* is favored by higher elevations, lower temperatures and higher moisture (Poole et al. 2013).

FCR is characterized by honey-brown symptoms on the roots, sub-crown internode, crown, and shoot internodes. However, symptoms usually are not readily noticed in infected plants until after heading. The infections at the crown results in a constriction of the vascular system, resulting in a reduction in water flow from the roots. The blockage of the xylem causes the plants to die prematurely, forming heads that are either empty or partially filled with shriveled grain known as whiteheads. Drought stress often worsens these symptoms during the later stages of wheat development (Cook 1980; Poole et al. 2013).

The first documented severe outbreaks of FCR in the region occurred in 1964. Two fields planted with the semi-dwarf soft white wheat variety Gaines (released 3 years prior) in Ritzville and

Harrington, WA sustained significant damage from FCR. Investigations concluded that *F. culmorum* was the pathogen at fault at both locations. The Ritzville field was found to have 3000 propagules per gram of soil (ppg) of *F. culmorum*, and the Harrington field had 1500 ppg of *F. culmorum*. This was significant given that as little as 100 ppg of *F. culmorum* can be adequate to cause crop damage in conditions favorable to FCR. (Cook 1980).

FCR can have very negative impacts on yield when it is not managed. A report in the PNW documented that FCR decreased yields as much as 35%, with an average of 9.5% over 13 commercial fields in the PNW, and was as high as 61% in inoculated experiments (Smiley et al., 2005). During 2006 in Australia, a major world wheat producer, it was estimated that FCR caused more than AU$56 million in lost revenue (Chakraborty et al. 2006).

Continuous re-cropping of wheat and/or barley results in a buildup of stem residue in the soil, providing an ideal host for *F. culmorum* to overwinter and infect a new crop. Primary inoculum originates in the soil as chlamydospores and infested plant debris in the top 10 cm of the soil. The source of infection occurs either at openings around emerging crown roots, or by the infection of newly emerging crown roots (Cook 1980). Plants that are injured or stressed are more susceptible to FCR. Drought stress during the seedling stage and post anthesis is very important for disease development and severity. Numerous studies have shown that incidence and severity of FCR is positively correlated with years of higher temperatures and lower moisture (Smiley et al. 2005).

Residue management and crop rotation are key to managing FCR. In Australia, Burgess and others (1996), looked at the possibility of controlling FCR through stubble burning and rotation with sorghum. Stubble burning was effective at controlling infection for four seasons when compared to no stubble management, yet no yield increase was detected, possibly due to the loss of nutrients when burning the stubble. Rotating wheat with sorghum also showed significantly lower incidence than continuous wheat production in three rotation cycles. In general, rotating to a non-host crop for at least one-year and use of tillage to bury crop residues are advised for controlling FCR (Cook 2010).

Work done by Smiley and others (1996) with suggested an inverse relationship between soil pH and FCR. As the soil pH declined following increasing rates of ammonium nitrate fertilizer, the incidence of FCR increased. However, it was not made clear in this study whether the pathogen was being affected directly by soil pH, or if the increase in disease was caused by a reduction of plant vigor due to plant stress from high rates of N fertilizer. A study in Ontario, Canada on the relationship of various environmental factors on the prevalence of basal diseases of wheat found no correlation between soil pH and F. culmorum (Hall and Sutton 1998). There seems to be no conclusive results as to the effect of soil pH on this pathogen.

Rhizoctonia Root Rot

Rhizoctonia root rot is a common disease of wheat in temperate climates worldwide, and is responsible for about a 10-30% reduction in yield in the PNW (Okubara et al. 2008). *Rhizoctonia solani* anastomosis group (AG) 8 and *R. oryzae* are the two most important causal agents of Rhizoctonia root rot. Anastomosis groups are a way of differentiating isolates of *R. solani* by the ability of their hyphae to fuse with other hyphae. Only hyphae of isolates within the same AG group can complete fusion. The pathogens are generally found in the upper 10-15 cm of the soil, where they are easily able to attack the developing roots of young seedlings (Paulitz 2010a).

Rhizoctonia oryzae was first discovered in eastern Washington and northeastern Oregon in the late 1980s (Paulitz et al 2003). *Rhizoctonia oryzae* persists in the soil on crop residue as microsclerotia (Davis et al. 2008). Work done by Paulitz and others (2002) revealed the preference of *R. oryzae* to areas of higher rainfall and silt loam soils. Paulitz also discovered the host range of *R. oryzae* to be quite wide, including wheat, barley, and pea (Paulitz 2002). This wide host range makes management of this disease difficult. *Rhizoctonia solani* AG 8 was originally discovered in Australia in the 1930s (Paulitz 2006) and was first described in the PNW in 1986 (Weller et al. 1986). It is most common in areas of lower precipitation and higher temperatures (Okubara et al.). *Rhizoctonia solani* spreads from crop to crop by surviving on crop residue in the soil as dark-walled, monilioid hyphae.

Roots infected by *Rhizoctonia* spp. exhibit brown, small (usually 2-3 mm), sunken lesions where the root cortex has collapsed, girdling the roots and producing an appearance similar to sausage links. The roots may sever at these points, creating reddish brown points, a characteristic symptom known as "spear-tipping" or simply "spearing." These symptoms are generally more severe in spring-planted wheat due to the favorable cool, wet soil conditions. Effects of the disease are not readily noticed until damage to the roots is severe enough to stunt or kill the plant (Paulitz 2010a). When root pruning is severe, shoot symptoms resemble that of drought or nutrient deficiency.

Rhizoctonia oryzae can retard and prevent the formation of seminal and crown roots, and cause preemergence damping off, and though rare, can kill seedlings before emergence (Paulitz 2010a). *Rhizoctonia solani* AG 8 is the causal agent of Rhizoctonia bare patch, in which patches as large as several meters in diameter can form where the crop is either severely stunted or dead. Logically, these patches result in reduced yield and create spaces for weeds to sprout. The distinctness of these patches is a reflection of the distribution and growth of mycelium in the soil (Weller et al. 1986).

Rhizoctonia root rot is difficult to manage for several reasons. Unlike many other diseases, true resistance to Rhizoctonia root rot has not been identified in any developed cultivars at this time, leaving breeders with no genetic options (Okubara, Schroeder, and Paulitz 2008; Paulitz 2010a). Due to the wide host range, crop rotations are not always effective either. Eliminating the "green bridge" is the most effect method of control. Green bridging occurs when a pathogen is transferred from a host to a new seedling after its host is killed via herbicide treatment. For example, when volunteers and weeds that are infected with *Rhizoctonia* spp. are killed prior to seeding with herbicides such as glyphosate or paraquat, the pathogen can survive on the dying host long enough to infect the new seedlings as they emerge after planting. To eliminate the green bridge threat, it is recommended to wait 2-3 weeks after spraying herbicides to plant (Paulitz, et al. 2002; Babiker et al. 2011)

Lucas and others (1993) observed that annual tillage induced disease decline faster than no-till or tillage every other year. They noted decline in Rhizoctonia root rot could not be attributed to the presence of *R. oryzae*, ruling out a possible negative interaction between the two species. Additionally, they observed that a decline did not occur in the absence of a host, suggesting that a susceptible host is necessary. While no-till and continuous cropping of cereals favor *Rhizoctonia* spp., it is also important to note that in some cases, the pathogen eventually declines to background levels after a few years (Lucas, et al. 1993).

Little is known about the effects of soil acidity on *R. solani* AG-8 or *R. oryzae*. In fact, currently, no literature exists on the effect of soil acidity on *R. oryzae*. In sugar beets (*Beta vulgaris*), Watanabe and others (2011) found no correlation to either disease incidence by *R. solani* AG 2-2 or indigenous disease suppressiveness to soil pH in soils with pH values ranging from 4.5 to 7.2. In a study of long-term cropping systems in Australia, there was no evidence of Rhizoctonia root rot, caused by *R. solani* AG-8, being affected by a reduction in soil pH due to nitrogen source (MacNish 1988). However, in one of two test sites with lime treatment, he saw a significant increase in incidence of Rhizoctonia root rot in limed plots verses non-limed plots in 1985 to 1986, and significant increases in severity in 1984 to 1986. However, at the second site, lime had no effect on the occurrence of rhizoctonia root rot. At this time, the literature is inconclusive as to the effect of soil acidity on Rhizoctonia root rot.

Literature Cited

Ahmad, F., and Tan, K. H. 1986. Effect of lime and organic matter on soybean seedlings grown in aluminium-toxic soil. Soil Sci. Soc. Am. J. 50:656–661.

Anderson, N. P., Hart, J. M., Sullivan, D. M., Christensen, N. W., Horneck, D. A., and Pirelli, G. J. 2013. Applying lime to raise soil pH for crop production (Western Oregon). Oregon State Univ. Ext. Publ. EM 9057.

Aniol, A. 1984. Induction of aluminum tolerance in wheat seedlings by low doses of aluminum in the nutrient solution. Plant Physiol. 76:551–5.

Baber, F. 1904. Uber Bildung von Amrnoniak. 90.

Babiker, E. M., Hulbert, S. H., Schroeder, K. L., and Paulitz, T. C. 2011. Optimum timing of preplant applications of glyphosate to manage Rhizoctonia root rot in barley. Plant Dis. 95:304–310.

Barber, S. A. 1984. Liming materials and practices. *In* Soil Acidity and Liming, ed. Fred Adams. Madison: American Society of Agronomoy, Inc., p. 171.

Bockus, W. W. 1985. Effect of lime and sulfur application to low-pH soil on incidence of Cephalosporium stripe in winter wheat. Plant Dis. 69:576.

Burgess, L. W., Backhouse, D., Swan, L. J., and Esdaile, R. J. 1996. Control of Fusarium crown rot of wheat by late stubble burning and rotation with sorghum. Australas. Plant Pathol. 25:229–233.

Camberato, J. 2014. Low soil pH and limestone recommendations for mineral soils: The confusion of 'Buffer pH.' West Lafayette. Available at: https://ag.purdue.edu/agry/extension/SiteAssets/soilfertilityassets/Buffer-pH.pdf.

Cato, M. P., and Varro, M. T. 1979. On Agriculture. eds. William Davis Hooper and Harrison Boyd Ash. Harvard University Press.

Chakraborty, S., Liu, C. J., Mitter, V., Scott, J. B., Akinsanmi, O. A., Ali, S., et al. 2006. Pathogen population structure and epidemiology are keys to wheat crown rot and Fusarium head blight management. Australas. Plant Pathol. 35:643–655.

Climatemps. 2012. Weather averages. Available at: http://www.durban.climatemps.com/#table [Accessed January 1, 2018].

Cook, R. J. 1980. Fusarium foot rot of wheat and its control in the Pacific Northwest. Plant Dis. 64:1061–66.

Cook, R. J. 2003. Take-all of wheat. Physiol. Mol. Plant Pathol. 62:73–86.

Cook, R. J. 2010. Fusarium root, crown, and foot rots and associated seedling diseases. *In* Compendium of Wheat Diseases and Pests, eds. William W. Bockus, Robert L. Bowden, Robert M. Hunger, Wendell L. Morrill, Timothy D. Murray, and Richard W. Smiley. St. Paul: American Phytopathological Society, p. 37–39.

Davis, R. A., Huggins, D., Cook, R. J., and Paulitz, T. C. 2008. Can placement of seed away from relic stubble limit Rhizoctonia root rot in direct-seeded wheat? Soil Tillage Res. 101:37–43.

Delhaize, E., Ryan, Peter R, and Randall, P. J. 1993a. Aluminum tolerance in wheat (*Triticum aestivum* L.). Plant Physiol. 103:695–702.

Delhaize, E., Ryan, P. R., and Randall, P. J. 1993b. Aluminum tolerance in wheat (*Triticum aestivum* L.) (II. Aluminum-stimulated excretion of malic acid from root apices). Plant Physiol. 103:695–702.

DeWitt, J. L. 2017. World Food Unlimited: Producing Abundant, Safe Food, Sustainably, Using Modern Agricultural Technologies. World Food Unlimited. p. 18.

Doerge, T. A., Bottomley, P. J., and Gardner, E. H. 1985. Molybdenum limitations to alfalfa growth and nitrogen-content on a moderately acid, high-phosphorus soil. Agron. J. 77:895–901.

Doncheva, S., Amenós, M., Poschenrieder, C., and Barceló, J. 2005. Root cell patterning: A primary target for aluminum toxicity in maize. J. Exp. Bot. 56:1213–1220.

Fernández, F., and Hoeft, R. 2009. Managing soil pH and crop nutrients. In Illinois Agronomy Handbook, University of Illinois, p. 91–112.

Foy, C. D. 1984. Physiological effects of hydrogen, aluminum, and manganese toxicities in acid soil. *In* Soil Acidity and Liming, ed. Fred Adams. Madison: American Society of Agronomy, Inc., p. 57–97.

Fujii, K., Funakawa, S., and Kosaki, T. 2012. Soil acidification: natural processes and human impact. Pedologist. 55:415–425.

Hart, J. M., Sullivan, D. M., Anderson, N. P., Hulting A.G., Horneck, D. A., and Christensen, N. W. 2013. Soil acidity in Oregon: understanding and using concepts for crop production. Oregon State Univ. Ext. Publ. EM 9061.

Hede, A. R., Skovmand, B., Lopez-Cesati, J., and Lopex-Cesati, J. 2001. Acid soils and aluminum toxicity. *In* Application of Physiology in Wheat Breeding, eds. M. P. Reynolds, J. I. Ortiz-Monasterio, and A. McNab. Mexico: CIMMYT, p. 172–182.

Hill, B. E., Mallarino, A, P., and Pagani, A. 2009. Buffer pH methods: ongoing Iowa laboratory and field studies. p. 20–27. *In* Proc. 19th Soil/Plant Analysis Workshop, Bettendorf, IA. Feb. 24-25, 2009.

Johnson, G. V. 1992. Causes and effects of soil acidity. Oklahoma State University Extension Facts F-2239.

Johnson, R. D. 2011. Soil pH its relationship with crop biodiversity and production. USDA Natural Resources Conservation Service, Boise, ID, Technical Note No. 8. Available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_044840.pdf.

Khosro Mohammadi. 2012. Effective factors on biological nitrogen fixation. African J. Agric. Res. 7:1782-1788.

Koenig, R., Schroeder, K., Carter, A., Pumphrey, M., Paulitz, T., Campbell, K., Huggins, Dave. 2011. Soil acidity and aluminum toxicity in the Palouse region of the pacific northwest. Washington State University Extension Fact Sheet FS050E.

Lapinskas, E. B. 2007. The effect of acidity on the distribution and symbiotic efficiency of rhizobia in Lithuanian soils. Eurasian Soil Sci. 40:419–425.

Love, C. S. 1987. Effect of Soil pH on Cephalosporium Stripe in Wheat. Plant Dis. 71:727-731.

Lucas, P., Smiley, R. W., and Collins, H. P. 1993. Decline of Rhizoctonia Root Rot on Wheat in Soils Infested with *Rhizoctonia solani* AG-8. Phytopathology 83:260–265.

Macnish, G. C. 1988. Changes in take-all (*Gaeumannomyces graminis* var. tritici), Rhizoctonia Root Rot (*Rhizoctonia solani*) and Soil Ph in continuous wheat with annual applications of nitrogenous fertilizers in western Australia. Aust. J. Exp. Agric. 28:333–341.

Mahler, R. L. 1994. Liming materials. University of Idaho Extension Publication CIS787.

Mahler, R. L. 2005. Northern Idaho Fertilizer Guide: Chickpeas. University of Idaho Extension Publication CIS826.

Mahler, R. L. 2015. Northern Idaho Fertilizer Guide: Lentils. University of Idaho Extension Publication CIS1083.

Mahler, R. L., and McDole, R. E. 1987. Effect of soil pH on crop yield in northern Idaho. Agron. J. 79:751-755.

Mahler, R. L., and McDole, R. E. 1985. The influence of lime and phosphorus on crop production in northern Idaho.

Makoil, J. H. J. R., Bambara, S., and Ndakidemii, P. A. 2013. Rhizobium inoculation and the supply of molybdenum and lime affect the uptake of macroelements in common bean (*P. vulgaris* L.) plants. Aust. J. Crop Sci. 7:784–793.

Mamo, M., Wortmann, C. S., and Shapiro, C. A. 2009. Lime use for soil acidity management. University of Nebraska Extension G1504.

Millaleo, R., Reyes-Diaz, M., Ivanov, A. ., Mora, M. ., and Alberdi, M. 2010. Manganese as essential and toxic element for plants: transport, accumulation and resistance mechanisms. Journal Soil Science Plant Nutrition 10:470–481.

Miller, J. 2016. Soil pH affects nutrient availability. University of Maryland Extension FS-1054.

Morrison, K. J., and Vogel, O. A. 1962. Gaines: a semidwarf winter wheat for the Pacific Northwest. Washington State University Extension Circ. 332.

Mundt, C. C. 2010. Cephalosporium stripe. *In* Compendium of Wheat Diseases and Pests, eds. W. W. Bockus, R. L. Bowden, R. M. Hunger, W. L. Morrill, T. D. Murray, and R. W. Smiley. St. Paul: The American Phytopathological Society, p. 23–25.

Nelson, L. B. 1990. *History of the U.S. Fertilizer Industry*. Muscle Shoals: Tennessee Valley Authority, p. 363.

Nyle C. Brady. 1984. Major changes in soil pH. *In* The Nature and Properties of Soils, New York: Macmillan Publishing Company, p. 198–199.

Okubara, P. A., Schroeder, K. L., and Paulitz, T. C. 2008. Identification and quantification of *Rhizoctonia solani* and *Rhizoctonia oryzae* using real-time polymerase chain reaction. Phytopathology 98:837–847.

Okubara, P., Schroeder, K., and Paulitz, T. C. 2014. Rhizoctonia bare patch and root rot: distribution and management. REACCH Annual Report 3:34–35.

Paulitz, T. C. 2002. First report of *Rhizoctonia oryzae* on pea. Plant Dis. 86:442.

Paulitz, T. C. 2006. Low input no-till cereal production in the Pacific Northwest of the U.S.: the challenges of root diseases. Eur. J. Plant Pathol. 115:271–281.

Paulitz, T. C. 2010a. Rhizoctonia root rot. *In* Compendium of Wheat Diseases and Pests, eds. W. W. Bockus, R. L. Bowden, R. M. Hunger, W. L. Morrill, T. D. Murray, and R. W. Smiley. St. Paul: American Phytopathological Society, p. 47–48.

Paulitz, T. C. 2010b. Take-all. *In* Compendium of Wheat Diseases and Pests, eds. W. W. Bockus, R. L. Bowden, R. M. Hunger, W. L. Morrill, T. D. Murray, and R. W. Smiley. St. Paul: The American Phytopahological Society, p. 79–81.

Paulitz, T. C., and Schroeder, K. L. 2016. Acid soils: how do they interact with root diseases? Washington State University Extension FS195E.

Paulitz, T. C., Smiley, R. W., and Cook, R. J. 2002. Insights into the prevalence and management of soilborne cereal pathogens under direct seeding in the Pacific Northwest, U.S.A. Can. J. Plant Pathol. 24:416–428.

Paulitz, T. C., Zhang, H., and Cook, R. J. 2003. Spatial distribution of *Rhizoctonia oryzae* and Rhizoctonia root rot in direct-seeded cereals. Can. J. Plant Pathol. 25:295–303.

Poole, G. J., Smiley, R. W., Walker, C., Huggins, D., Rupp, R., Abatzoglou, J., Garland-Campbell, K., Paulitz, T.C. 2013. Effect of climate on the distribution of *Fusarium* spp. causing crown rot of wheat in the Pacific Northwest of the United States. Phytopathology 103:1130–40.

Poschenrieder, C., Gunsé, B., Corrales, I., and Barceló, J. 2008. A glance into aluminum toxicity and resistance in plants. Sci. Total Environ. 400:356–368.

Quincke, M. C., Murray, T. D., Peterson, C. J., Sackett, K. E., and Mundt, C. C. 2014. Biology and control of Cephalosporium stripe of wheat. Plant Pathology 63:1207-1217

Rice, W. a., Clayton, G. W., Olsen, P. E., and Lupwayi, N. Z. 2000. Rhizobial inoculant formulations and soil pH influence field pea nodulation and nitrogen fixation. Can. J. Soil Sci. 80:395–400.

Sasaki, M., Yamamoto, Y., Ma, J. F., and Matsumoto, H. 1997. Early events induced by aluminum stress in elongating cells of wheat root. Soil Sci. Plant Nutr. 43:1009–1014.

Sasaki, T., Tsuchiya, Y., Ariyoshi, M., Ryan, P. R., Furuichi, T., and Yamamoto, Y. 2014. A domain-based approach for analyzing the function of aluminum-activated malate transporters from wheat (*Triticum aestivum*) and *Arabidopsis thaliana* in xenopus oocytes. Plant Cell Physiol. 55:2126–2138.

Sasaki, T., Yamamoto, Y., Ezaki, B., Katsuhara, M., Ahn, S. J., Ryan, P. R., Delhaize, E., Matsumoto, H. 2004. A wheat gene encoding an aluminum-activated malate transporter. Plant J. 37:645–653.

Scharf, P. C. 2000. Liming Missouri soils. University of Missouri Extension G9102.

Schillinger, W. F., and Papendick, R. I. 2008. Then and now: 125 Years of dryland wheat farming in the Inland Pacific Northwest. Washington State University Extension EM004E.

Schroeder, K. L., and Pumphrey, M. 2013. It's all a matter of pH. Wheat Life, January 2013, pp. 56-59

Shepherd, J. F. 1975. The Development of wheat production in the Pacific Northwest. Agric. Hist. 49:258–271.

Sivaguru, M., and Horst, W. J. 1998. The distal part of the transition zone is the most aluminum-sensitive apical root zone of maize. Plant Physiol. 116:155–163.

Slattery, J. F., and Coventry, D. R. 1995. Acid-tolerance and symbiotic effectiveness of *Rhizobium leguminosarum* bv. trifolii isolated from subterranean clover growing in permanent pastures. Soil Biol. Biochem. 27:111–115.

Smiley, R. W., Collins, H. P., and Rasmussen, P. E. 1996. Diseases of wheat in long-term agronomic experiments at "Pendleton" Oregon. Plant Dis. 80:813-820.

Smiley, R. W., Gourlie, J. A., Easley, S. A., Patterson, L.-M., and Whittaker, R. G. 2005. Crop damage estimates for crown rot of wheat and barley in the Pacific Northwest. Plant Dis. 89:595–604.

Staff, S. S. Web Soil Survey. Web Soil Surv. Available at: https://websoilsurvey.sc.egov.usda.gov/.

Sullivan, D. M., Horneck, D. A, and Wysocki, D. J. 2013. Eastern Oregon liming guide. Oregon State University Extension Publication EM 9060.

Taiz, L., Zeiger, E., Moller, I. M., and Murphy, A. 2015. Group 4: deficiencies in mineral nutrients that are involved in redox reactions. *In* Plant Physiology and Development, Sunderland: Sinauer Associates, Inc., p. 128–129.

Thompson, W. H., McFarland, C. R., Brown, T. T., and Huggins, D. R. 2016. Agricultural lime and liming, part 3: aglime product selection and comparison calculator user guide. Washington State University Extension Publication FS213E.

United States Department of Agriculture. 1993. Liming to Improve Soil Quality in Acid Soils.

Warmann, G. 1995. Economics of liming Kansas cropland. Kansas State University Agriculture Experiment Station and Cooperative Extension Service MF2137.

Watanabe, K., Matsui, M., Honjo, H., Becker, J. O., and Fukui, R. 2011. Effects of soil pH on Rhizoctonia damping-off of sugar beet and disease suppression induced by soil amendment with crop residues. Plant Soil. 347:255–268.

Weisany, W., Raei, Y., and Allahverdipoor, K. H. 2013. Role of some of mineral nutrients in biological nitrogen fixation. Bull. Env. Pharmacol. Life Sci. 2:77–84.

Weller, D. M., Cook, R. J., MacNish, G., Bassett, E. N., Powelson, R. L., and Petersen, R. R. 1986. Rhizoctonia root rot of small grains favored by reduced tillage in the Pacific Northwest. Plant Dis. 70:70–73.

Zebarth, B., Forge, T., Goyer, C., and Brin, L. 2015. Effect of soil acidification on nitrification in soil. Can. J. Soil Sci. 95:359-363.

Chapter 2: Investigating the effect of soil pH on Rhizoctonia root rot (*R. solani* AG-8 and *R. oryzae*) and Fusarium crown rot (*F. culmorum*)

Introduction

Soil pH has been declining steadily in northern Idaho for decades, primarily due to the consistent use of ammonium-based nitrogen fertilizers. During this period, growers in the region have also experienced a decline in yield. Aluminum toxicity is usually the cause of reduced yields in soils with a pH below 5.5 (Aniol 1984). Yield loss due to aluminum toxicity has been recently documented in the PNW (Koenig et al. 2011; Schroeder and Pumphrey 2013).

While the primary impact of soil acidification is aluminum toxicity and reduced fertilizer efficiency, variation in soil pH also can influence the incidence and severity of soil-borne fungal pathogens of wheat. The differing effects of soil pH on *Cephalosporium gramineum*, the causal agent of Cephalosporium stripe, and *Gaeumannomyces graminis*, the causal agent of take-all, have been well-documented. Bockus and Claassen (1985) were the first to provide evidence suggesting a relationship between soil pH and incidence of Cephalosporium stripe in field conditions. The results of their studies showed that incidence of Cephalosporium stripe was significantly reduced when lime was used to raise soil pH. These results were confirmed by Love and Bruehl (1987). Their work showed higher disease incidence of Cephalosporium stripe in spring wheat at pH levels of 4.5 and 5.0, few diseased tillers at 6.0 to 7.0, and no disease at pH 8.0.

Cook (2003) identified take-all as possibly the most studied root disease of any crop, and one of the most important root diseases of wheat around the world. Liming generally favors take-all, particularly at soil pH levels above 6.0. The relationship between take-all, soil pH and N fertilizers was investigated by MacNish (1988) in field plots in Australia. They showed that incidence of take-all increased when soil was treated with lime to raise pH. According to Cook (2003), while the severity of take-all is well known to increase with liming, the reason for this phenomena is still not known.

Fusarium crown rot and Rhizoctonia root rot are important diseases in wheat production in northern Idaho. Work done by Smiley and others (1996) with Fusarium crown rot suggested an inverse relationship between soil pH and Fusarium crown rot with increasing rates of ammonium nitrate fertilizer. A study in Ontario, Canada by Hall and Sutton (1998) on the relationship of various environmental factors on the prevalence of basal diseases of wheat found no correlation between soil pH and *F. culmorum*. There seems to be no conclusive results as to the effect of soil pH on this pathogen at this time.

In sugar beets (*R. solani* AG 2-2), Watanabe and others (2011) found no correlation to either disease incidence or indigenous disease suppressiveness to soil pH in soils with pH values ranging from 4.5 to 7.2. In a study of long-term cropping systems in Australia, MacNish (1988) saw no evidence of a Rhizoctonia root rot caused by *R. solani* AG-8 being affected by a reduction in soil pH due to nitrogen source. However, in one of two test sites with lime treatment, he saw a significant increase in incidence in limed plots verses non-limed plots in 1985 to 1986, and significant increases in severity in 1984 to 1986. However, at the second site, lime had no effect on the occurrence of Rhizoctonia root rot.

Current information relating to the relationship between soil pH and Fusarium crown rot and Rhizoctonia root rot is lacking and in some cases contradictory. Therefore, the objective of this study was to investigate the relationships between soil pH and the most common causal agents of Fusarium crown rot and Rhizoctonia root rot in northern Idaho; *F. culmorum*, *R. solani* AG-8, and *R. oryzae*, respectfully. This chapter describes seedling assays conducted in the greenhouse to examine a range of soil pH values for all three pathogens. Companion field studies were conducted at the University of Idaho Parker Research farm in Moscow, ID for *F. culmorum* and *R. oryzae* to test the effect of soil pH in field conditions.

Methods and Materials

Soil collection. Growth chamber studies were conducted in 2015 and 2017 at the University of Idaho Sixth Street Greenhouse in Moscow, ID. Native soils (Westlake-Latahco complex) from the University of Idaho Parker Research farm east of Moscow (46.729881°, -116.948888°), Idaho were selected in the fall of 2014 and summer of 2016. Samples were collected to a depth of 15 cm and were air dried and sieved. Samples collected for this experiment were analyzed in the lab for pH using a 1:1 soil to water ratio. Soil pH was 4.18 in 2014 and 4.02 in 2016.

The soils were limed to raise soil pH to 5, 6 and 7 using NuCal™ liquid lime (Columbia River Carbonates, Woodland, WA). This material was used as a liming agent to achieve a faster and more homogeneous pH change. A curve was first generated to determine the amount of NuCal™ needed to adjust the pH of each soil. A 1:9 dilution of NuCal™ was performed and 0.0, 0.5, 1.0, 2.0, 4.0, 6.0, 8.0, 12.0, and 15.0 ml of the dilution was added to 100 g of soil. Deionized water was added to bring the soil moisture up to 15%. Change in pH was tracked for 2 weeks following lime treatment by taking weekly pH readings using the same 1:1 ratio described earlier (Table 2.1). From this data, NuCal™ rates of 2.0, 4.0, and 8.0 ml of Diluted NuCal™ per 100 grams of soil were selected to achieve soil pH close to 5.0, 6.0 and 7.0 respectively.

The soil samples collected in the summer of 2016 were sieved and air dried as before. Another curve was generated using the same protocol from 2015, with the following exceptions. The quantity of soil used for each test was increased to 300 g, so the quantity of diluted NuCal™ added was 0.0, 1.5, 3.0, 6.0, 12.0, 18.0, 24.0, 36.0, and 45.0 ml. Soil pH was measured in triplicate each week for 3 weeks following treatment. NuCal treatments of 6.0, 12.0, and 45.0 ml diluted NuCal per 300 g soil were selected to achieve soil pH readings close to 5.0, 6.0, and 7.0 respectively. Buckets of soil for each target pH were treated with the appropriate NuCal™ treatment 3 weeks prior to planting. The soils were stirred by hand weekly. Four days prior to planting the soil pH was again measured to confirm the pH of each treatment.

Inoculum preparation. Soil-borne pathogens examined were *Rhizoctonia oryzae* isolate 0801387 (Paulitz et al. 2003), *R. solani* AG-8 isolate C1 (Smith et al. 2003), and *Fusarium culmorum* isolate 19. The pathogens were grown on potato dextrose agar (PDA) for 3 to 7 days. Flasks containing 250 ml of whole oats and 250 ml of DI water were autoclaved twice for 15 minutes at a 24-hour interval. The flasks of autoclaved oats were inoculated with four to five square centimeter pieces of agar containing actively growing hyphae. The flasks were sealed by wrapping parafilm around the base of each tinfoil cap and incubated in a dark cabinet at room temperature (~21°C) for a minimum of 3 weeks. Each week the flasks were mixed by shaking to encourage uniform colonization of the grain.

Once the oats were thoroughly colonized, the pathogens were harvested by spreading the oat inoculum onto Kraft paper suspended on wire racks in a laminar flow hood to dry. After 24 hours, the inoculum was transferred to a laboratory bench to air dry for another 24 hours. About 8 to 10 oats were collected and placed on PDA and incubated in the dark cabinet to confirm the purity of each batch of inoculum.

Once drying was complete, the oats were ground using four 3-second pulses in a coffee grinder. The ground inoculum was then sieved through 18 and 60 mesh screens to collect the particles measuring between 0.25 to 1 mm in size. Inoculum caught in the 18-mesh sieve was reground and re-sieved. Ground inoculum was stored at 4°C until use.

The ground inoculum was enumerated by serial dilution to estimate the number of propagules per gram (ppg) of each pathogen. One hundred milligrams of inoculum were suspended in 10 ml of deionized water in a Falcon tube. Serial 10-fold dilutions were made by transferring 1 ml from the original suspension into 9 ml of DI water. Half a milliliter of each inoculum dilution was transferred to 2% strength water agar plates in duplicate and spread evenly on the agar plate. This process was replicated three times fungal isolate.

Colonies forming on the plates were enumerated for 2 days beginning 24 hr after the dilutions were made. A field microscope set at 120x power was used to count propagules forming on the agar. On the second day, totals were calculated for each plate and the two plates for each dilution were averaged and the counts were converted to ppg.

Greenhouse assay. The soft white spring wheat cultivar Babe was selected to represent a common spring wheat grown in northern Idaho. The wheat was planted in to SC10 Ray Leach Cone-tainers (Stuewe and Sons, Inc.; Tangent, OR), with a single seed in each cone-tainer. There were 3 replicates, with 5 plants per replicate. At planting, 850 g of soil was measured into 1-gallon re-closable plastic bags for each treatment. For each pH level (4, 5, 6, and 7), there were three treatments that included no inoculum, low inoculum (15 ppg), and high inoculum (150 ppg), giving a total of 12 treatments for each pathogen. Ground inoculum was added to the soil and mixed by turning the bag for 1 minute.

Soil was added to each cone-tainers to within 1 cm from the top and then lightly tamped by tapping the conetainer gently on the table. Prior to planting, soil was watered with 10 ml of water and one seed was added to each conetainer, lightly pressed into the soil, and covered with about 1 cm of soil. The racks were covered with a sheet of plastic until emergence to minimize evaporation (about 4 days after planting). Plantings were transferred to a Conviron® growth chamber (Controlled Environments Ltd.; Winnipeg, Manitoba, Canada) set at a constant 15°C and a 12-hr photoperiod. The conetainers were arranged in a randomized complete block design within the growth chamber. Emergence was recorded daily, beginning 3 days after planting until all plants had germinated. Plants were watered only when the soil surface dried out to maintain a moisture content similar to that at the onset of the study.

Plants were destructively harvested 3 weeks after planting. At harvest, the conetainers were split open lengthwise with scalpels to remove the plants with the roots intact. The soil was gently brushed away from the roots and plant height and first leaf length measured. Roots were then washed

to remove all soil particles and scored for disease. Seminal and crown roots were enumerated, noting how many were diseased. Both Rhizoctonia root rot and Fusarium crown rot were rated on a scale of 0 to 8 (Schroeder and Paulitz 2007), with 0 being no disease present, and 8 being severely diseased. For Rhizoctonia root rot, disease rating was determined by two factors, number of roots diseased and the number of roots speared-off. *F. culmorum* disease rating was determined by three factors, number of roots infected, severity of root discoloration, and overall plant vigor and was scored on a 0-8 scale, with 0 being no disease present to 8 being severe symptoms.

Field study: Fusarium crown rot. A field study was conducted at the University of Idaho Parker Farm in Moscow, ID in 2016 and 2017 to evaluate the impact of soil pH on Fusarium crown rot. A site was selected that had very low pH and high plant available aluminum (KCl Al). Soil was a Westlake-Latahco complex, 0 to 3 percent slopes with a pH of 4.39.

A 50/50 mixture of *Fusarium culmorum* (Wm. G. Sm.) Sacc. isolates 19 and 23 were used for this study. Isolates were grown separate on millet. Millet was prepared by mixing 3 l of millet with 1,350 ml of distilled water in a disposable aluminum turkey roaster. The roasters were covered with 4 layers of tinfoil and autoclaved for 60 min, and re-autoclaved 24 hr. later for another 60 min. After cooling completely, each roaster was inoculated with 1 cm pieces of colonized agar plugs from a culture of either *F. culmorum* isolate 19 or 23, and thoroughly stirred. Roasters were stored in a dark cabinet at room temperature (~21°C) for 3 weeks, with stirring once a week. After colonizing the millet, the inoculum was air dried on Kraft paper elevated on wire racks until completely dry. Once dry, inoculum was stored in sealable plastic bags until planting. *Fusarium* inoculum was applied at planting at the rate of 3.5 g m^{-1} linear row by mixing inoculum directly with the seed.

Half of the plots were limed on May 11, 2016 with 22,400 kg ha^{-1} of NuCal™ just prior to planting. Application of lime was completely randomized. Lime was immediately incorporated to a depth of 7.5 to 15 cm with three passes of a cultivator. The plot was seeded on May 11 in 2016 and May 22 in 2017 using a seeding density of 302 seeds square meter $^{-1}$.

Experimental design was a split-plot design with lime treatment as the main plot, with inoculum and cultivar as the sub-plots. The sub-plot treatments consisted of the hard red spring wheat cultivar Glee (higher susceptibility) and the hard white spring wheat cultivar WB Hartline (moderately susceptibility), each with and without *F. culmorum* inoculum. Assignments for all treatments were random. The trial consisted of four replicate blocks.

Composite soil samples were collected on June 21 in 2016 and June 28 in 2017. In 2016, composite samples were taken from the limed strips and the non-limed strips. In 2017, composite samples were taken from each strip (10 strips, 5 limed and 5 non-limed). Samples were collected to a depth of 30 cm and partitioned into four equal depths (0-7.5, 7.5-15, 15-22.5, and 22.5 to 30). Samples were analyzed by Best Test Labs in Moses Lake, WA to determine soil pH. Plant establishment counts were recorded on June 1 in both 2016 and 2017. The number of plants in a 0.5 m row were counted from three random spots within each plot. A seedling assessment was performed on June 14 of 2016 and June 30 of 2017. Ten plants were removed from each plot. Plant height was recorded and roots were rated for disease using a 0 to 3 scale , with 0 being a healthy root and plant, 1 showing some sign of infection on the roots, 2 showing some sign of infection on the root and/or characteristic chocolate brown discoloration on the lower culm, and 3 being a severely diseased/discolored root and lower culm. At plant maturity, a mature plant height was recorded, and the plots were harvested using a Wintersteiger plot combine and measurements included total grain yield, test weight and grain protein. Test weight was determined using a Cox funnel and protein was measured using a Foss Infratec™ Nova (Foss, Hilleroed, Denmark). After harvest, stem samples from 15 plants in each plot were collected and mainstems were assessed for incidence and severity of Fusarium crown rot.

Field study: Rhizoctonia root rot. A two-year field study was established at the University of Idaho Parker Farm in Moscow, ID to assess the impact of soil pH on Rhizoctonia root rot (*R. oryzae*) in spring wheat adjacent to the Fusarium crown rot study described above. The Rhizoctonia root rot study was limed and planted May 22, 2017 with the same lime rate and seeding density as

previously described. Plots were planted May 25 in 2018. The experimental design for the *R. oryzae* trial was a split-plot design, with lime treatment as the main plot, and inoculum treatment as the sub-plot. Since there is no tolerance to Rhizoctonia root rot within spring wheat germplasm (Smith et al. 2003), only a single cultivar Seahawk was chosen as a representative cultivar for northern Idaho. Inoculated plots were randomized within each limed strip and the trial consisted of four replicate blocks. Stand establishments counts were conducted as described above on June 1 in 2017 and June 4 in 2018.

Rhizoctonia oryzae isolate 0801387 inoculum was prepared using a protocol similar to that described for *F. culmorum* inoculum, except oats and cereal rye were used as a medium instead of millet. The oat and cereal rye medium were prepared by mixing 1 liter each of oats and cereal rye with 2 liters of DI water in a disposable aluminum turkey roaster. All other preparations were same as the previous protocol. The inoculum was air dried and ground using a Chard® GM150 grain mill. The inoculum was applied at planting with the seed at a rate of 20% of the seed weight per plot. For example, if 100 g of seed was planted, then 20 g of inoculum was applied.

A seedling assessment was performed on June 26 in 2017 and June 15 in 2018 for seedling height, number of tillers, first leaf length, and seminal and crown root counts and ratings. Ten plants were removed from each plot for this assessment. A rating scale of 0-5 was used. Soil samples were collected on June 29 in 2017 and June 19 in 2018 as described above. Harvest was also conducted as previously described.

Statistics. An ANOVA was generated for all data using the general linear model procedure in the SAS program (SAS Institute, 2016, version 9.4) with an alpha of 0.5. Trend analysis was conducted for the greenhouse studies using orthogonal contrasts to test linear, quadratic and cubic trends for pH and inoculum effects.

Results

Greenhouse: *Rhizoctonia solani* AG-8. Inoculum rates had highly significant effects on all crop metrics (Table 2.2). Soil pH had significant effects on plant height, disease rating and disease incidence (Table 2.2). The relationships between plant height, disease rating, and disease incidence and soil pH were linear, quadratic, and linear, respectfully (Table 2.3). There was a significant interaction between soil pH and inoculum for first leaf length and plant heights (Table 2.2, Figures 2.1 and 2.2). First leaf lengths increased incrementally with soil pH in the non-inoculated plants. Inoculation at the low (15 ppg) level of inoculation suppressed the increase in first leaf length with pH and in the high (150 ppg) level, first leaf lengths were generally reduced with soil pH.

Greenhouse: *Rhizoctonia oryzae*. Inoculum rates had highly significant effects on first leaf length, plant height, disease rating, and disease incidence (Table 2.4). The effect of soil pH was significant on first leaf lengths, and highly significant on plant height, disease rating, and disease incidence. The relationships between first leaf lengths, plant height, disease rating, and disease incidence were cubic, linear, quadratic, and linear, respectfully (Table 2.5) There was a significant interaction between soil pH and inoculum for disease rating and disease incidence (Table 2.4 and Figures 2.3 and 2.4). Disease ratings at the 15 ppg level increased with soil pH up to a pH of 6 and dropped off to its lowest level at pH 7. Similar results were seen at the 150 ppg level (Figure 2.3). Results for seminal root disease incidence were similar to disease rating for both inoculation levels (Figure 2.4).

Field study: Rhizoctonia root rot. Soil pH in the top 7.5 cm was 4.16 in non-limed plots and 5.16 in limed plots 13 months after liming (Table 2.7). Inoculum treatment was significant for seedling disease rating (Table 2.6) alone. Lime and the interaction between lime and inoculum had no significant effect on any of the crop metrics measured (Table 2.8).

Greenhouse: *Fusarium culmorum*. Inoculum rates had highly significant effects on first leaf length, plant height, disease rating and disease incidence (Table 2.9). The effect of soil pH was highly significant for plant height, disease rating and disease incidence (Table 2.9). The relationships between plant height, disease rating, and disease incidence and soil pH were linear, quadratic, and quadratic, respectfully (Table 2.10). There was a significant interaction between soil pH and inoculum for first leaf length, disease rating, and disease incidence (Table 2.9, Figures 2.5, 2.6 and 2.7). First leaf lengths increased incrementally as soil pH increased in the non-inoculated plants and decreased as soil pH increased in the inoculated plants, with the exception of pH 7 at the 150 ppg inoculation level which had the highest values (Figure 2.5). Disease rating and seminal root disease incidence increased incrementally as soil pH increased in the inoculated plants up to pH 6 and decreased at pH 7 (Figures 2.6 and 2.7).

Field study: Fusarium crown rot. In 2016, soil pH in the top 7.5 cm in non-limed plots was 4.39 and 5.39 in limed plots one month after liming (Table 2.11). Thirteen months after liming, soil pH in non-limed plots was 4.64 and 5.84 in limed plots. KCl extractable Al in the top 7.5 cm in 2016 was 330 ppm in non-limed plots and 32 ppm in limed plots one month after liming (Table 2.12). Thirteen months after liming, these values had decreased to 167 ppm in non-limed plots and 1 ppm in limed plots. In the seedling analysis of the *F. culmorum* field studies, inoculum had highly significant effects on the number of tillers per plant and seedling disease rating (Table 2.13) and liming had a significant effect on seedling height (Table 2.13).

Inoculum had significant effects on yield and protein content of the grain (Table 2.14). Lime significantly affected mature plant height, yield, and protein (Table 2.14). The influence of cultivars was highly significant for yield, test weight, and protein (Table 2.14). There was a significant interaction between lime and inoculation for protein (Table 2.14, Figure 2.8). Protein increased with liming in non-inoculated plots but decreased with lime in inoculated plots.

Inoculum had a highly significant effect on post-harvest stem ratings and the number of diseased internodes per stem (Table 2.15). Cultivars also had a significant effect on stem rating (Table 2.15) with WB Hartline having higher disease ratings than Glee.

Discussion

Soil pH has been declining in northern Idaho for several decades. As growers look to ameliorate their low soil pH by liming, many questions remain unanswered, including questions on how common root diseases of the region will respond to changes in soil pH. The effects of soil pH on diseases such as Cephalosporium stripe and take-all have been well documented (Love 1987; Murray and Walter 1991; Stiles and Murray 1996; MacNish 1988; Cook 2003; Lebreton et al. 2014), but there is a lack of published research on the relationship between soil pH and the soil-borne diseases Fusarium crown rot and Rhizoctonia root rot and their causal agents. Therefore, the objective of these studies was to investigate these relationships. In these studies, consistent trends were seen in disease response to soil pH. Although these trends were not always statistically significant, they provide compelling evidence to the interaction seen between soil pH and the soil-borne diseases tested.

In greenhouse assays to examine the impact of soil pH on *R. solani* AG-8 soil pH had a significant effect on plant heights, disease ratings and disease incidence independent of inoculum rate. Similarly, inoculum rate had a significant effect on first leaf length, plant height, disease rating, and disease incidence independent of soil pH. In the case of first leaf lengths and plant heights, there was significant interactions between soil pH and inoculum rate. First leaf lengths increased as soil pH increased in the non-inoculated plants. However, in the low rate of inoculum, first leaf lengths stayed virtually the same and in the high rate of inoculum, the first leaf lengths decreased as soil pH increased, suggesting that at a high enough rate, *R. solani* AG-8 will have a greater impact on young plants as soil pH increases. Yet when plant heights are considered, the effects of soil pH on the pathogen are very different. In non-inoculated plants, plant heights decrease going from pH 4 to 5, but then increase as soil pH increases to 7. This is likely due to a reduction in aluminum toxicity with

increasing soil pH, as it has been well documented that aluminum quantities at a soil pH below 5.2 are toxic to wheat (Taylor 1988; Panda et al. 2009; Koenig et al. 2011). The same trend is seen in the low (15 ppg) and high (150 ppg) inoculum rates, although plant heights are overall shorter as the inoculum rate increases, suggesting that even though the pathogen is having an effect on the plant, these effects can be mitigated by increasing soil pH up to 7. Given the limited published data on this pathogen, there are no other studies to corroborate these findings.

The impact of soil pH on *R. oryzae* was evaluated under both greenhouse and field conditions. As with *R. solani* AG-8, inoculum rate had a highly significant effect independent of soil pH on all plant metrics that were measured. Soil pH likewise had significant effects on all plant metrics independent of inoculum rate. There was a highly significant interaction between soil pH and inoculum rate for both disease rating and disease incidence. In both cases, disease ratings in both the low and high inoculum levels generally increased as soil pH increased from 4 to 6, and then decreased at a pH of 7, suggesting that *R. oryzae* favors a soil pH of 6.

While the cultivar Seahawk does have tolerance to aluminum toxicity (Froese et al. 2015), it did not perform well at the field test site east of Moscow, ID. Inoculum had a significant effect on seedling disease rating independent of liming. There were no significant interactions between lime and soil pH to compare to the greenhouse results. With the lack of published work on the interaction between soil pH and *R. oryzae* and the lack of significant results from this field study, further research should to be done. However, the trends seen in the greenhouse studies suggests that growers should be diligent in managing for Rhizoctonia root rot as they begin liming to manage soil pH.

The impact of soil pH on *F. culmorum* was also evaluated under both greenhouse and field conditions. Inoculum rates significantly impacted all the crop metrics measured in the greenhouse, including first leaf length, plant height, disease rating, and disease incidence. Soil pH had significant impacts on plant height, disease rating and disease incidence. There were significant interactions between soil pH and inoculum rate on first leaf length, disease rating, and disease incidence. First leaf

lengths increased as soil pH increased in non-inoculated plots. In the inoculated plots however, first leaf lengths decreased as soil pH increased for both the low and high rates of inoculum from pH 4 to 6. At a soil pH of 7 in the low rate, first leaf length stayed the same as pH 6 and in the high rate of inoculum, it actually increased from pH 6 to 7. This interaction is interesting when considered in context with the decrease in disease rating and seminal root disease incidence going from a soil pH of 6 to 7. These results seem to suggest that like *R. oryzae*, *F. culmorum* favors a soil pH of 6, and the effects of the pathogen are diminished at a soil pH of 7.

In the field studies for *F. culmorum*, inoculum had significant effects independent of soil pH on number of tillers per plant, seedling disease rating, yield, protein, stem disease ratings, and disease incidence. Liming had a significant impact independent of inoculum on seedling height, mature plant height, yield, and protein. There was a cultivar response between Glee and WB Hartline for yield, test weight, protein and stem disease rating independent of liming and inoculum. For protein, there was a significant and interesting interaction between lime and inoculum. For non-inoculated plots, lime increased protein content regardless of the cultivar. In the inoculated plots, protein was overall higher for both non-limed and limed plots, but limed plots had slightly lower protein content than non-limed. This may be due to reduced yields in inoculated vs. non-inoculated plots. A similar phenomenon is seen in drought stressed wheat having greater protein content due to lower yields (Jones and Oloson-Rutz, 2012).

While many intriguing results were seen in the data from these greenhouse and field studies, many were not statistically significant, particularly in the field studies. However, the data from the greenhouse studies is strong enough to make a few recommendations for growers in northern Idaho as they begin managing soil acidity by liming. The interactions between soil pH and disease ratings suggest that while substantial increases in disease incidence and severity are unlikely, growers should be diligent in managing field conditions for disease. For Rhizoctonia root rot, this includes using proper burndown intervals to manage volunteer and grassy weeds (“greenbridge” control) and seeding

into soils and residues that will be favorable for rapid seedling growth. In the case of Fusarium crown rot, growers should avoid situations that will create drought stress later in the growing season. This includes properly managing nitrogen fertilizer inputs to avoid overfertilization and avoiding wet seeding conditions in the spring that could result in soil compaction.

Table 2.1. Dilutions of NuCal™ and deionized water to generate a pH gradient for greenhouse assays.

1:9 Diluted NuCal™ (ml)	Deionized Water (ml)	Soil pH (1:1)*		
		Week 0	Week 1	Week 2
0	15	4.49	4.32	4.18
0.5	14.5	4.74	4.55	4.30
1.0	14	5.03	4.69	4.51
2.0	13	5.52	5.08	4.87
4.0	11	6.35	6.15	5.84
6.0	9	6.57	6.72	6.60
8.0	7	6.60	7.10	6.86
12.0	3	6.84	7.09	6.99
15.0	0	6.62	7.11	7.04

*Soil pH was measured using a 1:1 soil to water slurry method.

Table 2.2. P-values for *R. solani* greenhouse study.

Source	df	First Leaf Length	Plant Height	Disease Rating	Disease Incidence
		P-value*			
Experiment (Ex)	1	**0.0042**	0.9809	**<0.0001**	**<0.0001**
Rep (Ex)	4	0.8732	0.9249	0.1551	0.4716
pH	3	0.7157	**<0.0001**	**<0.0001**	**0.0022**
Inoculum	2	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
pH x Inoc	6	**0.0177**	**0.0163**	0.05	0.0547

* P-values < 0.05 in bold.

Table 2.3. Means squares from the analyses of variance of 1st leaf length, plant height, disease rating, and disease incidence from two experiments, four pH levels, and three inoculum levels.

Source	df	First Leaf Length		Plant Height		Disease Rating		Disease Incidence	
Experiment (Ex)*	1	22.367	***	0.004	***	912.069	***	360.802	***
Rep (Ex)	4	3.294		6.931		3.735		2.247	
pH	3	3.641	ns	503.734	ns	13.042	ns	9.441	ns
Linear	1	1.010	ns	238.292	ns	5.240	ns	4.732	ns
Quadratic	1	0.038	ns	231.398	ns	5.443	ns	4.047	ns
Cubic	1	2.574	ns	33.024	ns	2.089	ns	0.494	ns
Inoc	2	236.524	***	2569.291	***	1258.424	***	975.605	***
Linear	1	197.428	***	2309.600	***	1061.131	***	892.660	***
Quadratic	1	35.417	***	233.477	***	172.102	***	68.660	***
pH x Inoc	6	41.989	*	122.794	*	7.109	ns	7.921	ns
Error	299	802.146		2321.527		2969.129		1819.201	

***** Experiment Mean Squares (MS) were tested for significance against the replicate within experiments (Rep (Ex)) MS; All other MS's were tested for significance against the replicate error (Error).

Table 2.4. P-values for *R. oryzae* greenhouse study.

Source	df	First Leaf Length	Plant Height	Disease Rating	Disease Incidence
			P-value*		
Experiment (Ex)	1	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Rep (Ex)	4	0.3079	0.3851	0.5867	0.6639
pH	3	**0.0275**	**<0.0001**	**<0.0001**	**0.0001**
Inoculum	2	**<0.0001**	**<0.0001**	**<.0001**	**<0.0001**
pH x Inoc	6	0.6057	0.1693	**<0.0001**	**<0.0001**

*****P-values <0.05 in bold

Table 2.5 Means squares from the analyses of variance of 1st leaf length, plant height, disease rating, and disease incidence from two experiments, four pH levels, and three inoculum levels.

Source	df	First Leaf Length		Plant Height		Disease Rating		Disease Incidence	
Experiment (Ex)*	1	273.125	***	760.067	***	89.169	***	13.518	***
Rep (Ex)	4	20.563		41.780		3.592		2.186	
pH	3	39.490	**	1386.102	***	71.997	***	19.788	***
Linear	1	5.353	ns	1011.499	***	6.200	*	0.740	ns
Quadratic	1	0.392	ns	75.448	**	39.948	***	12.441	***
Cubic	1	34.251	**	262.359	***	25.242	***	6.610	**
Inoc	2	442.999	***	1970.971	***	1059.993	***	1202.169	***
Linear	1	431.150	***	1690.078	***	960.231	***	<.0001	***
Quadratic	1	13.167	ns	291.772	***	93.899	***	<.0001	***
pH x Inoc	6	19.298	ns	91.673	ns	44.899	***	21.395	***
Error	313	2050.361		2883.436		371.334		267.464	

***** Experiment Mean Squares (MS) were tested for significance against the replicate within experiments (Rep (Ex)) MS; All other MS's were tested for significance against the replicate error (Error).

Table 2.6. Analysis of variance (ANOVA) for seedling assessment of *R. oryzae* field study.

Source	df	Tillers	First Leaf Length	Seedling Height	Seedling Disease Rating
			P-value		
Year	1	**<0.0001**	0.58	**<0.0001**	**<0.0001**
Lime	1	0.4512	0.1932	0.534	0.3682
Inoculum	1	0.076	0.2865	0.5458	**<0.0001**
Lime*Inoc	1	0.9397	0.8353	0.5107	0.0993

Table 2.7. Soil pH for *R. oryzae* field trials conducted east of Moscow, ID. Samples were collected 13 months after liming in the spring of 2018.

Lime	Depth (cm)			
(Y/N)	0.0-7.5*	7.5-15.0*	15.0-22.5*	22.5-30*
N	4.16	4.22	4.67	5.08
Y	5.16	4.61	4.74	5.37

*These are single measurements

Table 2.8. Analysis of variance (ANOVA) for yield results of *R. oryzae* field study.

Source	df	Yield	TWT
		P-value	
Year	1	**0.0141**	**0.0316**
Lime	1	0.193	0.7188
Inoculum	1	0.5336	0.6493
Lime*Inoc	1	0.6279	0.6168

Table 2.9. P-values for *F. culmorum* greenhouse study.

Source	df	First Leaf Length	Plant Height	Disease Rating	Disease Incidence
		P-value			
Experiment (Ex)	1	**<0.0001**	**<0.0001**	0.7945	0.0595
Rep (Ex)	4	0.0403	0.0509	0.1283	0.2459
pH	3	0.5729	**<0.0001**	**<0.0001**	**<0.0001**
Inoculum	2	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
pH x Inoc	6	**0.0224**	0.2846	**0.0002**	**0.0005**

Table 2.10. Means squares from the analyses of variance of 1st leaf length, plant height, disease rating, and disease incidence from two experiments, four pH levels, and three inoculum levels.

Source	df	First Leaf Length		Plant Height		Disease Rating		Disease Incidence	
Exeriment (Ex)*	1	261.893	***	1452.060	***	0.106	ns	3.908	ns
Rep (Ex)	4	42.369		133.121		11.264		5.965	
pH	3	8.358	ns	405.976	***	60.952	***	32.402	***
Linear	1	3.045	ns	276.225	***	17.500	***	8.182	**
Quadratic	1	2.827	ns	123.086	**	36.837	***	21.154	***
Cubic	1	2.593	ns	4.980	ns	9.224	*	4.304	*
Inoc	2	112.152	***	614.031	***	599.084	***	384.669	***
Linear	1	80.441	***	441.877	***	584.780	***	382.951	***
Quadratic	1	39.845	**	210.643	***	29.271	***	0.000	ns
pH x Inoc	6	62.699	*	103.727	ns	42.112	***	27.491	***
Error	290	1211.187		4078.070		457.692		318.871	

***** Experiment Mean Squares (MS) were tested for significance against the replicate within experiments (Rep (Ex)) MS; All other MS's were tested for significance against the replicate error (Error).

Table 2.11. Soil pH for *F. culmorum* field trials conducted east of Moscow, ID. Samples were collected 1 and 13 months after liming.

Year	Lime (Y/N)	Depth (cm)			
		0.0-7.5	**7.5-15.0**	**15.0-22.5**	**22.5-30**
2016	N	4.39	4.60	5.01	5.40
	Y	5.39	4.87	5.23	5.76
2017	N	4.64	4.79	5.16	5.51
	Y	5.84	4.98	5.28	5.83

*These are single measurements

Table 2.12. KCl AL for *F. culmorum* field trials conducted east of Moscow, ID. Samples were collected 1 and 13 months after liming.

Year	Lime (Y/N)	Depth (cm)			
		0.0-7.5	**7.5-15.0**	**15.0-22.5**	**22.5-30**
2016	N	330	172	28	2
	Y	32	100	10	0
2017	N	167	100	16	3
	Y	1	50	9	1

*These are single measurements

Table 2.13. Analysis of variance (ANOVA) for seedling assessment of *F. culmorum* field study.

Source	df	Tillers	Seedling Height	Seedling Disease Rating
			P-value	
Year	1	0.3638	**<0.0001**	0.2627
rep(year)		0.4296	0.6208	0.7159
Lime	1	0.8902	**0.0065**	0.6526
Inoculum	1	**<0.0001**	0.2885	**<0.0001**
Lime x inoc	1	0.0767	0.4238	0.0953
Cultivar (CV)	1	0.4569	0.4366	0.4652
Inoc x CV	1	0.3934	0.221	0.7784

Table 2.14. Analysis of variance (ANOVA) for yield of *F. culmorum* field study.

Source	df	Mature Plant Height	Yield	TWT	Protein
		P-value			
Year	1	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
rep(year)		0.5648	**0.0029**	**0.0002**	**<0.0001**
Lime	1	**0.0005**	**<0.0001**	0.1993	**0.0079**
Inoculum	1	0.8847	**0.0018**	0.007	**<0.0001**
Lime x inoc	1	0.8847	0.5143	0.7466	**0.0214**
Cultivar (CV)	1	0.6754	**<0.0001**	**<0.0001**	**<0.0001**
Inoc x CV	1	0.3124	0.5544	0.0028	0.1314

Table 2.15. Analysis of variance (ANOVA) for post-harvest stem ratings of *F. culmorum* field study.

Source	df	Stem Rating	Diseased Internodes
		P-value	
Year	1	**<0.0001**	**<0.0001**
rep(year)		0.0816	**0.0161**
Lime	1	0.2122	0.1264
Inoculum	1	**<0.0001**	**<0.0001**
Lime x inoc	1	0.2902	0.1914
Cultivar (CV)	1	**0.0179**	0.0188
Inoc x CV	1	0.4519	0.1466

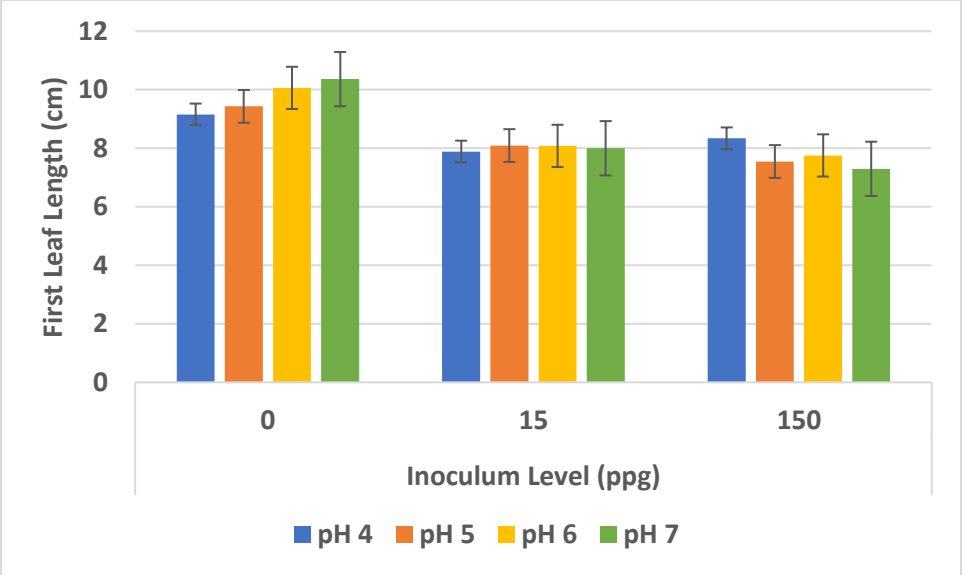

Figure 2.1. pH by inoculum level interaction on first leaf length for *R. solani* AG-8. P-value 0.0177. Error bars indicate standard error.

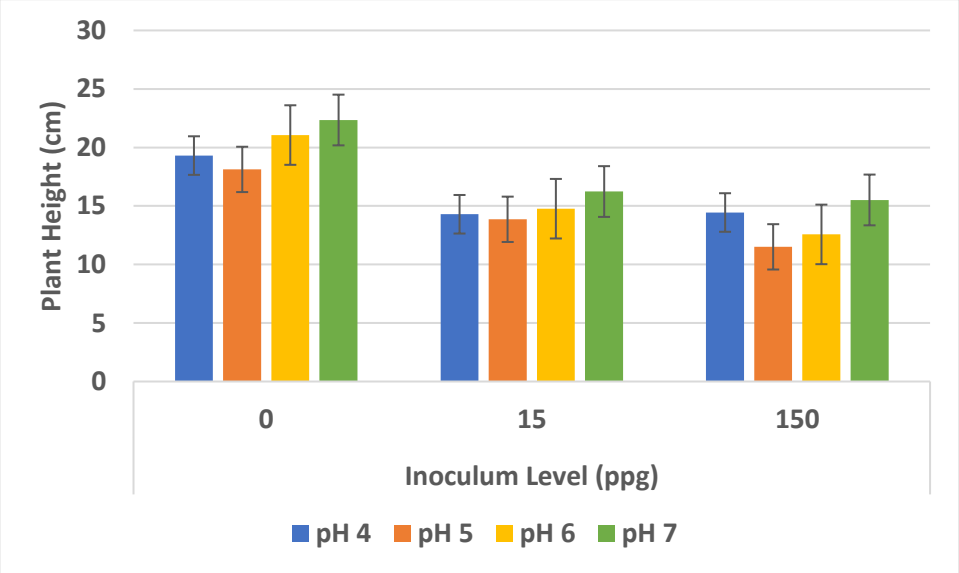

Figure 2.2. pH by inoculum level interaction on plant height for *R. solani* AG-8. P-value 0.0163. Error bars indicate standard error.

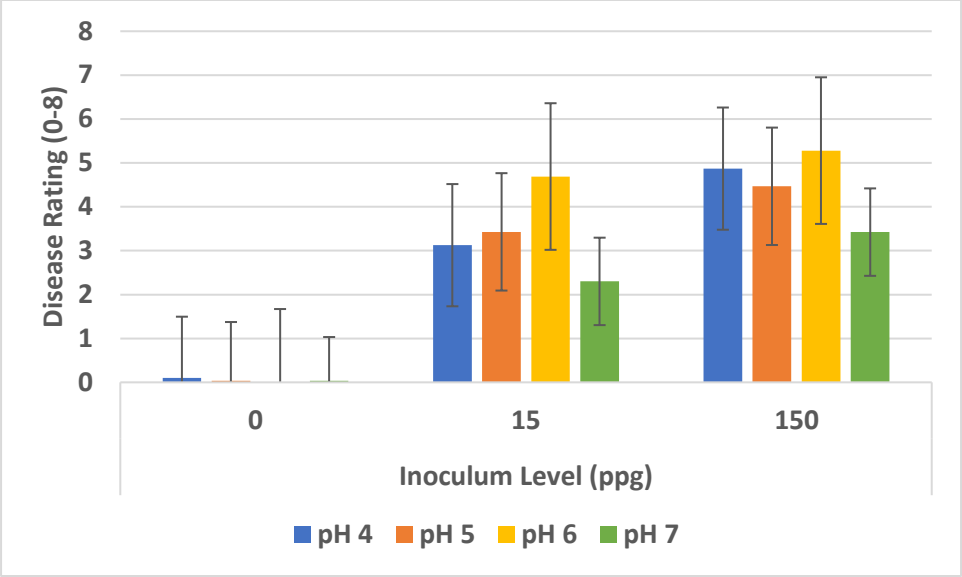

Figure 2.3. pH by inoculum level interaction on disease rating for *R. oryzae*. P-value <.0001. Error bars indicate standard error.

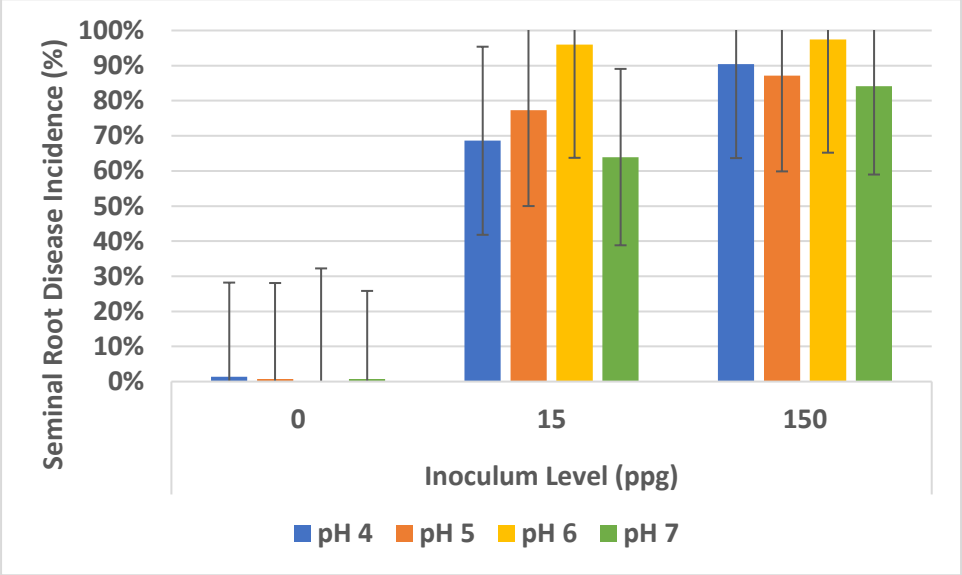

Figure 2.4. pH by inoculum level interaction on seminal root disease incidence for *R. oryzae*. P-value <.0001. Error bars indicate standard error.

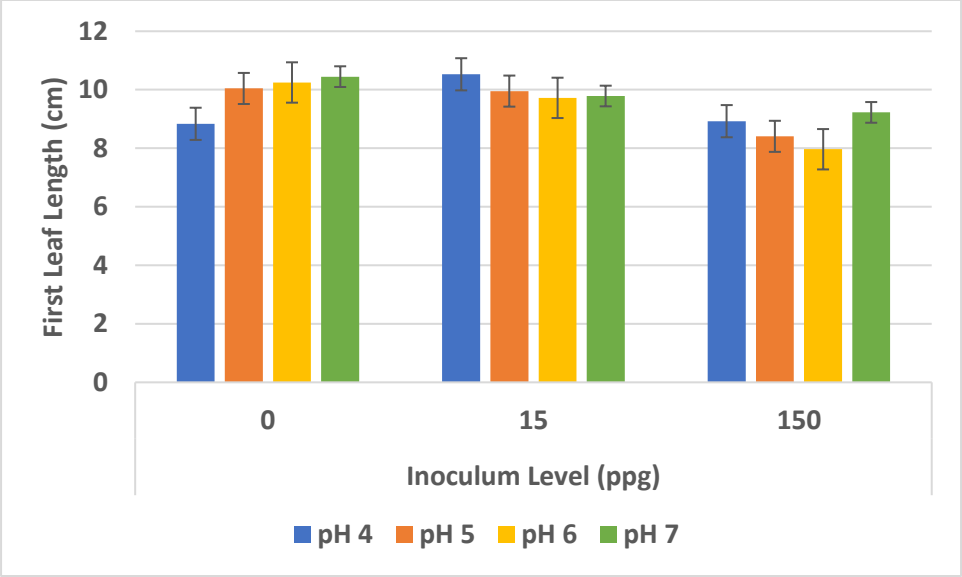

Figure 2.5. pH by inoculum level interaction on first leaf length for *F. culmorum*. P-value 0.0224. Error bars indicate standard error.

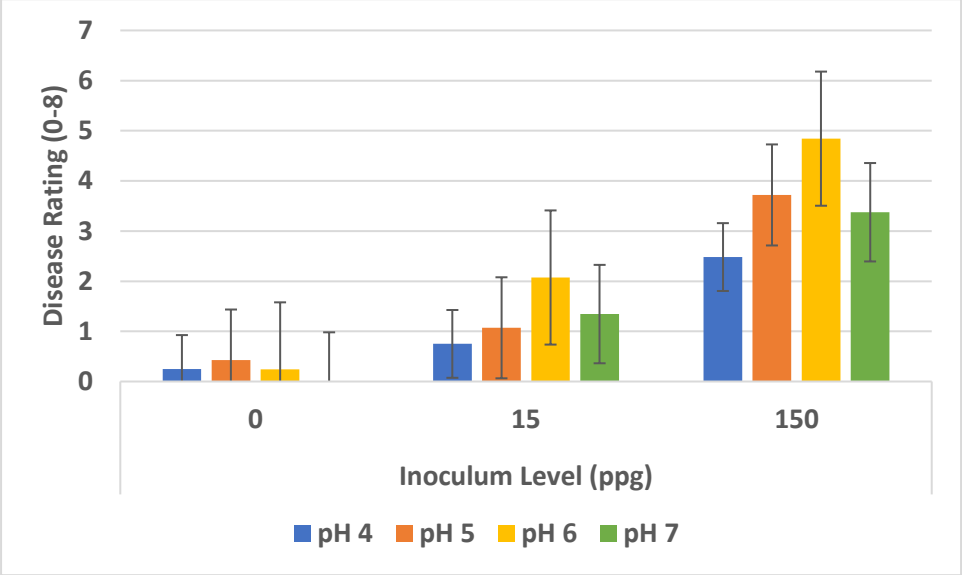

Figure 2.6. pH by inoculum level interaction on disease rating for *F. culmorum*. P-value 0.0002 Error bars indicate standard error.

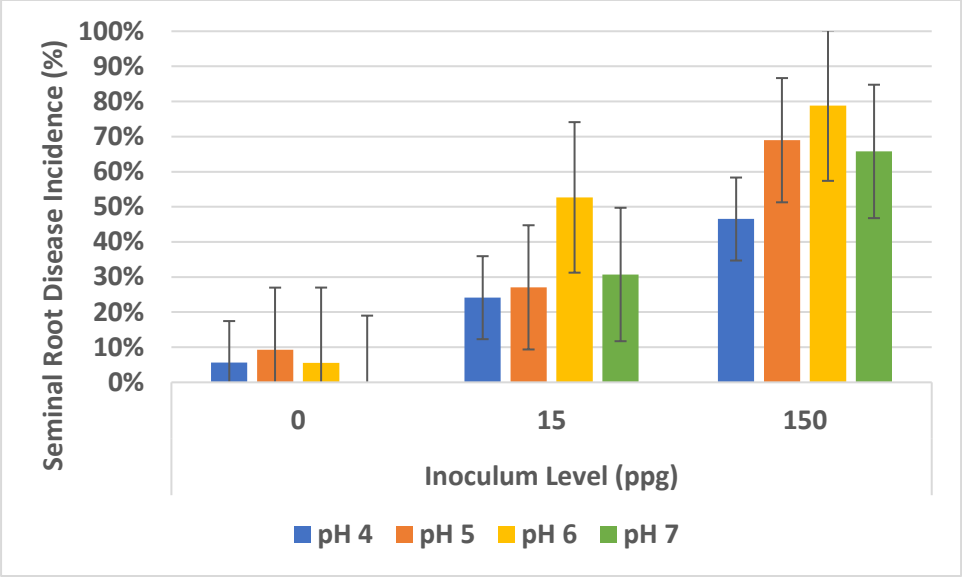

Figure 2.7 pH by inoculum level interaction on seminal disease incidence for *F. culmorum*. P-value 0.0005. Error bars indicate standard error.

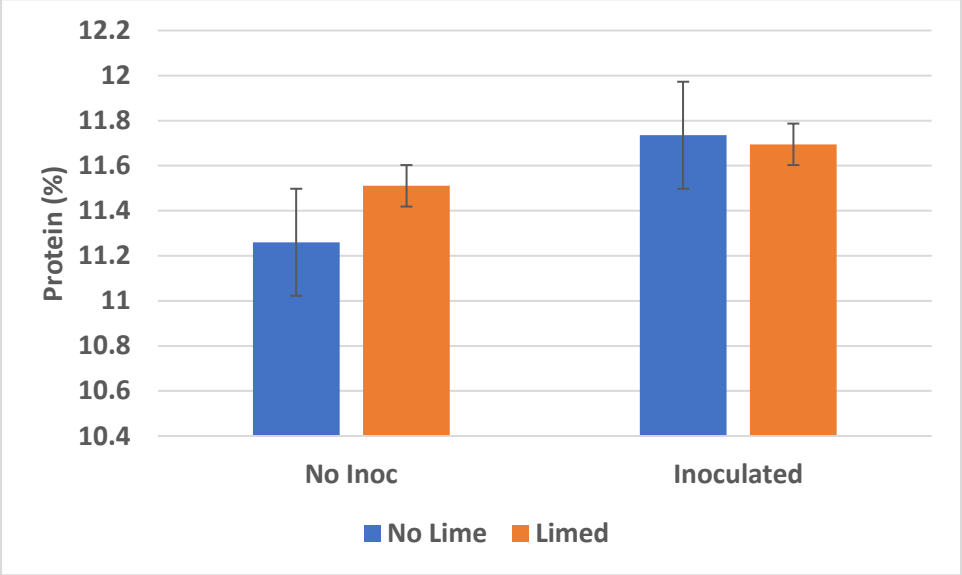

Figure 2.8. Lime by inoculum interaction on protein content for *F. culmorum* field trials. P-value 0.0214. Error bars indicate standard error.

Literature Cited

Aniol, A. 1984. Induction of aluminum tolerance in wheat seedlings by low doses of aluminum in the nutrient solution. Plant Physiol. 76:551–555.

Bockus, W. W. 1985. Effect of lime and sulfur application to low-pH soil on incidence of cephalosporium stripe in winter wheat. Plant Dis. 69:576.

Caires, E. F., Alleoni, L. R. F., Cambri, M. A., and Barth, G. 2005. Surface application of lime for crop grain production under a no-till system. Agron. J. 97:791–798.

Jones, C., Olson-Rutz, K. 2012. Practices to Increase wheat grain protein. Montana State University Extension EB0206

Cook, R. J. 2003. Take-all of wheat. Physiol. Mol. Plant Pathol. 62:73–86.

Erginbas-Orakci, G., Poole, G., Nicol, J. M., Paulitz, T., Dababat, A. A., and Campbell, K. 2016. Assessment of inoculation methods to identify resistance to fusarium crown rot in wheat. J. Plant Dis. Prot. 123:19–27.

Fageria, N. K., Ballgar, V. C., and Wright, R. J. 1988. Aluminum toxicity in crop plants. J. Plant Nu. 11:303–319.

Froese, P. S., Carter, A. H., and Pumphrey, M. O. 2015. Recommended crop species and wheat varieties for acidic soil. Washington State University Extension FS169E.

Hall, R., and Sutton, J. C. 1998. Relation of weather, crop, and soil variables to the prevalence, incidence, and severity of basal infections of winter wheat in Ontario. Can. J. Plant Pathol. 20:69–80.

van Herwaarden, A. F., Farquhar, G. D., Angus, J. G., Richards, R. A., and Howe, G. N. 1998. "Haying-off", the negative grain yield response of dryland wheat to nitrogen fertiliser. I. Biomass, grain yield, and water use. Aust. J. Agric. Res. 49:1067–1082.

Koenig, R., Schroeder, K., Carter, A., Pumphrey, M., Paulitz, T., Campbell, K., et al. 2011. Soil acidity and aluminum toxicity in the Palouse region of the Pacific Northwest. Washington State University Extension FS050E.

Lebreton, L., Daval, S., Guillerm-Erckelboudt, A. Y., Gracianne, C., Gazengel, K., and Sarniguet, A. 2014. Sensitivity to pH and ability to modify ambient pH of the take-all fungus *Gaeumannomyces graminis* var. *tritici*. Plant Pathol. 63:117–128.

Love, C. S. 1987. Effect of soil pH on Cephalosporium stripe in wheat. Plant Dis. 71:727-731.

MacNish, G. C. 1988. Changes in take-all (*Gaeumannomyces graminis* var. *tritici*), Rhizoctonia root rot (*Rhizoctonia solani*) and soil pH in continuous wheat with annual applications of nitrogenous fertiliser in Western Australia. Aust. J. Exp. Agric. 28:333–341.

Mohebbi, S., and Mahler, R. L. 1989. The effect of soil ph on wheat and lentils grown on an agriculturally acidified northern Idaho soil under greenhouse conditions. Communications in Soil Science and Plant Analysis. 20:359-381

Murray, T. D., and Walter, C. C. 1991. Influence of pH and matric potential on sporulation of *Cephalosporium gramineum*. Phytopathology. 81:79–84.

Nuttall, J. G., O'Leary, G. J., Khimashia, N., Asseng, S., Fitzgerald, G., and Norton, R. 2012. "Haying-off" in wheat is predicted to increase under a future climate in south-eastern Australia. Crop Pasture Sci. 63:593–605.

Panda, S. K., Baluška, F., and Matsumoto, H. 2009. Aluminum stress signaling in plants. Plant Signal. Behav. 4:592–597.

Paulitz, T. C., Smith, J. D., and Kidwell, K. K. 2003. Virulence of *Rhizoctonia oryzae* on wheat and barley cultivars from the Pacific Northwest. Plant Dis. 87:51–55.

Ritchie, F., Bain, R. A., and McQuilken, M. P. 2009. Effects of nutrient status, temperature and pH on mycelial growth, sclerotial production and germination of *Rhizoctonia solani* from potato. J. Plant Pathol. 91:589–596.

Schroeder, K. L., and Paulitz, T. C. 2007. Effect of inoculum density and soil tillage on the development and severity of Rhizoctonia root rot. Phytopathology 98:304–314.

Schroeder, K. L., and Pumphrey, M. 2013. It's all a matter of pH. Wheat Life, January 2013, pp. 56–59.

Smiley, R. W., Collins, H. P., and Rasmussen, P. E. 1996. Diseases of wheat in long-term agronomic experiments at "Pendleton" Oregon. Plant Dis. 80:813-820.

Smiley, R. W., Gourlie, J. A., Easley, S. A., Patterson, L.-M., and Whittaker, R. G. 2005. Crop damage estimates for crown rot of wheat and barley in the pacific northwest. Plant Dis. 89:595–604.

Smith, J. D., Kidwell, K. K., Evans, M. A., Cook, R. J., and Smiley, R. W. 2003. Evaluation of spring cereal grains and wild germplasm for resistance to *Rhizoctonia solani* AG-8. Crop Sci. 43:701–709.

Stiles, C., and Murray, T. 1996. Infection of field-grown winter wheat by *Cephalosporium gramineum* and the effect of soil pH. Phytopathology 86:177–183.

Watanabe, K., Matsui, M., Honjo, H., Becker, J. O., and Fukui, R. 2011. Effects of soil pH on rhizoctonia damping-off of sugar beet and disease suppression induced by soil amendment with crop residues. Plant Soil. 347:255–268.

Chapter 3: Evaluation of liming rates and investigating economic return of lime applications to low pH soils in northern Idaho

Introduction

Soil pH has been declining in northern Idaho and other locations in the Inland Pacific Northwest for decades. The introduction of semi-dwarf wheat varieties in the 1960s such as "Gaines" and "Nugaines", allowed farmers to increase wheat yields by applying greater amounts of inorganic nitrogen (N) fertilizers as these new varieties would not lodge under higher levels of N fertilizer (Morrison and Vogel 1962). Ammonium N fertilizers were widely used in the Pacific Northwest following the introduction of semi-dwarf wheat varieties (Shepherd 1975). As reported by Mahler and others (1985), the repeated use of these ammonium N fertilizers in the following decades led to a rapid decrease in soil pH. Mahler and McDole (1985, 1987) reported that average soil pH values in the top 30 cm of soil in northern Idaho had declined from a range of 6.5 to 7.2 in the 1860s, to a pH value of 5.7 by 1984, with 45% of agricultural soils being below 5.6. Northern Idaho is well suited for the production of winter wheat and grass seed. However, repeated use of ammonium forms of nitrogen fertilizers to support cereal grain production has been the leading contributor to this acidification (Mahler & McDole, 1987).

The primary impacts of soil acidification include aluminum toxicity which reduces plant vigor and yield (Delhaize and Ryan 1995), and reduced nutrient availability (Fernández and Hoeft 2009; Johnson 2011; McFarland et al. 2015). The greatest yield-limiting factor for soils with a pH below 5.5 is aluminum toxicity (Froese et al. 2015). As soil pH drops below 5.5, materials in the soil that contain aluminum (Al) dissolve, allowing Al to become plant soluble (Johnson 1992). The most easily observed symptom of aluminum toxicity is significant changes to the root architecture, including reduced root growth and root deformation. Belowground, toxic quantities of soluble Al cause plant roots to become thickened, stubby, swollen, have no fine branching, and turn brown (Koenig et al. 2011; Foy 1984). Aboveground, plants can appear stunted and chlorotic (Koenig et al. 2011). The

overall affect is a plant with reduced abilities to uptake water and nutrients from the soil (Delhaize et al. 1993).

The acidifying of northern Idaho soils poses a potential threat to growers in the region. The combination of a rain-fed environment with a Mediterranean climate limits crop choice for growers as the number of heat units accumulated during a season is generally not enough for warm season crops. The steep undulating hills of the Palouse are not practical for growing row crops such as potatoes and onion, common cash crops grown in southern Idaho. Due to these restrictions, growers are limited on crop choices, with cereal grains (wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*)), grain legumes (peas (*Pisum sativum*), chickpeas (*Cicer arietinum*), and lentils (*Lens culinaris*), and brassica crops (canola (*Brassica napus*), mustard (*Brassica juncea*), and rape (*Brassica napus*)) being the best suited and most common. There are also significant amounts of grass and forage hay grown in parts of northern Idaho.

Historically, cereal grains have been more important economically than legumes in the region, yet legumes serve as vital rotation crops, aiding in weed and disease management and providing a natural source of nitrogen via their symbiosis of rhizobia bacteria (Shepherd 1975; Schillinger and Papendick 2008). However, legumes are more sensitive to low pH than cereal grains due to the intolerance of nitrogen fixing bacteria to low soil pH values (Weese et al. 2015; Sullivan et al. 2016). Work by Mahler and McDole (1987) in northern Idaho showed that yield in lentils began to sharply decline blow a pH value of 5.6. In general, anything below a soil pH of 6.0 is considered low for legumes. A soil pH below 5.5 is low enough to cause crop injury and yield reduction due to sensitivities of the nitrogen fixing bacteria to low soil pH as well as limiting quantities of calcium and molybdenum, which are essential for symbiosis to occur (Khosro Mohammadi, 2012; Sullivan et al., 2013). In a recent survey of northern Idaho soils by Schroeder et al. (unpublished), only one out of 95 fields that were annually crop tested above a pH of 6.0 in the top 15 cm, with the majority near or

below 5.0, and several declining towards 4.0. Thus, the threat of reduced yields and even the inability to grow certain crops is very real in northern Idaho.

There are two main methods commonly used by growers to mitigate the effects of low soil pH and aluminum toxicity—growing aluminum tolerant cultivars and liming. Plants that are tolerant of aluminum protect themselves by producing organic anions such as malate and citrate (Sasaki et al. 2014). These organic anions are excreted by the roots and chelate Al in the soil solution, preventing absorption by the plant. This can be a viable option for growers who cannot afford to lime their fields. However, this is paramount to taking morphine for a broken leg—it may feel better, but the leg is not being healed. In other words, aluminum tolerant cultivars can offer increased yields over non-tolerant cultivars, but they do nothing to correct low soil pH which creates the conditions for aluminum toxicity; only adding lime to the soil can correct low soil pH (McFarland et al. 2015).

Washington State University has evaluated wheat cultivars commonly grown in northern Idaho for tolerance to acidic soils, as well as actively breeding improved cultivars for enhanced tolerance (Froese et al. 2015; McFarland and Huggins 2015). According to Froese and others (2015), this screening is made difficult due to the high spatial variation in soil pH and Al within test plots. This work is extremely important for growers in the region with acidic soils, however this work is limited to wheat and offers no recommendations for vital legume and brassica rotation crops grown in the area.

Liming is a necessary component of crop production for many areas in the U.S. When lime is added to soil in the form of calcium carbonate ($CaCO_3$), it reacts with hydrogen ions (the acidity) to neutralize soil pH with the net result being the formation of water and carbon dioxide (Sullivan et al. 2013). Scharf (2000) reports that liming a soil to raise the pH of 4.5 to 6.0 can increase soybean yields by 15% in Missouri. According to Mamo and others (2015), the cost of liming the top 15 to 20 cm of soil should be considered a capital investment of 5 to 10 years. In a Washington County, Nebraska study to examine liming a corn and soybean rotation, Mamo and others (2015) reported average

annual income was greater than the average annual expense by year 4 after a lime application that cost \$108 ha^{-1}, with a 5% interest rate.

Liming in northern Idaho was studied by Mahler in the 1980s. Field studies were conducted between 1982 and 1984 using locally-sourced ground limestone in rates of 0; 2,200; and 4,400 kg ha^{-1} applied to the soil surface and then incorporated to a depth of 15 cm (Mahler 1986). They observed that lime rates of 2,200 and 4,000 kg ha^{-1} resulted in significant net increases in soil pH of 0.48 and 0.79, respectfully. In this same study, lentil yields in the 2,200 and 4,000 kg ha^{-1} treatments were 23.7 and 22.4% higher than the controls. Mahler concluded that yields of spring pea, winter wheat, and spring barley in northern Idaho would respond to applications of lime when soil pH was sufficiently low.

However, liming poses challenges to growers in northern Idaho and the Palouse region. Lack of an established liming industry and transportation costs of outside sources of lime makes acquiring lime difficult for growers. Additionally, no buffer test for predicting lime requirement has been developed for the soils in our region, and according to McFarland and Huggins (2015), the commonly used Adams and Evans (Adams and Evans 1962), SMP (Shoemaker et al. 1961), and Woodruff (Woodruff 1948) buffer tests are likely over-predicting lime needed to ameliorate acidic soils in the Palouse. Research has recently been completed to determine correlations and calibrations of these common buffer tests to soils in the Palouse region (McFarland 2016).

The objectives of this study are 1) to examine the ability of lime applied at rates up to 6,726 kg of $CaCO_3$ ha^{-1} to ameliorate acidic soils in northern Idaho, 2) monitor changes in soil pH and other soil chemical properties, and 3) evaluate the return on investment of the liming applications over time and crop rotations to begin developing a feasibility model. This work represents the first 2 years of a 6 to 10-year study.

Methods and Materials

Field studies were carried out in five grower cooperator fields in northern Idaho to investigate the quantity of lime needed to ameliorate low soil pH and Al toxicity. The criteria for field site selection were soil with a pH below 5.0 in the top 15 cm, a base saturation of less than 50%, and potassium chloride (KCl) extractable Al above 20 ppm. Sites for the study were initially identified using an ExStik® waterproof pH meter (ExTech Instruments, Nashua, NH). If field measurements were near or below pH of 5.0, six composite 15 cm cores with a diameter of 1.5 cm were collected with a soil probe and analyzed for pH, base saturation and KCl extractable Al by Best Test Analytical Services (Moses Lake, WA).

Four sites were identified in 2016. Two of the sites are located near Potlatch, Idaho (Potlatch 1 & 2) and two near Tensed, Idaho (Tensed 1 & 2). Potlatch 1 is located 3 km, and Potlatch 2 is located 5 km northeast of Potlatch, ID. Tensed 1 is located 0.7 km north and Tensed 2 is located 3.9 km northeast of Tensed, ID. A fifth site was identified in the summer of 2017 6.5 km east of Moscow, ID. The soil at Potlatch 1 is a Joel silt loam, 7 to 25 percent slopes and is on a gentle slope with a south facing aspect. The soil at Potlatch 2 is a Taney ashy silt loam, moist, 2 to 8 percent slopes, and is on a gentle slope with a west facing aspect. The soil at Tensed 1 is Latahco silt loam, 0-2 percent slopes and is on a flat toe slope. The soil at Tensed 2 is a Southwick-Driscoll complex, 3 to 15 percent slopes and is on a summit. The soil at the Moscow site is a Larkin silt loam, 12 to 35 percent slopes and is on a terrace with a very gentle slope. The Potlatch and Tensed sites are all conventionally tilled. The Moscow site is no-till. To minimize the risk of mixing the topsoil between treatments, plots were managed using no-till for the duration of the study.

The four 2016 sites were limed October 5, 2016. The 2017 site was limed July 31, 2017. Crushed limestone (ag-lime) with a calcium carbonate ($CaCO_3$) equivalent (CCE) guaranteed analysis of 95% was obtained from Pioneer Enterprises in Grangeville, Idaho. Liming treatments used were 0; 2,242; 4,484; and 6,726 kg of $CaCO_3$ ha^{-1}. The quantity of ag-lime applied was adjusted for water

weight by drying a 500-g sample for 24 hours in a forced-air dryer and dividing the fresh weight by the difference to obtain percent moisture. Liming rates were then calculated by the following formula.

$$Lime\ Rate = \frac{\frac{Desired\ Lime\ Rate}{100 - \%\ Moisture}}{100} \div CCE$$

The experimental design was a randomized complete block, with four treatments and four replicates. Each plot measures 2.4 m by 30.5 m. Lime was applied to the plots by hand with buckets and feed scoops. To increase the accuracy of the lime application, the plots were divided into 2.4 m by 6 m (14.4 m^{-1}) sections and the appropriate amount of lime for that area was calculated and applied. The lime was incorporated into the soil by each cooperator by two passes of a cultivator operating at a 15 cm depth.

The crop selection at each location mirrored what the grower planted so that crop rotations typical of each location were followed. This also minimized the risk of herbicide injury and allowed for the cooperators to provide pest management at each location. Cultivars were consistent between sites and included UI-WSU Huffman for soft white winter wheat, Bronic for chickpea, Morena for lentil and HyClass 930 RR for canola. Each of these represent commonly grown varieties in the region. Plots were planted with a custom-built AgPro 8 ft. conservation research drill (AGPRO Inc., Lewiston, ID) equipped with eight Bourgault paired row openers (Bourgault Tillage Tools Ltd., Saint Brieux, SK, Canada) spaced 30.5 cm apart. Composite soil samples were taken down to a depth of 120 cm at 30 cm increments before planting every year to determine fertilizer needs at planting. Solutions of liquid fertilizer (solution 32, ammonium phosphate, and thisosul) were deep banded below the seed. Fertilizer rates followed north Idaho fertilizer guides based on projected yield goals for each crop and by location.

Each year in early to mid-May, soil samples were collected from each plot and location. Two composite samples were collected from each strip, one from the front half of the plot and a second

from the back half of the plot. Each composite sample consisted of 12 cores 1.5 cm in diameter collected to a depth of 30 cm. Each core was divided into four depth increments prior to compositing the samples: 0 to 7.5 cm, 7.5 to 15 cm, 15 to 22.5 cm and 22.5 to 30 cm. Soils were stored in a 4°C cooler. Soils were passed through a 2 mm stainless steel sieve and air dried for 72 hours at ambient temperatures (~22°C). A 200 g sample was packaged for each soil and sent to Best Test Analytical Services to determine pH, macro- and micronutrient content, total bases, base saturation, cation exchange capacity (CEC), lime requirement and quantity of KCl extractable Al.

At maturity, seed yield was obtained by harvesting each plot with a Wintersteiger plot combine. Seed quality was evaluated by recording test weight and protein for cereal grains. Test weight was determined using a Cox Funnel (Seedburo Equipment Company, Des Plaines, IL). Protein was measured using a Foss Infratec^{TM} Nova (Foss, Hilleroed, Denmark).

2016 – 2017 Crop Year. UI-WSU Huffman soft white winter wheat was planted on November 4th at three of the sites established in 2016—Potlatch 2, Tensed 1 and Tensed 2 at a rate of 248 seeds square meter^{-1}. Potlatch 1 remained fallow for this crop year due to prolonged spring rains resulting in prevented planting. Planting in the fall of 2017 was delayed due to frequent and steady rain throughout October. The wheat was planted at a depth of 2 cm. Tensed 1 and Tensed 2 had fertilizer pre-applied and incorporated by disk before planting. Potlatch 2 had all fertilizer applied at planting (Table 1).

Plant density was measured April 19, 2017 at all three winter wheat sites. A 0.5 m stick was placed next to one of the five middle rows in the plot and the number of plants counted. This was repeated five times randomly across the length of each plot. Soil samples were collected May 31, 2017 at both Tensed sites and June 1 at both Potlatch sites using the technique stated previously.

Spike counts were recorded on July 11, 2017 at all three winter wheat sites. The number of spikes in 1 m linear row were counted in the front, middle, and back of the plots. At Tensed 2,

whiteheads indicative of Fusarium crown rot were observed, so the number of white heads in 1 m of linear row in three separate rows in each plot was recorded for this site.

Mature plant heights were recorded July 26 at all three sites. Plots were harvested using a Wintersteiger Nursery Master plot combine. After determining seed yield, 1 kg of seed was retained for quality analysis as described previously. Only five of the middle rows were harvested to obtain yield data, while three outer rows were avoided. One kilogram of seed was subsampled from each plot for harvest quality analysis. Tensed 2 was harvested on August 8, while Tensed 1 and Potlatch 2 were harvested August 25.

2017 – 2018 Crop Year. Potlatch 1 was planted to UI-WSU Huffman soft white winter wheat September 26 at a rate of 248 seeds square m^{-1} and was fertilized to meet the yield goal (Mahler, 2007). Potlatch 2 was planted to Bronic chickpeas at a rate of 54 seeds square m^{-1} and no fertilizer was required. Tensed 1 was planted to HyClass 125 RR spring canola at a rate of 5.6 kg $hectare^{-1}$ and fertilized to meet a yield goal of 368 kg $hectare^{-1}$ (Mahler and Guy 2005). Tensed 2 was planted to Morena lentils at a rate of 86 seeds square m^{-1} and no fertilizer was required. Canopy cover data was collected at this site using Canopeo (Oklahoma State University, Stillwater Oklahoma) (Patrignani and Ochsner 2015).

Moscow was planted to HyClass 930 RR Canola July 31, 2017 at a rate of 5.6 kg $hectare^{-1}$. Unfortunately, the site was terminated in September due to uneven and thin plant establishment due to inadequate soil moisture at planting. In following with the grower's rotation, this site was recropped to soft white winter wheat using UI WSU Huffman on October 3 at a rate of 248 seeds square $meter^{-1}$. Dry fertilizer was broadcast pre-plant on the plots and incorporated with a harrow.

Plant densities, soil samples and wheat measurements were collected as described for the 2016-2017 crop year. For chickpea and lentil, plant height was recorded prior to harvest. Plant heights were recorded on canola just after flowering. Due to obvious visual responses to lime treatments in

plant density and appearance at Tensed 2, Greenseeker and Canapeo data were also collected to quantify relative plant health and vigor. Oil content was measured for the canola after harvest.

Data analysis and statistics. An ANOVA was generated for all data using the generalized linear mixed model (proc glimmix) procedure in SAS version 9.4 (SAS Institute, 2016) with an alpha of 0.1. Means were separated using the pdiff and lines options with LSMEANS for all studies.

The value of lime application was calculated for each site using net present value. This allowed for annualizing the cost of applying lime over the expected lifetime of each lime rate. Ten, 15, and 20 years were used for the three lime rates and a discount rate of 6% was applied (Table 3.1). Initial cost of lime for the three treatments (2,242; 4,484; and 6,726 kg/ha) were $215, $398, and $235 ha^{-1}, respectfully. The estimated farmgate value of wheat in 2017 was $163.5 mt^{-1}. Estimated farmgate values for wheat, lentil, and canola in 2018 were $202.1, $529.1, and $330.7 mt^{-1}, respectfully.

Results

Influence of liming on soil characters. Soil samples collected in 2017 for Potlatch 2, Tensed 1 and Tensed 2 and soil samples collected at Moscow in 2018 were taken 8 months after liming. Soil samples collected in 2018 at both Potlatch and Tensed sites were taken 20 months after liming. Samples were analyzed for both ammonium and nitrate forms of N, phosphorus (P), potassium (K), sulfur (S), boron (B), zinc (Zn), manganese (Mn), copper (Cu), iron (Fe), sodium (Na), manganese (Mg), total bases, base saturation, KCl Al, and pH. In all soil tests N, P, K, S, B, Zn, Cu, Fe, Na, and Mg were not impacted by liming. Soil pH, KCl Al, base saturation, Ca, and Mn were impacted by liming and the results from each are reported below.

Due to no planting at Potlatch 1 in 2017, soil samples were not analyzed that year. In 2018 the soil pH in the non-limed portions of the plot was 4.6 and the quantity of KCl Al was 68.4 ppm in the top 0 to 7.5 cm (Figures 3.2 & 3.3). There was an incremental and significant increase in soil pH with increasing lime rate reaching a maximum of 5.8 at the high lime rate from the 0 to 7.5 cm depth. While not as dramatic, there was a slight but significant increase in soil pH for soils collected from the

7.5 to 15 cm depth. Corresponding to an increase in soil pH, there was a substantial and significant decrease in KCl Al at the 0 to 7.5 cm depth, resulting in less than 1 ppm in the high rate of lime (Figure 3.3). There was also a significant decrease in KCl Al with all lime treatments at the 7.5 to 15 cm depth. The base saturation and quantity of Ca in the soil increased with increasing lime rates from a low of 49.3 % and 3.6 ppm in the no lime treatments to 76.8 % And 7.1 ppm in the high rate of lime treatment, respectively (Figures 3.4 and 3.5). Like KCL Al, the quantity of Mn significantly decreased with increasing lime rates at the 0 to 7.5 cm depth, with a slight but significant reduction at the 7.5 to 15 cm depth (Figure 3.6).

In 2017 and 2018, Potlatch 2 had significant increases in soil pH, Ca, and percent base saturation in the top 7.5 cm (Figures 3.7, 3.9, 3.10). There also were significant decreases in KCl Al and Mn in the top 7.5 cm with increasing lime rate (Figures 3.8, 3.11). In the top 7.5 cm of soil, the response to lime and trends were very similar to those described for Potlatch 1. In 2018, 20 months after lime application, the increases in soil pH, percent base saturation and Ca were more pronounced in the top 7.5 cm, and were significantly higher with increasing lime rate in the 7.5 to 15 cm deep layer of soil indicating further reactivity of applied lime in the soil. Likewise, the quantity of KCl Al was significantly reduced in the 7.5 to 15 cm depths with less than 1 ppm of KCl Al in the upper 15 cm of soil (Figure 3.8). The decrease in Mn at the 7.5 cm to 15 cm depth was significant in both years but was more pronounced 20 months after lime application (Figure 3.9). There was also a significant increase in soil pH and decrease in Mn at the 15 cm to 22.5 cm and 22.5 to 30 cm depths in the limed treatments when compared to the non-limed control.

In 2017 at Tensed 1 there was a significant increase in soil pH, base saturation and Ca and with a corresponding significant decrease in KCl Al and Mn in the 0 to 7.5 cm depth with increasing rates of lime as observed for the other locations (Figures 3.12, 3.13, 3.14, 3.15, 3.16). There also was a small but significant increase in soil pH between the no lime and high lime rate in 2017 at the 7.5 to 15 cm depth and a significant reduction in KCl Al with all lime treatments. Similar trends were observed

in 2018, although there did not appear to be a continual increase in soil pH or decrease in KCl Al. Likewise, the Ca concentration and base saturation were similar between 2017 and 2018. All values for Mn concentrations were lower in 2018, but there was not a response to liming below the top 7.5 cm depth (Figure 3.16).

In 2017 at Tensed 2, soil pH, base saturation and Ca increased significantly in the 0 to 7.5 cm depth of soil with increasing rates of lime, consistent with observations in the other locations (Figures 3.17, 3.18, 3.19, 3.20, 3.21). Additionally, there was a small but significant increase in soil pH at the 7.5 to 15 cm depth and a significant reduction in Mn at the same depth. Similar trends were seen in 2018 in soil pH, with a slight increase in base saturation and Ca at the 4,484 kg ha^{-1} rate compared to 2017. All values for KCl Al and Mn concentrations were lower in 2018.

At Moscow, soil samples were taken 8 months after liming in 2018. Soil pH, base saturation, and Ca increased and KCl Al and Mn decreased in response to increasing lime rates (Figures 3.22, 3.23, 3.24, 3.25, 3.26). While not significant, there was a sharp decrease in KCl Al and Mn in the 7.5 to 15 cm and 15 to 22.5 cm ranges. Congruently, there was also a non-significant but slight increase in soil pH, base saturation, and Ca at those depths.

Impact of liming on agronomic performance and seed yield.

Winter Wheat. Lime had a significant effect on spike count per plant, plant height, and yield (Tables 3.1 to 3.4) over five locations (Tensed 1 and 2, Potlatch 1 and 2, and Moscow). Spike counts per plant increased as the lime rate increased from 100 spikes per plant in the control to 120 spikes per plant in the 6,726 kg ha^{-1} rate of lime (Table 3.1). Linearity accounted for 96% (computed as contrast SS/Trt SS) of the relationship between spike counts per plant and lime rate (Tables 3.2). Plant heights were the same at 89 cm for the control, 2,242 and 4,484 kg ha^{-1} rates of lime. Plant heights for the 6,276 kg ha^{-1} rate of lime were 91 cm. For plant heights, linearity accounted for 57% of the relationship between plant heights and lime rate (Table 3.3). Yield also increased as lime rate

increased from 5,651 kg ha^{-1} in the control to 6,164 kg ha^{-1} in the 6,726 kg ha^{-1} rate of lime (Table 3.1). Again, linearity accounted for 96% of the relationship between yield and lime rate (Table 3.4) such that a 100 kg increase in yield was achieved by a 1.280 kg ha^{-1} increase in lime rate (Figure 3.26).

Potlatch 2 Chickpeas. In 2018, there was a significant increase in plant density for all rates of lime compared to the control with a 29% increase in stand when comparing the no lime to the high rate of lime (Table 3.5). Due to herbicide injury, most of the pods were aborted and seed yield from this location was very low. As a result, there is no yield data or post-harvest quality information for the chickpeas.

Tensed 1 Canola. None of the crop measurements for canola in 2018 were significant. There were no consistent trends in plant height due to lime rate (Table 3.6). Due to inconsistent stand establishment at planting, there was high variability between plots for yield (Table 3.6). Oil content for the 4,484 and 6,726 kg rates was 1% higher than the control and 2% higher than the 2,242 kg rate, although not significant (Table 3.6).

Tensed 2 Lentils. In 2018, plant density, Greenseeker data, and canopy cover data were significant for lentils (Table 3.7), with all increasing incrementally with increasing lime rate from values of 174 to 209 plants m^{-2} for plant density, 0.36 to 0.53 for Greenseeker, and 50.5% to 77.% for canopy cover. While not significant, there was a 22% rise in yield with lime rate with an incremental increase from the control to the 6,726 kg lime rate (Table 3.7).

Economics of lime application. The cost ha^{-1} for the three liming rates was $215 (2,242 kg ha^{-1}), $398 (4,484 kg ha^{-1}), and $581 (6,727 kg ha^{-1}), and are estimated to be effective for 10, 15, and 20 years, respectfully (Table 3.8). With an assumed discount rate of six percent, the annualized costs of each lime application for these timelines are $30, $42, and $49 ha^{-1}. In nearly every case, there was an increase in yield of either winter wheat, lentil or canola that resulted in a positive return (Table 3.9). The exception is the spring canola yield following an applications of the 4,484 kg ha^{-1} lime at Tensed

1 in 2018. In nearly every example, the lowest return was observed with the lime rate of 2,242 kg ha^{-1}. The average increased return was \$51, \$68 and \$88 ha^{-1} for the 2,242; 4,484; and 6,726 kg rates, respectively. When taking into account the annualized cost of lime application, there was still a net gain in return for 4 of the 7 site years for all treatments (Table 3.10). The exceptions are the low rate of lime in Moscow winter wheat, the moderate and high rate of lime in the Tensed 1 spring canola in 2018 and all liming treatments in Tensed 2 winter wheat in 2017. Across all site-years, there was an average return over costs of \$21, \$26 and \$39 ha^{-1} for the 2,242; 4,484; and 6,726 kg rates, respectively. The annualized cost of lime was 63% higher for the 6,726 kg ha^{-1} rate compared to the 2,242 kg ha^{-1} rate, but the average return after accounting for the annualized cost for the seven site-years was 85.7% higher for the higher rate compared to the low rate of lime.

Discussion

This project sought to evaluate the impact of lime application on crop performance and soil chemistry at multiple locations in northern Idaho as well as the economic return of lime applications. Decades of declining soil pH along with a lack of an established liming industry in the region, limited access to local sources of lime, and transportation costs of outside sources necessitated the need for a multiyear study examining the economics of liming in northern Idaho. In this study, the application of lime consistently resulted in increased soil pH and percent base saturation coinciding with reduced KCl Al and Mn concentrations. These benefits were mostly confined to the top 7.5 cm of soil, but trends were evident in the 7.5 to 15 cm layer as well. The improved pH and reduced aluminum toxicity usually resulted in improved plant health and increased yield.

Results from the soil tests and yield responses were consistent with previous studies. In the 1980s, Mahler and others studied the effects of liming in the Palouse. Mahler (1983) reported increased yield, N and P uptake, *Rhizobium meliloti* survival and P availability in andic soils of northern Idaho when lime was used to increase pH above 6.6. The highest reported yields were at a pH of 7.4. Similarly, in our study, increased yields were largely associated with decreases in Al

concentrations. In a 5-year study initiated in 1981, Mahler and McDole (1987) found that soil pH greatly affected yields of lentil, spring pea, winter wheat, and spring barley—all staple crops grown in the region. They found that lentil and pea were least tolerant to acidic soils, requiring a minimum pH value of 5.65 and 5.52, respectfully to maximize yields. Spring cereals were shown to be more tolerant, with a minimum pH of 5.23 for barley, and 5.19 and 5.37 for wheat (cultivar dependent).

Mijangos and others (2010) saw an increase in forage yield with liming in a grassland soil at Gorbeia Natural Park in northern Spain. In a clay loam with an initial soil pH of 4.6 there was a 1.07 ton of dry matter (DM) ha^{-1} increase over the control plots with an increase in pH to 4.7. In long-term cropping studies in Ponta Grossa, PR, Brazil, Caires and others (2005) determined a surface applied lime rate of 4.2 t ha^{-1} was optimal for increasing wheat, soybean and corn yields in no-till systems. Yield increases for soybeans and corn at 4.2 t ha^{-1} were very small in comparison to the response in wheat, however the trend was clear. In a study on the long-term impact of liming on hardwood trees, Long and others (2011) observed that 21 years after a single lime application, soil pH averaged 6.6 in the top 5 cm, while soil pH in untreated plots remained at 3.7 to 3.8 during the duration of the study.

Change in soil pH was highly significant between the control and high lime rates in the top 7.5 cm at all sites in both years of the study. At sites with 2 years of soil data, significant changes in 2017 also were observed in 2018, with some indication that there were additional increases in soil pH along with continuing declines in KCl Al, indicating that lime is still reacting in the soil. These results are in agreement with previous work. In the studies performed by Caires and others in Spain (2005), at 4 t ha^{-1} of dolomitic limestone, the effects of lime on soil pH in the top 5 cm of soil lasted for a little over 4 years, and a little over 2 years in the 5 to 10 cm depth. In long-term studies lime applications in Saskatchewan, Canada, Malhi and others (1995) reported soil pH values remaining higher than non-limed controls for 29 years after two single applications 1n 1963 of calcium hydroxide at 6.1 and 9.1 t ha^{-1} (values for calcium hydroxide were multiplied by a factor of 1.35 to convert to $CaCO_3$ equivalent), and increased wheat yields in 12 out of 12 crop years. Soil in the study was a Dark Brown loam with

an original pH of 4.9. When soil samples were taken in 1992, so pH in the 6.1 t ha^{-1} plot was 5.5 and 6.5 in the 9.1 t ha^{-1} plot.

Soil data from 2018 also revealed evidence that vertical movement of the liming material is occurring, possibly from additional mixing by the drill openers during planting. In the case of Potlatch 2, significant changes to soil pH, Ca and base saturation between treatments were seen only in the top 7.5 cm, but in 2018, changes in soil pH were significant at the 7.5 to 15 cm depth. Likewise, a decrease in KCl Al and Mn at the 7.5 to 15 cm depth was not significant in 2017, but was in 2018, indicating that lime may have moved down into these depths. An opposite effect was seen at Tensed 1, where changes in soil pH and KCl Al were significant in the top 15 cm in 2017, but only in the top 7.5 cm in 2018, however there was an overall reduction in KCl Al at the 0.0 to 7.5 cm and 7.5 to 15 cm depths between the two years.

Future soil tests at these locations will help to confirm trends in soil characteristics, however it is in line with results from previous work. In a study by Malhi and others (1998), surface applied lime was added to established smooth bromegrass stands at rates to increase soil pH to near 7.0. Four years after liming, soil pH was 6.85 in the 0 to 5 cm depth, and pH was slightly increased in the 5 to 10 cm depth, indicating the lime was still reacting after 4 years and had also moved deeper in the soil. Work by Gashco and Parker (2001) on two different soils in Georgia, U.S. showed changes in soil pH, Ca, and Mg levels in the 30 to 45cm depths 8 years after initial lime applications in one of the soils. After 20 years, lime had moved and was reacting as deep as 75 to 90 cm in the same soil. In the other soil, after 3 years the high rate of lime (14 Mg ha^{-1}) increased soil pH in the 30 to 45 cm depth and after 17 years soil pH, Ca. and Mg were increased at all depths up to 90 cm.

The combination of all these changes in the soil chemistry resulted in significant increases in spike count per plant, plant heights, and yield of winter wheat. As observed in the yield response, there is a strong linear relationship between lime rate and yield increase. This increase begins to flatten out after 4,484 kg ha^{-1} of lime. The difference in yield between the control and 2,242 kg ha^{-1} was 255 kg

ha^{-1}, and the yield increase was 213 kg ha^{-1} between the 4,484 and 2.242 kg ha^{-1} lime rates; however there was only a 75 kg ha^{-1} increase between the highest lime rate of 6,727 kg ha^{-1} and the 4,484 kg ha^{-1} lime rate. Based on these observations, it is possible that liming at rates beyond 6,727 kg ha^{-1} may have increasingly diminished returns in yield, and therefore may not be profitable for growers.

The canola at Tensed 1 and chickpeas at Potlatch 2 did not produce reliable yield data due to agronomic problems at each site. Inconsistent planting depths within and between plots at Tensed 1 resulted in highly variable plant densities, and thus unreliable yield and crop data. During 2018 at Potlatch 2, an herbicide application to the chickpeas caused significant crop injury and thus produced very low yields, resulting in unreliable yield data for this site. However, plant densities at chickpea at this location measured prior to herbicide injury increased with lime rate. This indicates that higher liming rates may have influenced increased germination since no aborted plants were reported in the lower rates and control.

The results of this study have been very insightful and encouraging thus far. Seeing significant results in soil chemical characteristics the first year that continued into the second year is promising that these rates of lime may be enough to ameliorate the acidifying soils of northern Idaho. Though, it is important to remember when liming a field, there is both active and reserve acidity in the soil, and both must be neutralized to achieve lasting shifts in soil pH (Ziadi and Sen Tran 2008; Mamo et al. 2015). Active acidity is what is typically measured by soil pH sticks and meters and refers to the hydrogen ions in the soil solution (Coleman and Mehlich 1957). Reserve acidity refers to the hydrogen ions adhered to the cation exchange sites in the soil (Allaway 1957). Lime reacts with the active acidity first, and as it is neutralized, the reserve acidity is released into the soil solution, effectively buffering the soil against changes in pH (Spies and Harms 1988). Therefore, when soil laboratories are calculating lime requirements, they use buffer tests which act as a quick lime and have been calibrated to the soil type being tested to determine how much lime is required to neutralize both active and reserve acidity (Machacha 2004; Viswakumar et al. 2010; Anderson et al. 2013). Thus, the quantity of

lime applied must be sufficient to neutralize both active and reserve acidity to achieve a lasting change in soil pH. Lime requirements to achieve a soil pH of 6.5 (Adams-Evans buffer test) for the sites in this study suggested rates of 7 mt ha^{-1} at Potlatch 1, 9 mt ha^{-1} at Potlatch 2, 10 mt ha^{-1} at Tensed 1, 11 mt ha^{-1} at Tensed 2, and 9 mt ha^{-1} at Moscow.

From this study, increases in yields, along with associated economic data, have shown that initial lime costs could be recovered in as little as 6 to 7 years. However, a reality of the liming in northern Idaho is that no long-term empirical data exists. Consequently, no conclusions can or should be drawn until several additional years of results can be produced. This study should continue for at least 4 to 8 more years due to the long-term nature of liming benefits and economics.

While effects on soil chemical properties and crop response are important, a major concern for many growers is the cost and return on investment of lime applications. But before any discussion of the economics of liming, it is important to remember that liming needs to be thought of as a capital improvement rather than an annual cost such as fertilizer. Fertilizer costs are expected to be returned within the crop year, whereas the benefits of lime should be expected to be seen for many years after application. Malhi and others (1995) focused on the same long-term effects of liming in Canada, namely improving soil pH, crop yield, and economics. They counseled that due to the high cost, liming should not be categorized as an annual operating cost, but rather amortized out for a long period of time. For this reason, the cost of lime was amortized using net present value.

Net present value is a way of calculating a return on investment by accounting for the monetary gain expected over the life of an investment and converting those future returns into current monetary values using a discount rate to account for the devaluing of money in the future (Gallo 2014). A life expectance of 10, 15, and 20 years for the three rates, and a 6% discount rate were used in the calculations. When calculated in this manner, the annualized cost of lime was outweighed by the increased return for most locations and crops with the exception of Tensed 1 spring canola and Tensed 2 winter wheat as the yields were not increased by a sufficient amount to increase return. However, the

average value over the cost of lime for all seven site-years was $21, $26, and $39 ha^{-1} for the 2242, 4484, and 6726 kg lime rates, respectfully, and four of the seven site-years had positive values over the cost of lime. Therefore, the data is thus far showing a steady positive return on investment for growers in northern Idaho.

These economic analyses demonstrate why it is important for growers to budget lime applications the same way they budget for other capital expenditures. It is also made clear by this data that even though two different soils may have similarly low pH, yield responses may not be the same for both fields due to a variety of factors such as cropping history or other crop stresses in a given year. Additionally, due to the high cost of liming and the variability between sites, this data also suggests growers interested in liming fields should consider experimenting with test strips for a minimum of 2 years first, rather than liming fields entirely, and record yield and economic returns on their own farm in order to make better financial decisions.

The economic data collected from this study will prove useful to growers seeking financing for lime applications. My father who worked in agricultural lending for 27 years at Northwest Farm Credit Services and for 12 years at Old West Federal Credit Union, and has farmed his whole life was very excited to hear about this study when I first started at UI in 2016. In his professional opinion, growers could use the economic and agronomic findings of this research to help secure financing to cover the high cost of lime. As an ag lender, he noted that it would behoove a lien holder to provide financing to a grower for liming if it will improve production of the land because as that improves the value of the land, which also benefits the lien holder. This economic and agronomic data will be useful in developing extension tools that can be used by growers in discussion with their lenders.

One of the additional challenges of liming that many growers in northern Idaho face is a high percentage of the harvested cropland is being rented (USDA 2019) (Table 3.8). In the United States Department of Agriculture (USDA) 2017 Census of Agriculture, harvested cropland is divided into three tenure groups: full owners (operate only land they own), part owner (operate land they own and

rent), and tenants (operate only land they rent). According to the 2017 Census of Agriculture, 23% of the harvested cropland in northern Idaho is operated by full owners, 62% is operated by part owners, and 15% is operated by tenants, indicating that a significant portion of harvested cropland in northern Idaho is rented rather than owned. Given that lime applications are capital expenditures that require several years to recoup the initial cost (Mamo et al. 2015), growers who rent land on short-term leases will not likely be able to afford the investment of a full lime application.

Potential solutions for this dilemma can be found in other parts of the country where liming is common. Growers of annual ryegrass seed in western Oregon sometimes band granular lime at planting on leased land to obtain a return on investment (Hart et al. 2011; Anderson et al. 2013). However, as Anderson and others point out, when lime is banded, the application quantity is reduced to rates insufficient to increase soil pH; therefore this practice is best suited to soil pH levels between 5.0 and 5.5 in western Oregon and is recommended as a short-term management option for annual ryegrass production. Work by Wildey (2003) in Palouse, WA, showed that 220 kg ha^{-1} of subsurface banded lime was able to raise soil pH in the top 10 cm of soil, although no grain yield response was seen. Similarly, work by Brown and others (2008) in Pullman, WA showed no significant increase in yield when subsurface banded lime was applied with banded N fertilizer, though there was an upward trend in two of the four study years. In light of these results, it may not be advisable economically for growers in northern Idaho to band low rates of lime at planting.

From interviews with growers in Austria to determine if rented land is treated differently than owned land, Leonhardt and others (2019) discovered that many growers are hesitant to spend a lot of money on liming, especially if rental agreements are short-term or insecure. Thus, another potential solution, suggested by Mamo and others (2015), is for landowners to pay part or all of the cost of liming a field. They also report that some leases state a landowner must repay a portion of a producer's investment in lime should the producer lose the lease. In Michigan, Bast and others (2011) suggest growers need to seek a multiyear lease, or ask the landowner split the cost of lime, amortized

over a four-year period. Based on results thus far in the present study, lime cost may need to be prorated out six years or more in northern Idaho.

Because of the complexities of land-ownership in northern Idaho, an annual workshop for northern Idaho growers and landowners to understand the importance of liming and to address the challenges of liming rented land could be implemented, including growers and landowners from other areas of the U.S. that have already addressed these issues. In addition, data from this research will be useful for developing extension articles that highlight the need and benefit of liming and the initial costs and length of time to receive a return on investment that can be used by land owners and operators when negotiating the terms of a rental agreement.

When this study was being planned and cooperators where being sought, I was amazed at the high level of interest in this research by every grower I spoke to. All were very eager to have this research performed on their land because they know they need to lime, but they do not know how much to apply, what it is going to cost, and how long it will take to see a return on their investment. This experience reaffirmed to me that soil acidity is indeed a real threat to crop production in northern Idaho, that growers are acutely aware of the problem, and that this research is critically important. The three key components of this study, investigating liming rates, soil and crop responses to liming, and the economic data will provide growers with the missing pieces to the soil acidity problem they are facing.

Table 3.1. Agronomic data for wheat in response to lime application.

Lime Rate (kg/ha)	Plant Density (pl/ m^2)	Spike Count (spk/ 1 m row)		Plant Height (cm)		Yield (kg/ha)		TWT (kg/hl)	Protein (%)
Control	166	100	C	89	B	5651	C	76	10.6
2242	163	104	CB	88	B	5876	B	76	10.5
4484	175	110	B	89	B	6089	A	77	10.3
6726	176	120	A	91	A	6164	A	76	10.2

Values with different letters are significantly different from each other.

Table 3.2 ANOVA and orthogonal contrasts for spike counts of winter wheat.

Source	DF	SS	MS	F-value	P-value
Site	4	18741.2	4685	30	<.0001
Rep (Site)	15	5770	385	2.46	0.0101
Trt	3	4274	1425	9.11	<.0001
Site*Trt	12	1603	134	0.85	0.5962
Contrast	**df**	**Contrast SS**	**MS**	**F-value**	**P-value**
Trt Linear	1	4089.6025	4089.6025	26.16	<.0001
Trt Quadratic	1	171.1125	171.1125	1.09	0.3010
Trt Cubic	1	13.3225	13.3225	0.09	0.7717

Table 3.3 ANOVA and orthogonal contrasts for plant height of winter wheat.

Source	**DF**	**SS**	**MS**	**F-value**	**P-value**
Site	4	2738.3	684.575	59	<.0001
Rep (Site)	15	694	46	3.99	0.0002
Trt	3	98	33	2.82	0.0493
Site*Trt	12	195	16	1.4	0.202
Contrast	**df**	**Contrast SS**	**MS**	**F-value**	**P-value**
Trt Linear	1	56.25	56.25	4.85	0.0328
Trt Quadratic	1	42.05	42.05	3.62	0.0633
Trt Cubic	1	0	0	0	1

Table 3.4 ANOVA and orthogonal contrasts for yield of winter wheat.

Source	**DF**	**SS**	**MS**	**F-value**	**P-value**
Site	4	259552231	64888057.8	811	<.0001
Rep (Site)	15	38716252	2581084	32.24	<.0001
Trt	3	3199266	1066422	13.32	<.0001
Site*Trt	12	718164	59847	0.75	0.6982
Contrast	**df**	**Contrast SS**	**MS**	**F-value**	**P-value**
Trt Linear	1	3069857.41	3069854.41	38.35	<.0001
Trt Quadratic	1	112950.45	112950.45	1.41	0.2411
Trt Cubic	1	16460.89	16460.89	0.21	0.6524

Table 3.5 Agronomic data for chickpeas at Potlatch 2 in 2018.

Lime Rate (kg/ha)	Plant Density (pl/m^2)		Plant Height (cm)	Yield (kg/ha)
Control	115	C	17	6
2242	126	B	17	6
4484	131	BA	16	5
6726	148	A	18	7

Values with different letters are significantly different from each other.

Table 3.6. Agronomic data for canola at Tensed 1 in 2018.

Lime Rate (kg/ha)	Plant Density (pl/m^2)	Plant Height (cm)	Yield (kg/ha)	Oil Content (%)
Control	143	43	1648	43
2242	131	45	1794	42
4484	58	44	1625	44
6726	60	43	1729	44

Table 3.7. Agronomic data for lentils at Tensed 2 in 2018.

Lime Rate	Plant Density (pl/m^2)		Greenseeker (NDVI Index)		Canopy Cover (%) *		Plant Height (cm)	Yield (kg/ha)
Control	174	C	0.36	C	50.5	C	12	1023
2242	182	B	0.39	CB	64.8	B	12	1172
4484	188	BA	0.44	B	62.5	B	13	1196
6726	209	A	0.53	A	77.8	A	13	1246

Values with different letters are significantly different from each other.
*Canopy cover measured using the Canopeo app

Table 3.8. Annualized cost of lime rates.

Lime Rate (kg/ha)	Cost of treatment* ($/ha)	Timeframe for liming efficacy (years)	Annualized cost of liming ($/ha)
2242	$215	10	$30
4484	$398	15	$42
6726	$581	20	$49

**Cost of ground limestone was $183 ha^{-1} plus $13 delivery fee.*
Discount Rate assumed to be 6%.

Table 3.9. Improved value of yield gains following lime application.

Lime Rate (kg/ha)	Moscow Winter Wheat*	Potlatch #1 Winter Wheat	Potlatch #2 Winter Wheat	Tensed #1 Winter Wheat	Tensed #1 Spring Canola**	Tensed #2 Winter Wheat	Tensed #2 Lentil***
			Value of Yield Gain ($/ha)				
2,242	$14	$54	$66	$44	$77	$22	$79
4,484	$54	$109	$121	$99	($12)	$11	$92
6,726	$95	$122	$110	$99	$43	$33	$117

**Commodity prices for soft white winter wheat were $163.5 mt^{-1} in 2017 and $202.1 mt^{-1} in 2018.*

**Commodity prices for canola in 2018 was $330.7 mt^{-1}

***Commodity prices for lentils in 2018 were $529.1 mt^{-1}

Table 3.10. Value of lime over the cost of annualized lime application costs.

Lime Rate (kg/ha)	Moscow Winter	Potlatch #1 Winter Wheat	Potlatch #2 Winter Wheat	Tensed #1 Winter Wheat	Tensed #1 Spring Canola	Tensed #2 Winter Wheat	Tensed #2 Lentil	Average Return*
				Value Over Cost of Lime ($/ha)				
2242	($16)	$24	$36	$14	$47	($8)	$49	$21
4484	$12	$67	$79	$57	($54)	($31)	$50	$26
6726	$46	$73	$61	$50	($6)	($16)	$68	$39

Table 3.11. Tenure of harvested cropland in northern Idaho by county, 2017 USDA Census of Agriculture.

County	Total HC	Full Owners *	Part Owners**	Tenants**
	(Hectares)			
Idaho	1,851,874	460,790	1,142,606	248,478
Latah	82,864	6,670	61,803	14,391
Nez Perce	79,407	4,499	41,016	33,892
Lewis	45,005	3,066	22,690	19,248
Benewah	24,808	1,690	20,330	2,788
Kootenai	18,436	4,571	12,951	914
Boundary	14,481	2,284	11,081	1,117
Bonner	9,458	4,386	4,115	957
Clearwater	7,141	NA	5,010	NA
Total	2,133,475	487,958	1,321,602	321,784

County	Total	Full Owners	Part Owners	Tenants
	Hectares	(% of total hectares)		
Idaho	1,851,874	25%	62%	13%
Latah	82,864	8%	75%	17%
Nez Perce	79,407	6%	52%	43%
Lewis	45,005	7%	50%	43%
Benewah	24,808	7%	82%	11%
Kootenai	18,436	25%	70%	5%
Boundary	14,481	16%	77%	8%
Bonner	9,458	46%	44%	10%
Clearwater	7,141	NA	70%	NA
Total	2,133,475	23%	62%	15%

* Operate only land they own
** Operate land they own and rent
*** Operate only land they rent

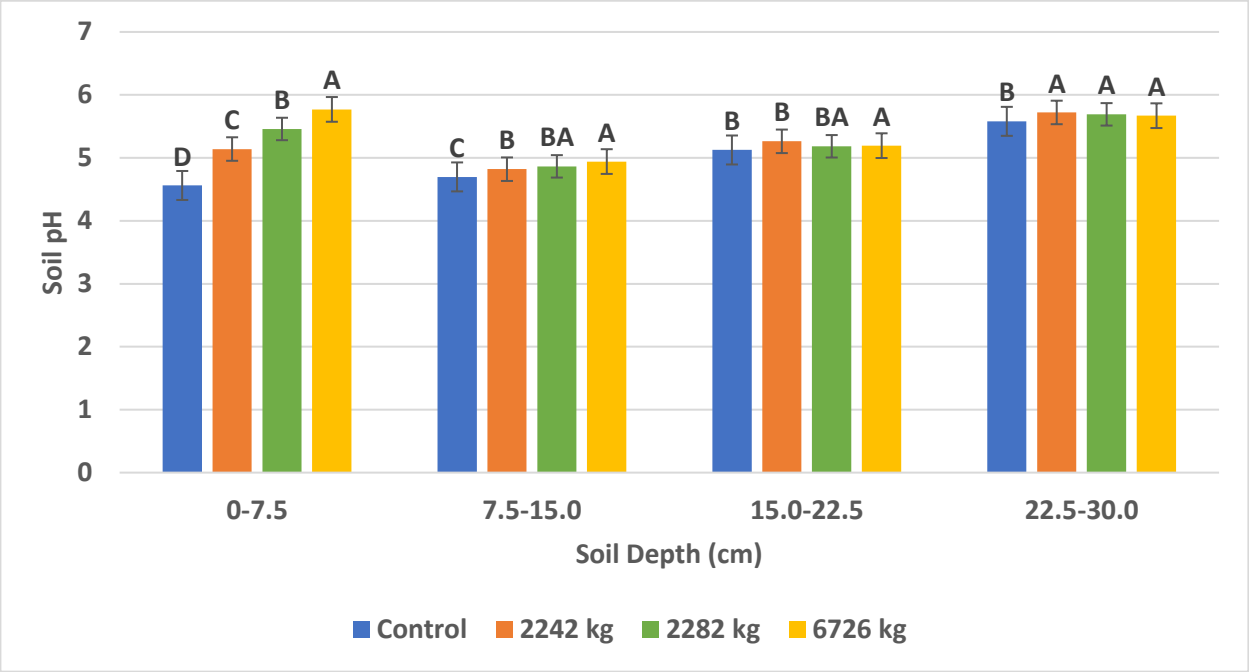

Figure 3.1. Effect of lime on soil pH at Potlatch 1 in 2018. Error bars indicate standard error.

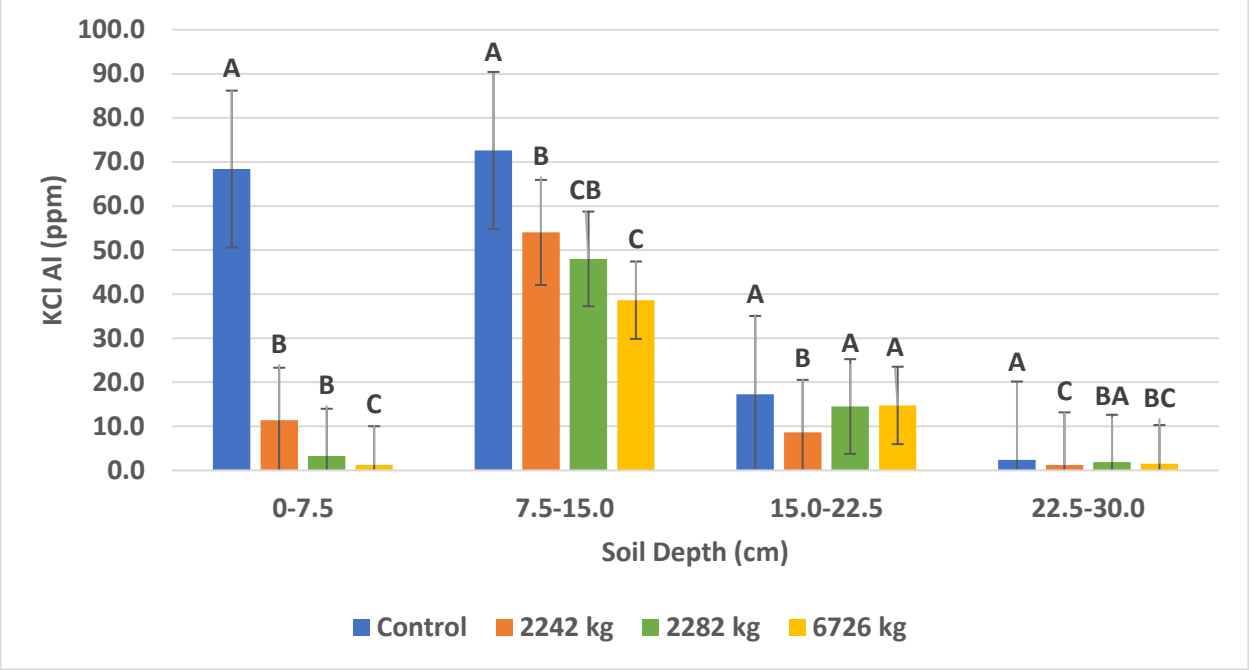

Figure 3.2. Effect of lime on KCl Al at Potlatch 1 in 2018. Error bars indicate standard error.

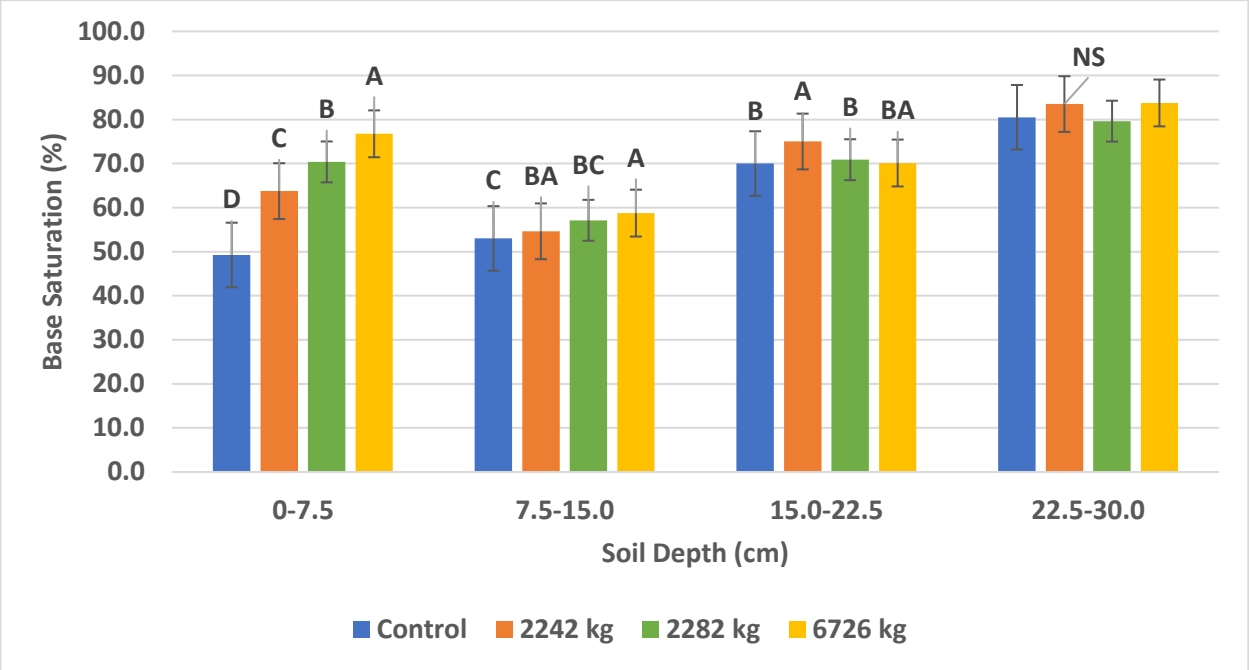

Figure 3.3. Effect of lime on base saturation at Potlatch 1 2018. Error bars indicate standard error.

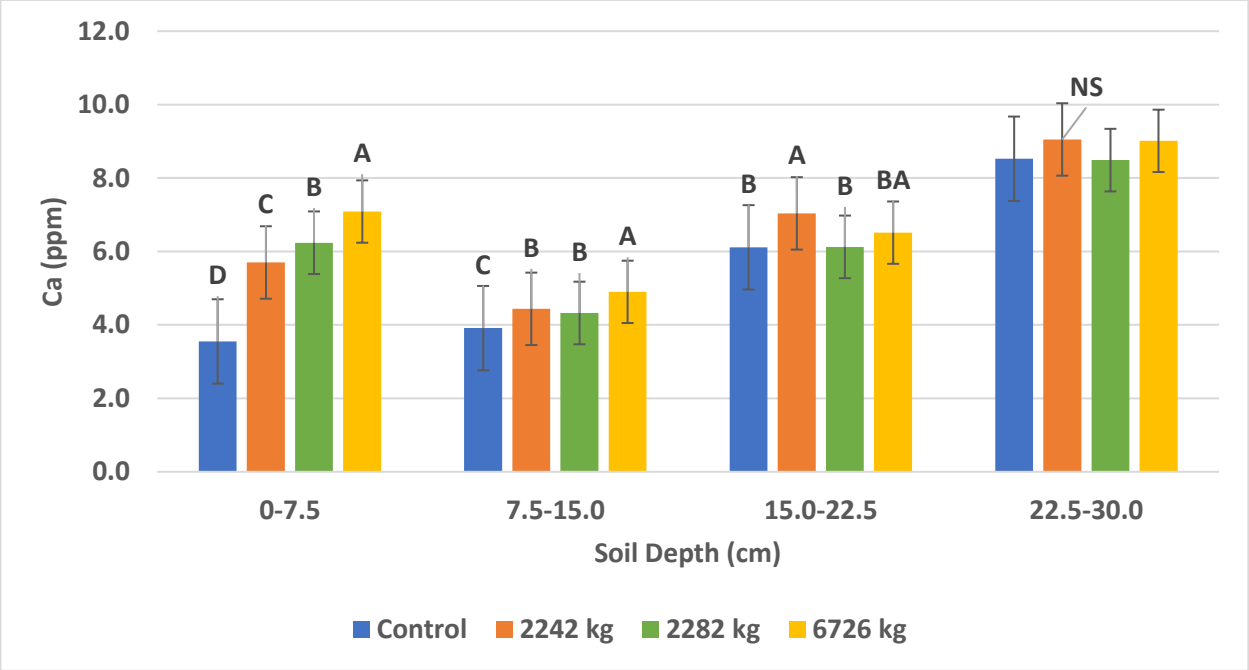

Figure 3.4. Effect of lime on Ca at Potlatch 1 2018. Error bars indicate standard error.

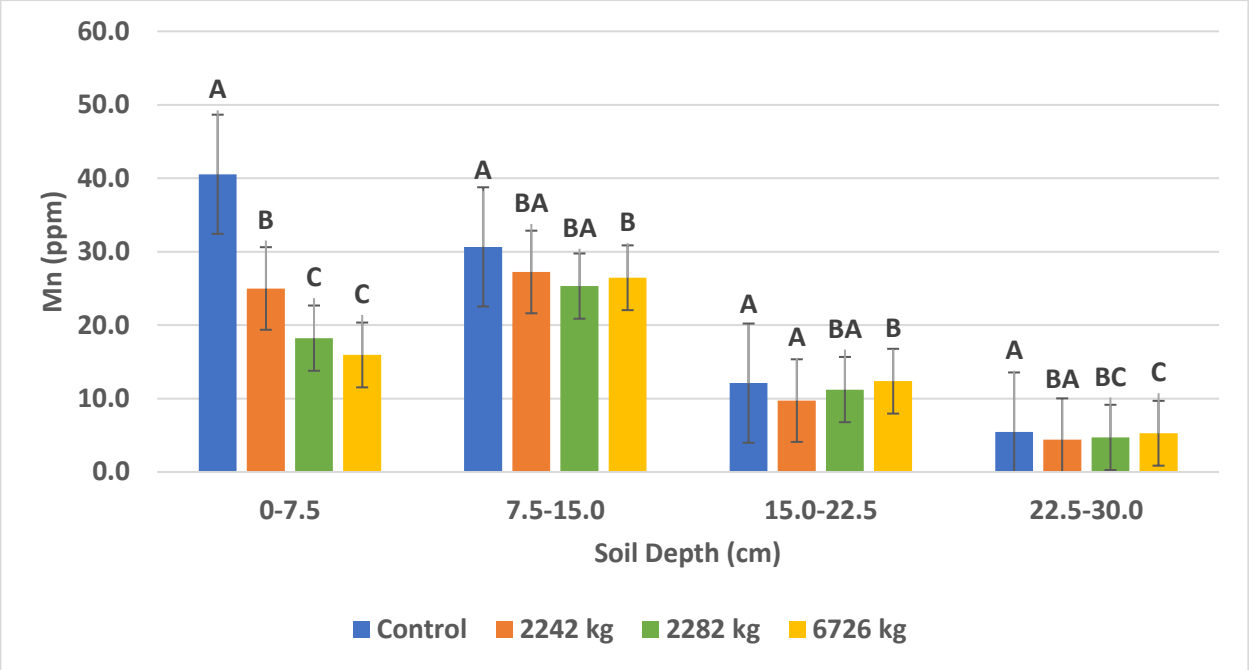

Figure 3.5. Effect of lime on Mn at Potlatch 1 2018. Error bars indicate standard error.

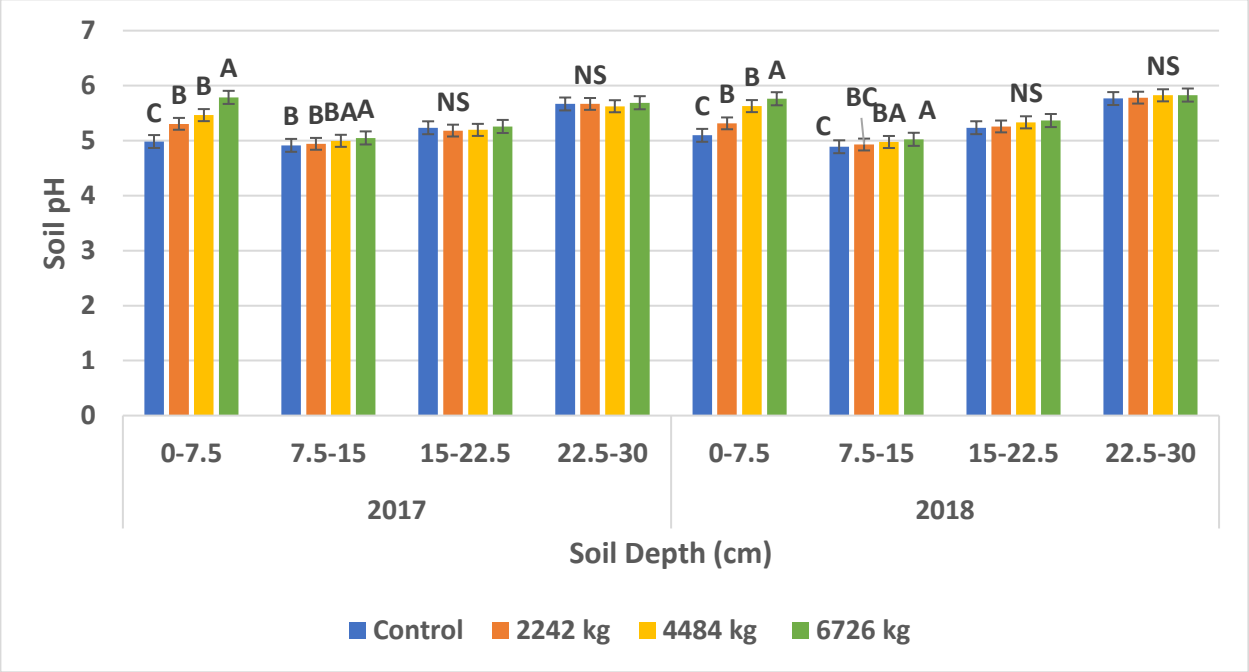

Figure 3.6. Effect of lime on soil pH at Potlatch 2. Error bars indicate standard error.

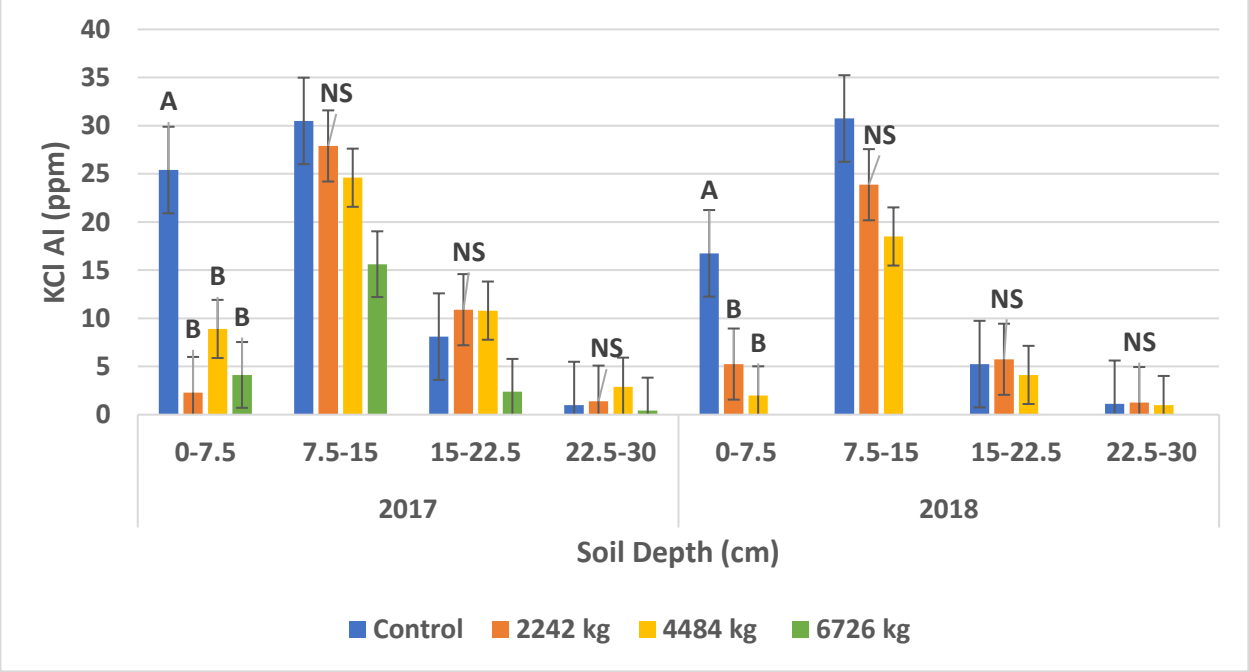

Figure 3.7. Effect of lime on KCl Al at Potlatch 2. Error bars indicate standard error.

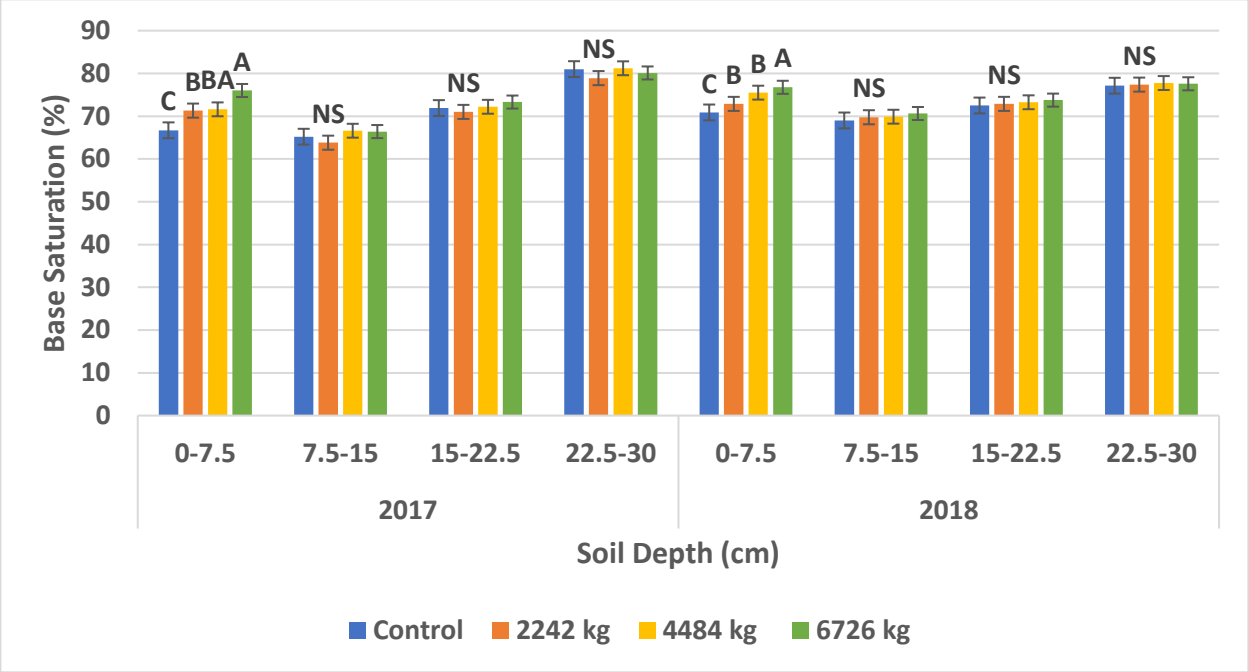

Figure 3.8. Effect of lime on base saturation at Potlatch 2. Error bars indicate standard error.

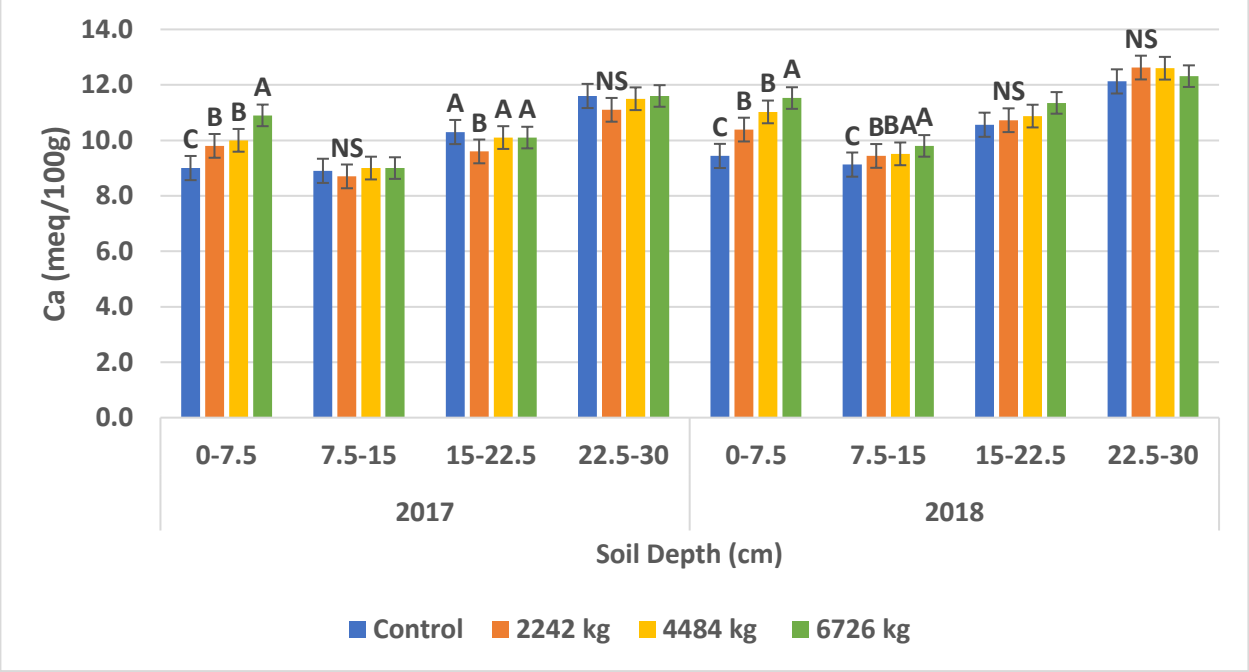

Figure 3.9. Effect of lime on Ca at Potlatch 2. Error bars indicate standard error.

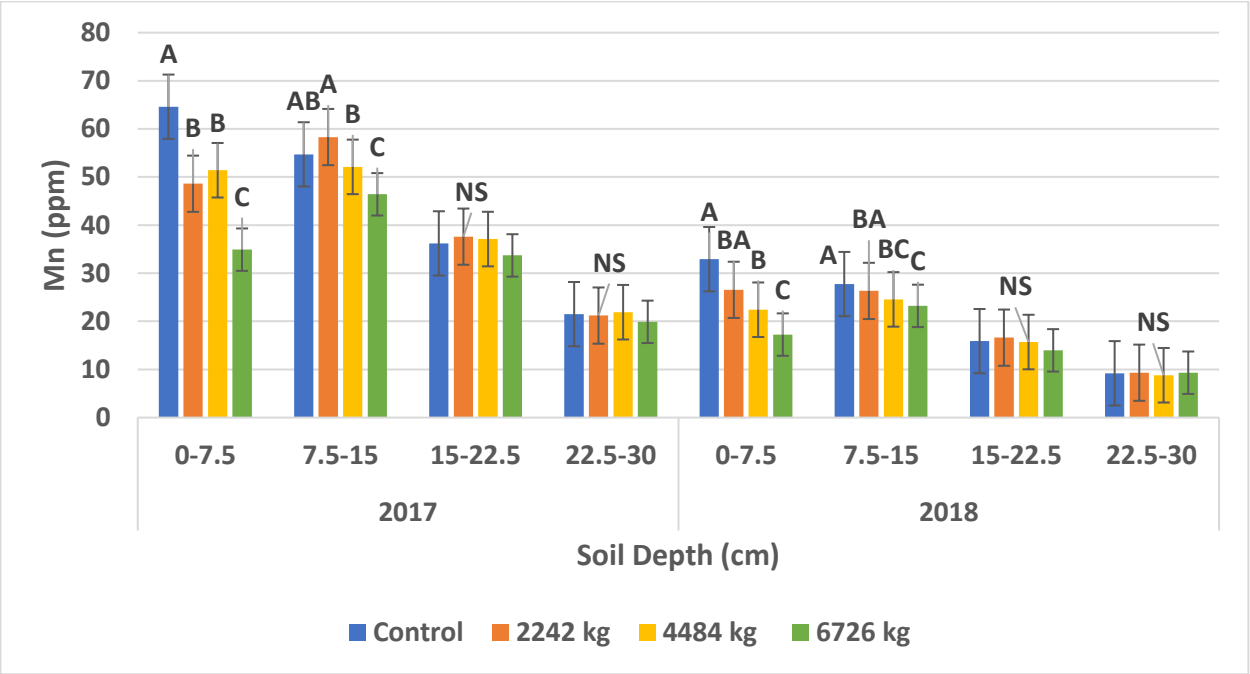

Figure 3.10. Effect of lime on Mn at Potlatch 2. Error bars indicate standard error.

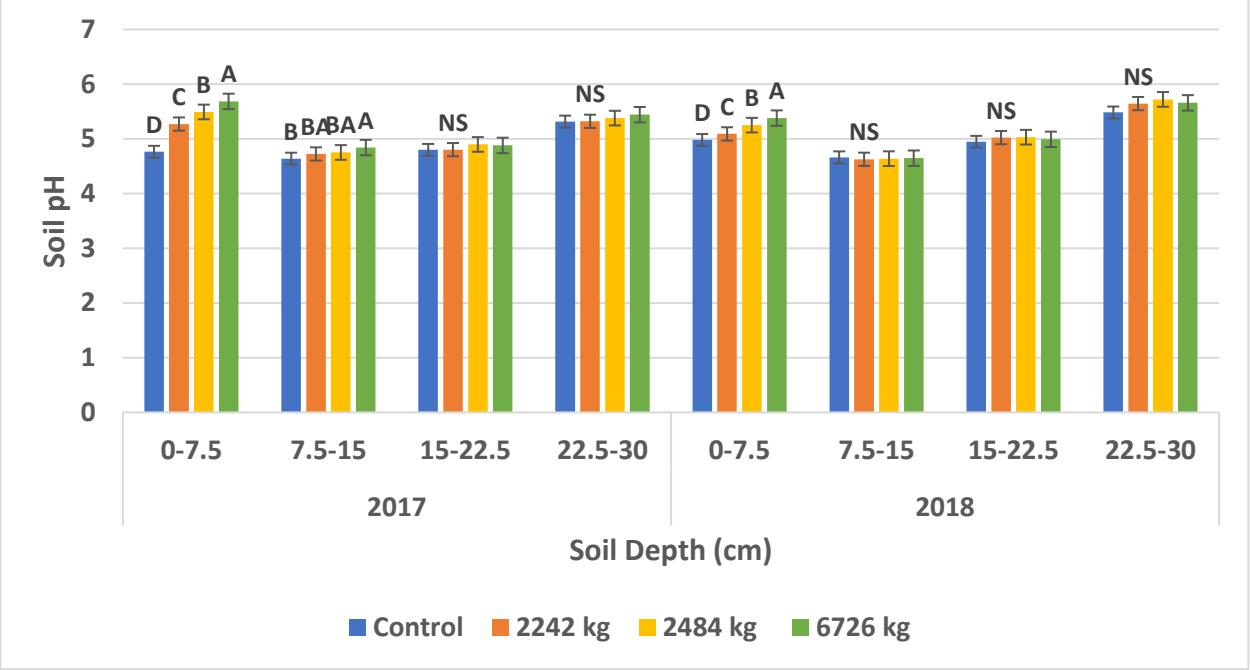

Figure 3.11. Effect of lime on soil pH at Tensed 1. Error bars indicate standard error.

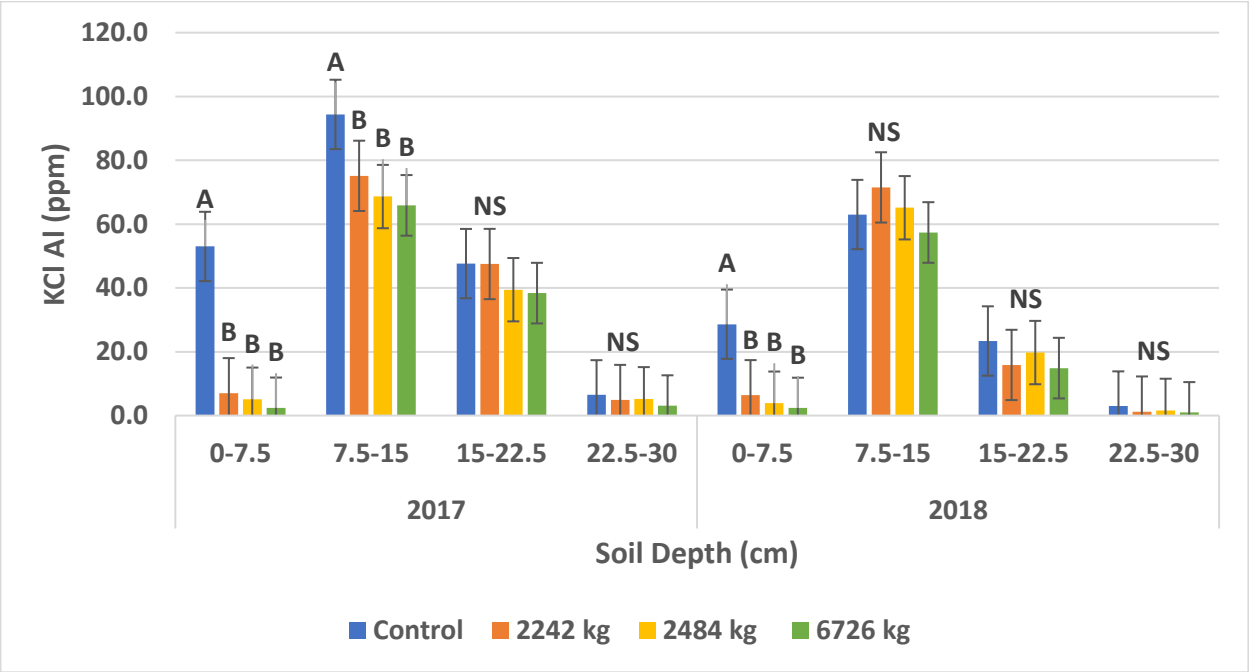

Figure 3.12. Effect of lime on KCl Al at Tensed 1. Error bars indicate standard error.

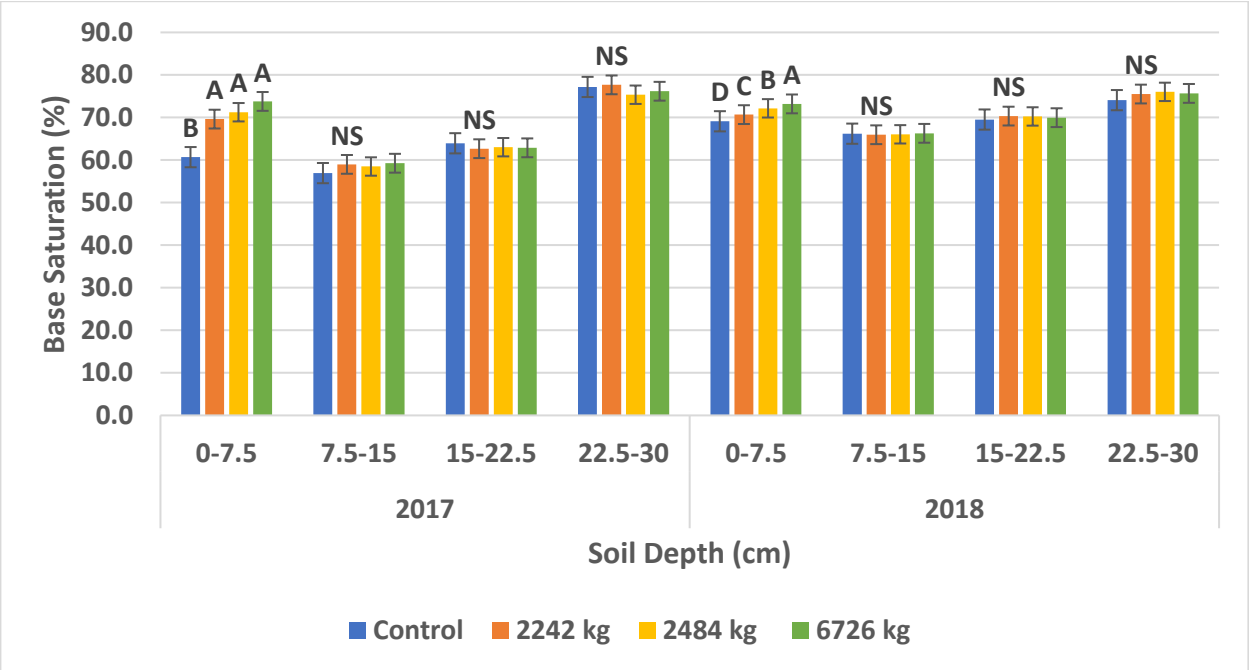

Figure 3.13. Effect of lime on base saturation at Tensed 1. Error bars indicate standard error.

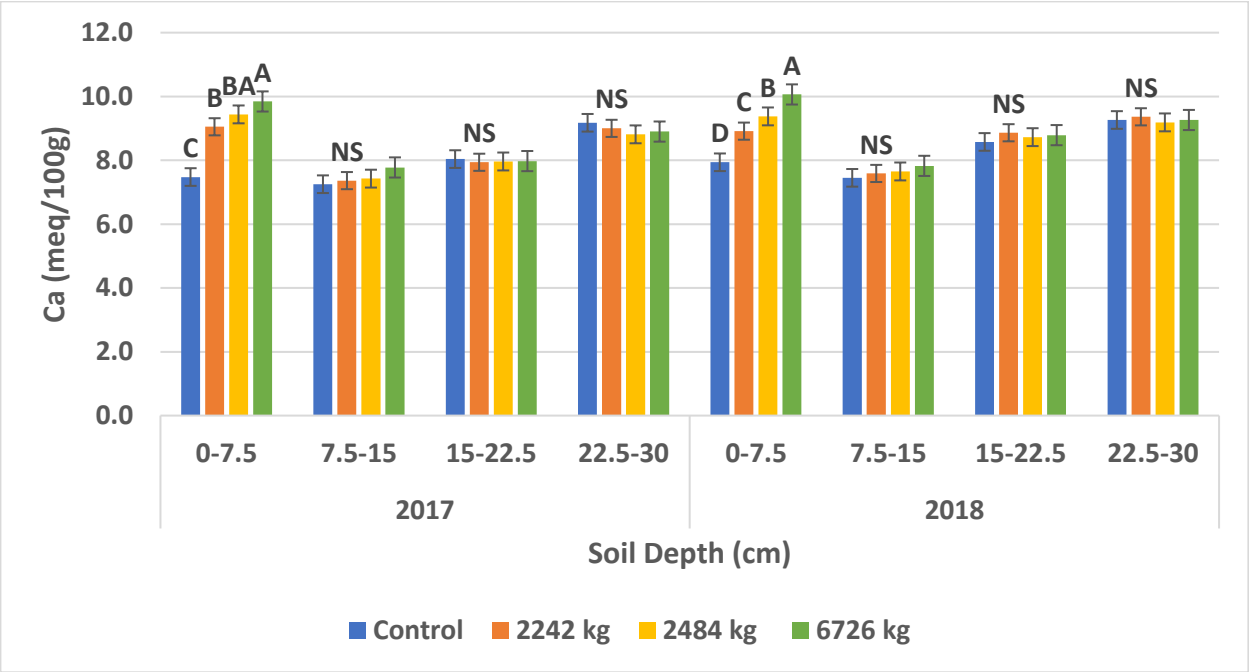

Figure 3.14. Effect of lime on Ca at Tensed 1. Error bars indicate standard error.

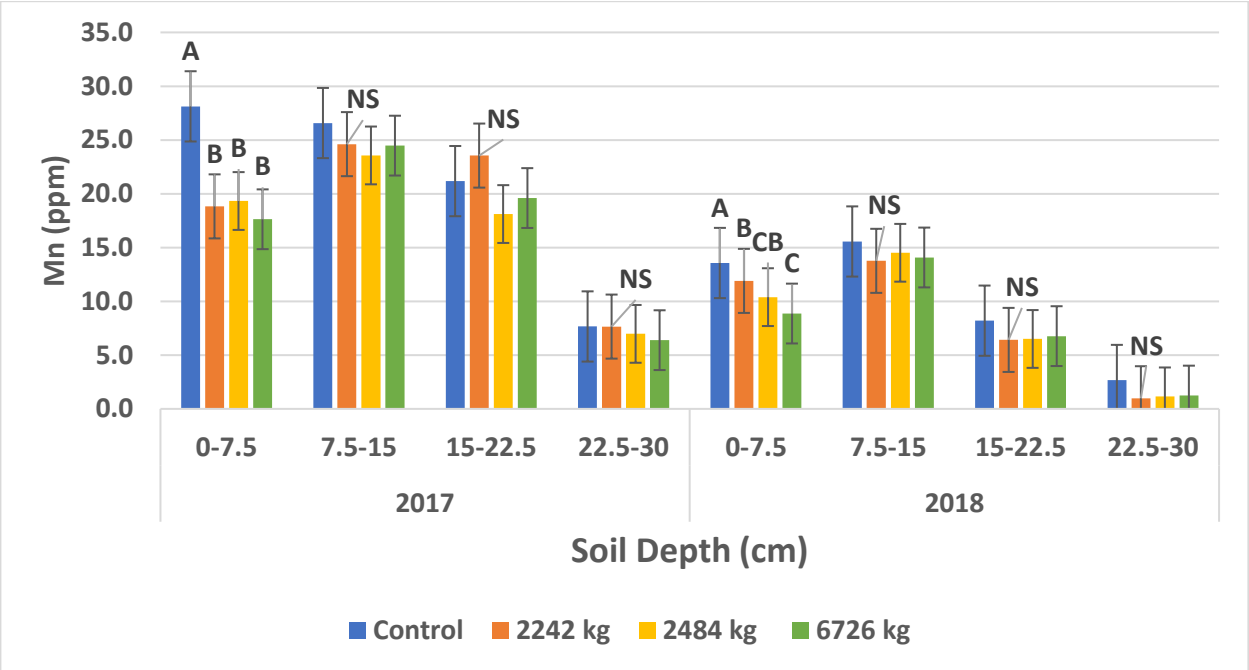

Figure 3.15. Effect of lime on Mn at Tensed 1. Error bars indicate standard error.

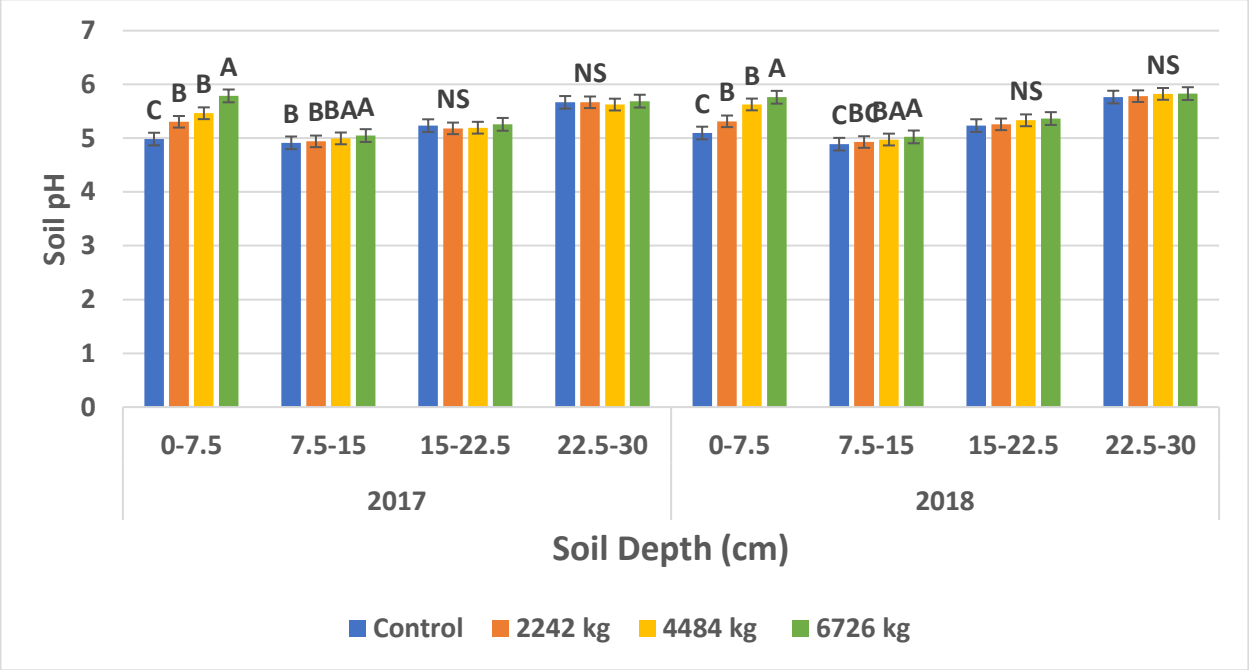

Figure 3.16. Effect of lime on soil pH at Tensed 2. Error bars indicate standard error.

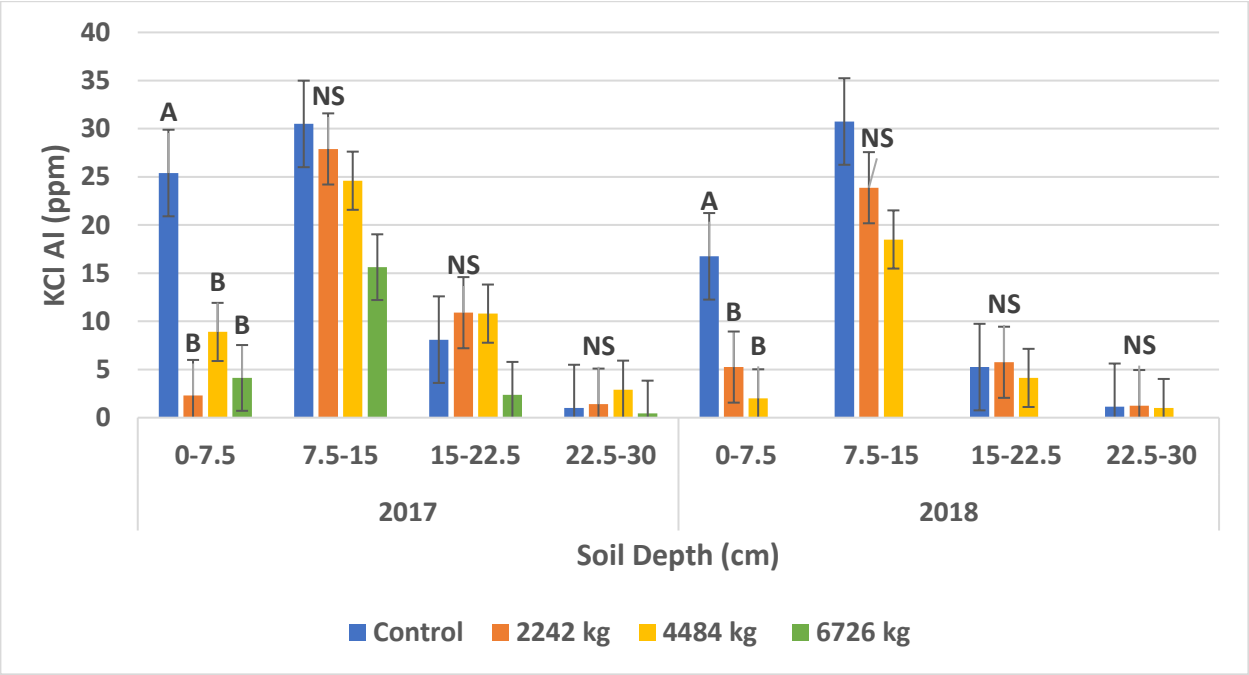

Figure 3.17. Effect of lime on KCl Al at Tensed 2. Error bars indicate standard error.

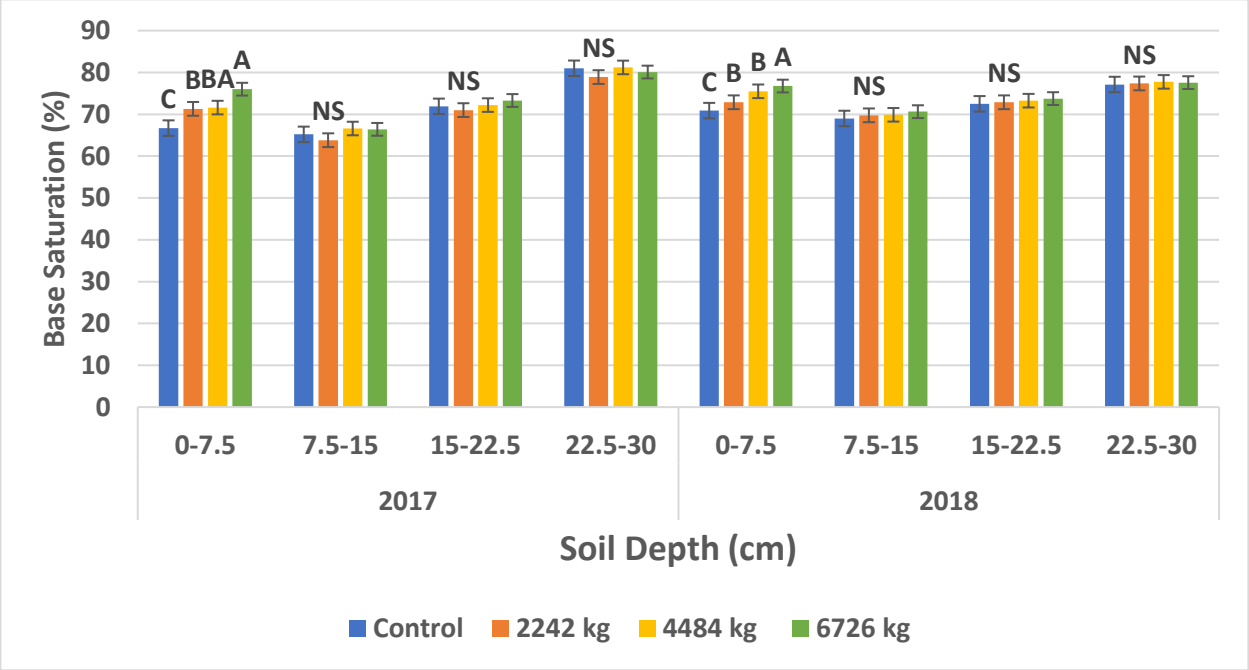

Figure 3.18. Effect of lime on base saturation at Tensed 2. Error bars indicate standard error.

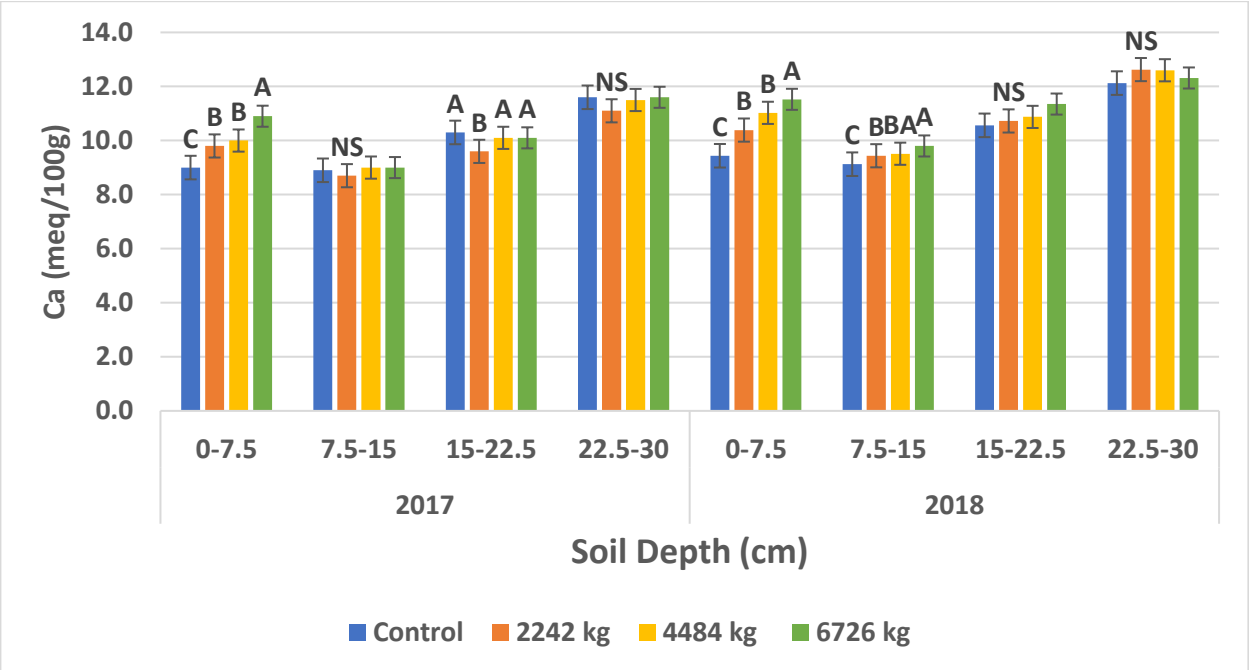

Figure 3.19. Effect of lime on Ca at Tensed 2. Error bars indicate standard error.

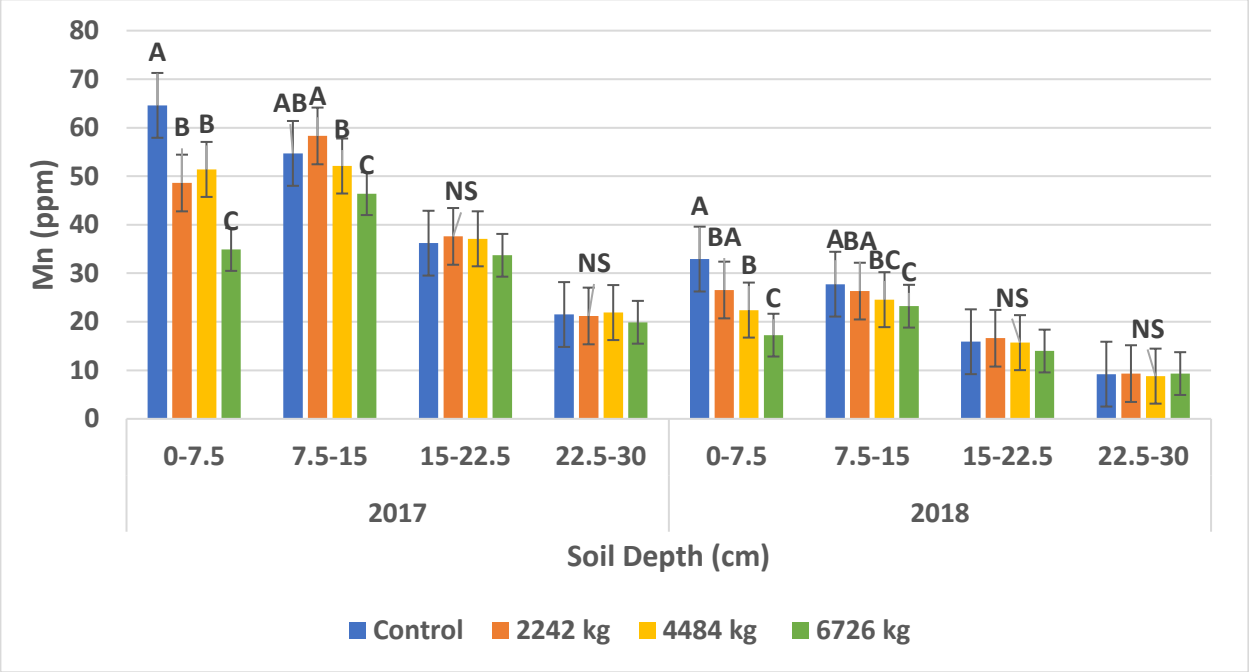

Figure 3.20. Effect of lime on Mn at Tensed 2. Error bars indicate standard error.

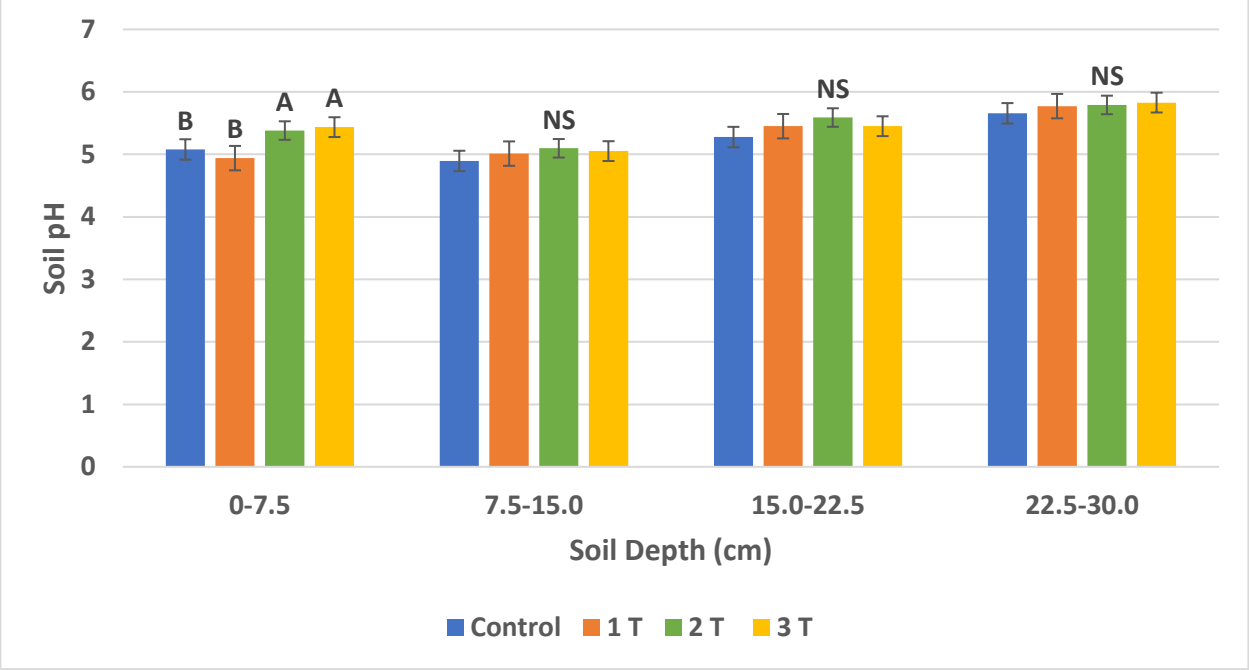

Figure 3.21. Effect of lime on soil pH at Moscow 2018. Error bars indicate standard error.

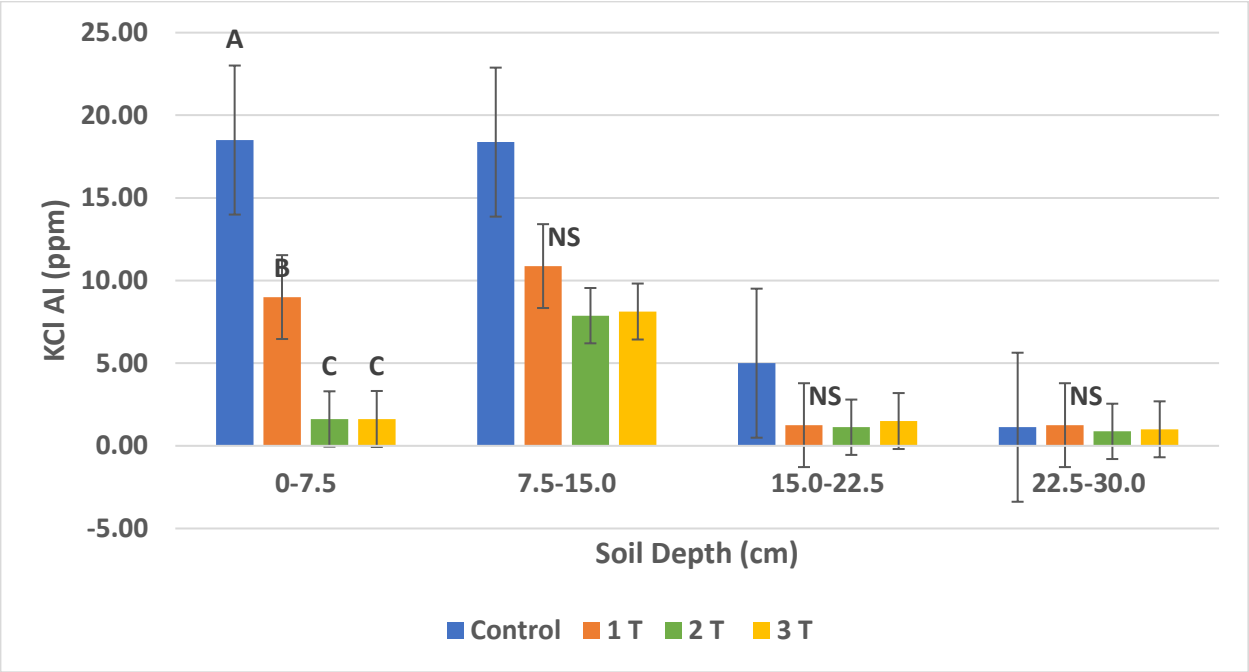

Figure 3.22. Effect of lime on KCl Al at Moscow 2018. Error bars indicate standard error.

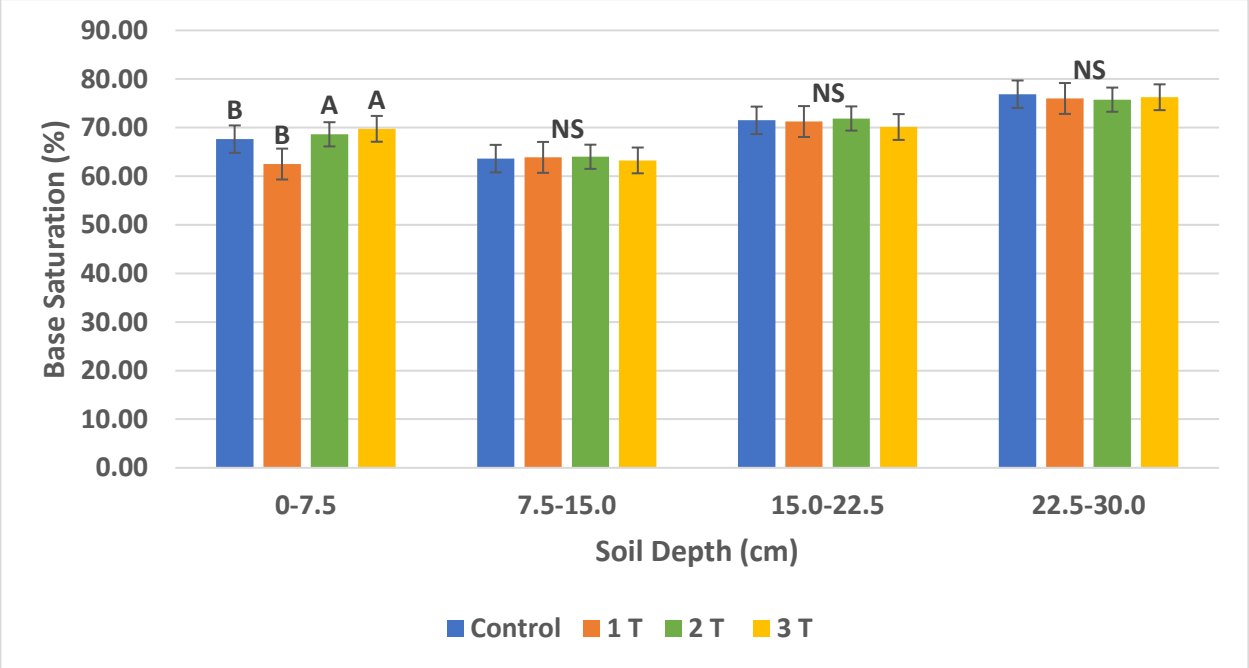

Figure 3.23. Effect of lime on base saturation at Moscow 2018. Error bars indicate standard error.

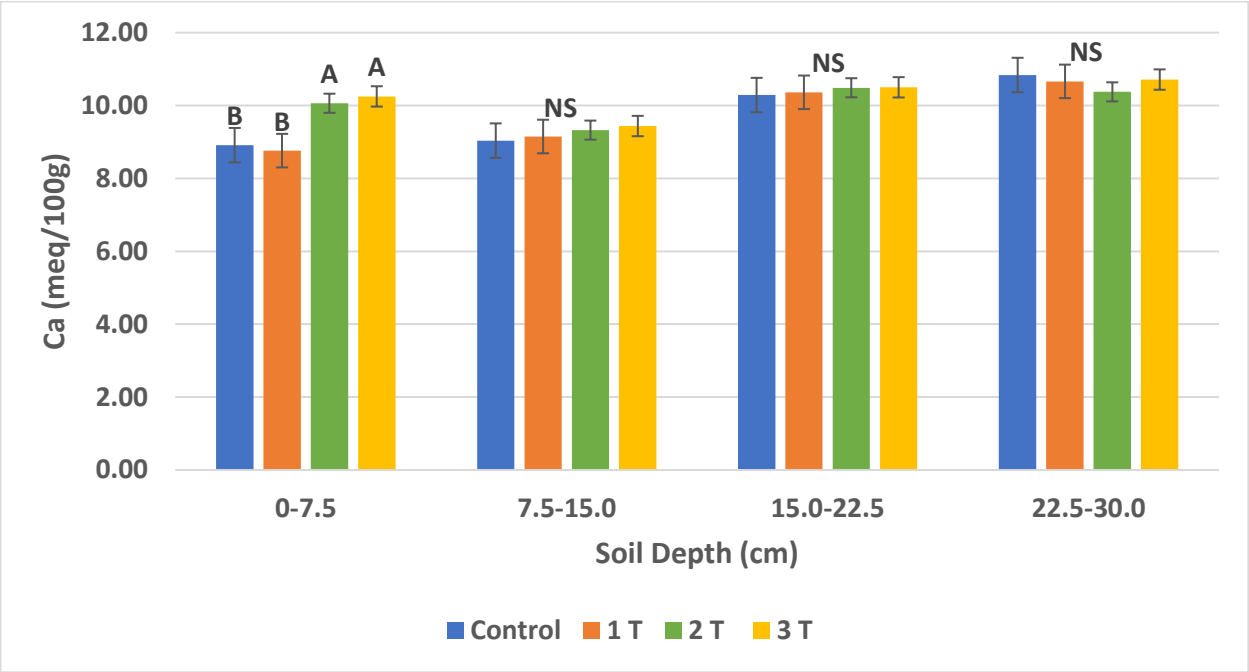

Figure 3.24. Effect of lime on Ca at Moscow 2018. Error bars indicate standard error.

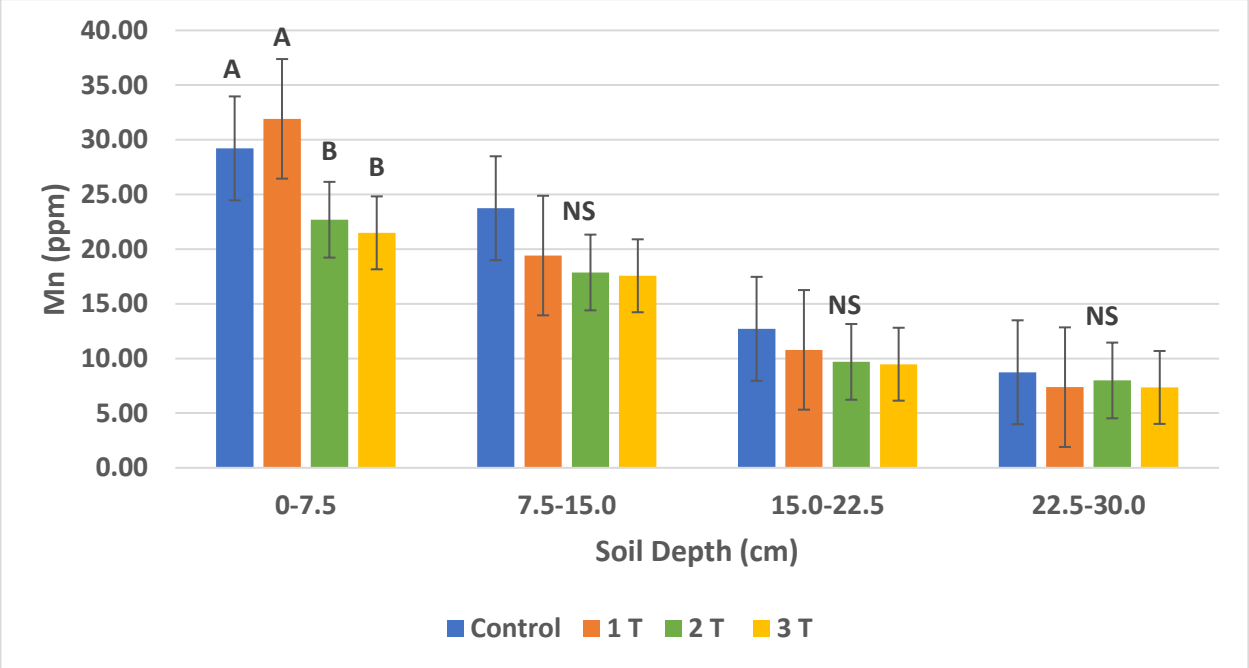

Figure 3.25. Effect of lime on Mn at Moscow 2018. Error bars indicate standard error.

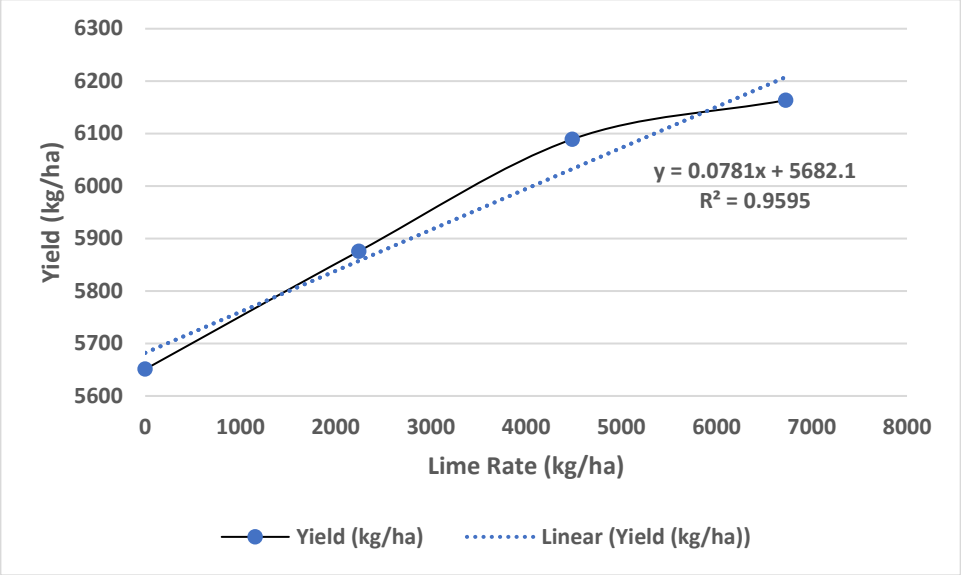

Figure 3.26 Effect of lime rate on yield of winter wheat.

Literature Cited

Adams, F., and Evans, C. E. 1962. A rapid method for measuring lime requirement of red-yellow Podzolic soils. Soil Sci. Soc. Am. J. 26:355–357.

Allaway, W. H. 1957. pH, soil acidity and plant growth. *In* Yearbook of Agriculture. Washington DC. U.S. Department of Agriculture. p. 67–71.

Anderson, N. P., Hart, J. M., Sullivan, D. M., Christensen, N. W., Horneck, D. A., and Pirelli, G. J. 2013. Applying lime to raise soil pH for crop production (Western Oregon). Oregon State University Extension EM 9057.

Bast, L., Warncke, D., and Christenson, D. 2011. Facts about soil acidity and lime questions and answers. Michigan State University Extension E-1566.

Brown, T. T., Koenig, R. T., Huggins, D. R., Harsh, J. B., and Rossi, R. E. 2008. Lime effects on soil acidity, crop yield, and aluminum chemistry in direct-seeded cropping systems. Soil Sci. Soc. Am. J. 72:634-640.

Caires, E. F., Alleoni, L. R. F., Cambri, M. A., and Barth, G. 2005. Surface application of lime for crop grain production under a no-till system. Agron. J. 97:791–798.

Coleman, N. T., and Mehlich, A. 1957. The chemistry of soil pH. *In* Yearbook of Agriculture, The United States Government Printing Office, p. 72–79.

Delhaize, E., and Ryan, P. R. 1995. Aluminum toxicity and tolerance in plants. Plant Physiol. 107:315–321.

Delhaize, E., Ryan, P. R., and Randall, P. J. 1993. Aluminum tolerance in wheat (*Triticum aestivum* L.) II. Aluminum-stimulated excretion of malic acid from root apices. Plant Physiol. 103:695–702.

Fernández, F. G., and Hoeft, R. G. 2009. Managing soil pH and crop nutrients. *In* Illinois Agronomy Handbook, University of Illinois Extension, p. 91–112.

Foy, C. D. 1984. Physiological effects of hydrogen, aluminum, and manganese toxicities in acid soil. *In* Soil Acidity and Liming, ed. Fred Adams. Madison: American Society of Agronomy, Inc., p. 57–97.

Froese, P. S., Carter, A. H., and Pumphrey, M. O. 2015. Recommended crop species and wheat varieties for acidic soil. Washington State University Extension FS169E.

Gallo, A. 2014. A refresher on net present value. Harv. Bus. Rev. 19:1–6.

Gascho, G. J., and Parker, M. B. 2001. Long-term liming effects on Coastal Plain soils and crops. Agron. J. 93:1305–1315.

Hart, J., Mellybye, M. E., Young III, W. C., and Silberstein, T. B. 2011. Annual ryegrass grown for seed (Western Oregon). Nutrient management guide. Oregon State University Extension EM 8854.

Johnson, G. V. 1992. Causes and effects of soil acidity. Oregon State University Extension F-2239.

Johnson, R. D. 2011. Soil pH its relationship with crop biodiversity and production. United States Dep. Agric. Tech. Note No. 8.

Mohammadi, K., Sohrabi, Y., Heidari, G., Khalesro, S., and Majidi, M. 2012. Effective factors on biological nitrogen fixation. African J. Agric. Res. 7:1782–1788.

Koenig, R., Schroeder, K., Carter, A., Pumphrey, M., Paulitz, T., Campbell, K., et al. 2011. Soil acidity and aluminum toxicity in the Palouse region of the Pacific Northwest. Washington State University Extension FS050E.

Leonhardt, H., Penker, M., and Salhofer, K. 2019. Do farmers care about rented land? A multi-method study on land tenure and soil conservation. Land Use Policy 82:228–239.

Long, R. P., Horsley, S. B., and Hall, T. J. 2011. Long-term impact of liming on growth and vigor of northern hardwoods. Can. J. For. Res. 41:1295–1307.

Machacha, S. 2004. Comparison of laboratory pH buffer methods for predicting lime requirement for acidic soils of eastern Botswana. Commun. Soil Sci. Plant Anal. 35:2675–2687.

Mahler, R. L. 1983. Influence of pH on yield and N and P nutrition of alfalfa grown on an Andic mission silt loam. Agron. J. 75:731-735.

Mahler, R. L. 2007. Northern Idaho fertilizer guide: winter wheat. University of Idaho Extension CIS453.

Mahler, R. L., and Guy, S. O. 2005. Northern Idaho fertilizer guide: spring canola. University of Idaho Extension CIS 1012.

Mahler, R. L., Halvorson, A. R., and Koehler, F. E. 1985. Long-term acidification of farmland in northern Idaho and eastern Washington. Commun. Soil Sci. Plant Anal. 16:83–95.

Mahler, R. L., and McDole, R. E. 1987. Effect of Soil pH on Crop Yield in Northern Idaho. Agron. J. 79:751-755.

Mahler, R. L., and McDole, R. E. 1985. The influence of lime and phosphorus on crop production in northern Idaho. Commun. Soil Sci. Plant Anal. 16:485–499.

Malhi, S. S., Mumey, G., Nyborg, M., Ukrainetz, H., and Penney, D. C. 1995. Longevity of liming in western Canada: soil pH, crop yield and economics. In Plant-Soil Interactions at Low pH: Principles and Management. Developments in Plant and Soil Science, eds. R. A. Date, N. J. Grundon, G. E. Rayment, and M. E. Probert. Vol 64.

Malhi, S. S., Nyborg, M., and Harapiak, J. T. 1998. Effects of long-term N fertilizer-induced acidification and liming on micronutrients in soil and in bromegrass hay. Soil Tillage Res. 48:91–101.

Mamo, M., Scientist, S., Wortmann, C. S., Specialist, N. M., Shapiro, C. a, Nutrition, S. S., et al. 2015. Lime use for soil acidity management. University of Nebraska Extension G1504.

McFarland, C., and Huggins, D. R. 2015. Acidification in the inland Pacific Northwest. Crop. Soils. 48:4–12.

McFarland, C. R. 2016. Liming no-till soils and determining lime requirement in the Palouse region. M.S. thesis. Washington State University, Pullman.

McFarland, C. R., Huggins, D. R., Koenig, R. T., and Dean, A. 2015. Soil pH and implications for management: an introduction. Washington State University Extension FS170E.

Mijangos, I., Albizu, I., Epelde, L., Amezaga, I., Mendarte, S., and Garbisu, C. 2010. Effects of liming on soil properties and plant performance of temperate mountainous grasslands. J. Environ. Manage. 91:2066–2074.

Morrison, K. J., and Vogel, O. A. 1962. Gaines: a semidwarf winter wheat for the Pacific Northwest. Washington State Universit Extension Circ. 332.

Patrignani, A., and Ochsner, T. E. 2015. Canopeo: A powerful new tool for measuring fractional green canopy cover. Agron. J. 107:2312–2320.

Sasaki, T., Tsuchiya, Y., Ariyoshi, M., Ryan, P. R., Furuichi, T., and Yamamoto, Y. 2014. A domain-based approach for analyzing the function of aluminum-activated malate transporters from wheat (*Triticum aestivum*) and *Arabidopsis thaliana* in xenopus oocytes. Plant Cell Physiol. 55:2126–2138.

Scharf, P. C. 2000. Liming Missouri Soils. University of Missouri Extension G9102.

Schillinger, W. F., and Papendick, R. I. 2008. Then and now: 125 Years of dryland wheat farming in the Inland Pacific Northwest. Agron. J. 100:166–182.

Shepherd, J. F. 1975. The development of wheat production in the Pacific Northwest. Agric. Hist. 49:258–271.

Shoemaker, H. E., McLean, E. O., and Pratt, P. F. 1961. Buffer methods for determining lime requirement of soils with appreciable amounts of extractable aluminum. Soil Sci. Soc. Am. J. 25:274–277.

Spies, C. D., and Harms, C. L. 1988. Soil acidity and liming of Indiana soils. Purdue Extension AY-267-W.

Sullivan, D. M., Horneck, D. a, and Wysocki, D. J. 2013. Eastern Oregon liming guide. Oregon State University Extension EM 9060.

Sullivan, T. S., Barth, V., and Lewis, R. W. 2016. Soil acidity impacts beneficial soil microorganisms. Washington State University Extension FS247E.

U.S. Department of Agriculture, National Agricultural Statistics Service (USDA, N. 2019. Idaho State and County Data. 2017 Census Agric. 1 Available at: https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_State_Level/Idaho/idv1.pdf.

Viswakumar, A., Mullen, R. W., Diedrick, K. A., Dick, W. A., and Basta, N. T. 2010. Evaluation of four buffer solutions for determining the lime requirement for Ohio soils. Commun. Soil Sci. Plant Anal. 41:424–437.

Weese, D. J., Heath, K. D., Dentinger, B. T. M., and Lau, J. A. 2015. Long-term nitrogen addition causes the evolution of less-cooperative mutualists. Evolution 69:631–642.

Wildey, T. I. 2003. The influence of seed placed lime to reduce the acidifying effects of nitrogen fertilizers in direct seeding systems. M.S. thesis. Washington State University, Pullman.

Woodruff, C. M. 1948. Testing soils for lime requirement by means of a buffered solution and the glass electrode. Soil Sci. 66:53–64.

Ziadi, N., and Sen Tran, T. 2008. Lime requirement. *In* Soil Sampling and Methods of Analysis, eds. M. R. Carter and E. G. Gregorich. Boca Raton: CRC Press.