LIMING NO-TILL SOILS AND DETERMINING LIME REQUIREMENT

IN THE PALOUSE REGION

by

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Abstract

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Soil acidification, accelerated by the application of ammonium-based fertilizer, is becoming an issue of emerging concern in the Palouse region of Eastern Washington and Northern Idaho. Understanding the response of Palouse soils to lime is key to any efforts for ameliorating acidic conditions. The three overall objectives of this project were to: (1) assess the impact of surface applied fluid and sugar lime materials on stratified soil pH and associated properties of no-till soils; (2) assess lime requirement from laboratory incubations with CaCO₃ and buffer test efficacy for Palouse soils; and (3) increase regionally relevant, science-based, information on soil acidification, liming and related agricultural management. Surface applied ultra-fine fluid and sugar lime at 2240 kg ha⁻¹, increased soil pH in the surface 2 cm by an average of 1.25 units at two research sites (near Pullman and Rockford, WA) within two years after application. Neither lime treatment, however, affected soil acidification beyond the 6-cm depth and did not address the lowest soil pH that averaged 4.5 at the 6 to 8-cm depth across the two sites, within two years following application. The lime treatments did not result in differences in measured crop response, likely due, in part, to failure of the treatments to significantly adjust soil pH levels in the most acidic soil zone. A laboratory incubation of ten major Palouse agricultural soils with initial pH values ranging from 4.4 to 5.3, indicated lime requirement values ranging from 3.36 to 8.36 Mg ha⁻¹ to achieve a target pH of 6 for a 15-cm depth. The Modified Mehlich and Woodruff buffer tests correlated to laboratory incubations and provided more accurate lime requirement estimates for Palouse soils than currently recommended SMP and Adams and Evans buffer tests. Results were further improved using local calibrations based on the experimental data. A collection of fact sheets and videos on acidificiation, and were developed as topic-focused Extension materials. These have focused on the fundamentals of pH, the process of acidification in the Palouse, and managing crops, pathogens, herbicides and liming for acid soils. The materials are currently housed on the WSU Small Grains Website.

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Dedication

This work is dedicated to my late grandfather, Stanley H. Fox. He was the first to teach me the value of

soil stewardship today, and for posterity.

CHAPTER ONE: THE IMPACT OF SURFACE-APPLIED LIME ON STRATIFIED SOIL ACIDITY, SOIL PROPERTIES AND CROP RESPONSE IN NO-TILL CROPPING SYSTEMS OF EASTERN WASHINGTON Abstract

Soil acidification, accelerated by intensive use of ammoniacal fertilizers, is becoming a land management factor on farms of the inland Pacific Northwest (iPNW). In no-till systems, deep-band applications of fertilizer are repeatedly applied in the same zone of the soil profile, and soil acidification is typically stratified in the upper 15 cm. Incorporating lime materials is not an option for growers choosing to adhere to no-till management strategies. Surface application of lime to no-till systems, particularly using materials with a small particle size and potentially higher reactivity, could provide a targeted way for growers to maintain no-till management and ameliorate acidic conditions in their fields. Our objective was to determine the impacts of surface applied lime on soil properties and crop response under no-till management. Two liming materials, an ultra-fine particle size fluid lime (1-2 μ m) and sugar lime, were applied to the soil surface at rates ranging from 0 to 2240 kg ha⁻¹ at two no-till sites in Eastern Washington. Soil and crop responses were measured over two years post-application. Soil pH was increased by the greatest lime rate (2240 kg ha⁻¹) by an average of 1.26, 0.76, and 0.29 pH units at the 0-2 cm, 2-4 cm, and 4-6 cm sampling depths, respectively, compared to the control. Base saturation increased with increasing pH, KCl Al decreased as pH increased and no relationship was seen between soil pH and DTPA Mn. No differences were seen between comparable application rates of the two materials. Canola, chickpea, and lentil above-ground biomass were inversely related to increasing concentrations of tissue Mn. Lime treatment did not affect mid-season biomass or yield during either of two crop years. As lime treatments did not ameliorate soil acidity beyond the 6 cm depth within the timeframe of this study, effects on crops would likely be minimal.

Introduction

Over thirty percent of the world's soils are naturally acidic. These soils commonly occur in regions of high precipitation, where natural processes have weathered the soils to represent traits of "typical" acidic soils, expressing relatively low base saturation, cation exchange capacity and organic matter. Acidic soils are often detrimental to crop production. The soils of the inland Pacific Northwest (iPNW) were near-neutral under native vegetative cover (Daubenmire, 1988) due to low annual precipitation, the presence of carbonates and high soil buffering capacity. Crop production practices, primarily the use of nitrogen-based fertilizers, have accelerated acidification in the iPNW (Mahler et al., 1985; Bezdicek et al., 2003). Since ammoniacal fertilizers became inexpensive and easily accessible in the 1960's, their use on farms has substantially increased (Nehring, 2013; Mahler et al., 1985). Ammonium-based fertilizers have an acidifying effect on soils as a consequence of incomplete nitrogen cycling back to dinitrogen gas (Bolan et al., 1991; Bouman et al., 1995; Rasmussen and Rhode, 1989; Sumner and Noble, 2003; Paul et al., 2003). The process of nitrification contributes hydrogen ions to the soil solution, which build up over time. In addition, if N fertilizers are converted to nitrate and not used by the crop, they become susceptible to leaching. Nitrate leaching is accompanied by base cations, which are removed from the root zone further accelerating soil acidification (Bouman et al., 1995; Rasmussen and Rhode, 1989).

High concentrations of hydrogen ions in the soil can be toxic to plants; however, poor crop performance under low pH conditions is most commonly attributable to phytotoxic levels of bioavailable Al and Mn and accompanying nutrient deficiencies (Marschner, 2012; Menzies, 2003; Foy, 1984). Aluminum toxicity is often a major contributor to poor crop performance on low pH soils (Foy, 1984).

The quantity of Al accessible to plants can be difficult to determine with soil testing (Percival et al., 1996). Plant tissue testing is also challenging as Al is not translocated in plant tissue, but often sequestered in plant roots. Excess availability of Mn²⁺ can also lead to crop toxicity and can be overlooked due to the prevalence of Al toxicity in many acidic soils (Bouman et al., 1995; Moroni et al., 2009). The bioavailability of Mn in soil can be even more difficult than Al to accurately measure using standard soil handling and analytical practices because of redox reactions that occur in soil and through sample collection and preparation (Menzies, 2003). Tissue analysis of Mn is often a better indicator of phytotoxicity than soil analysis given the propensity of Mn to accumulate in plant tissue (Foy, 1984). Soil acidity can also negatively impact leguminous crops such as pea, lentil and chickpea, compared to more tolerant grain crops (Mahler, 1986). The detrimental effects are often attributed to adverse environmental effects on microbial symbionts including rhizobacteria (Foy, 1984; Fuentes et al., 2006).

Soil acidification effects are often different in no-till cropping systems where the lack of soil mixing can stratify acidity in localized areas where ammonium-based fertilizers are applied. In the iPNW where fertilizers are deep-banded in no-till systems, stratified acidity can often occur within the surface 15 cm of the soil profile (Brown et al., 2008; Umiker et al., 2009; Jacobsen and Westerman, 1991; Rassmussen and Rhode, 1989; Conyers et al., 1996; Paul et al., 2003). With the steep topography of the Palouse landscape, the highly erodible soil benefits greatly from no-till farming practices (Huggins and Reganold, 2008). Stratified acidification, however, may be a barrier to the adoption of continuous no-till management in the region.

Liming is currently not a common practice in the iPNW, as liming materials are expensive, effective implementation strategies are not well established and levels of crop response to applied lime are still largely unknown. Incorporation of lime materials has been shown to benefit soil fertility and crop yield in the region (Mahler and McDole, 1985; Mahler, 1986; Bezdicek et al., 2003; Fuentes et al.,

2006). No-till producers face a dilemma, however, as low disturbance practices limit lime incorporation methods that can effectively target stratified acidity. Studies in other regions indicate that application of lime to the soil surface can effectively remediate the concentrated zone of acidity caused by repeated fertilization, at the same depth, found in no-till systems (Blevins et al., 1978; Caires et al., 2005; Conyers et al., 2003; Moschler et al., 1973). In the iPNW, evidence suggests that a broadcast application of lime can increase soil pH to 15 cm within two years, with magnitude of impact ranging from a pH increase of 1.9 units decreasing to a change of 0.3 units with depth; however, the ability of a surface application of lime to impact crop performance has yet to be determined (Brown et al., 2008).

Calcium carbonate is known to be relatively insoluble, with reactivity being heavily dependent on surface area of the material's particles (Barber, 1984; Conyers et al., 1996; Havlin et al., 2013). Lime material selection can make a difference in the impact of the product, particularly if a rapid response is an important outcome (Barber, 1984; Conyers et al., 1996). An ultra-fine fluid lime material of high quality calcium carbonate, with particle size of 1-2 μ m (Columbia River CarbonatesTM), was recently made available in the region. The high quality material, with the ultra-fine size, may be more effective at ameliorating stratified soil acidity both in terms of rapidness of reactivity and depth of effectiveness. Another commonly available liming material is a by-product of sugar beet processing (sugar lime), typically comprised of over 80% CaCO₃ and spanning a range of particle sizes.

The objective of this study was to characterize the ameliorative capacity of two surface-applied lime materials on soil acidity and crop response at two sites under no-till management.

Materials and Methods

Description of sites

Two sites with an established history of no-till management were selected for the field study. One site was on the Palouse Conservation Field Station (PCFS) in Pullman, WA (46.760552, -117.196297). The soil at the PCFS site formed under native prairie vegetation and has been under no-till crop production for twenty years with a three-year rotation of winter wheat- grain legume-spring wheat. The dominant soil series at the PCFS site is Thatuna, a fine-silty, mixed, superactive, mesic, Oxyaquic Argixeroll.

The second experimental site was near Rockford, WA (47.518938, -117.186431). The soil historically formed under forest cover and the site has a history of 100 years in crop production with a 30-year legacy of bluegrass seed production with large annual nitrate inputs of 168 kg ha⁻¹, prior to entering no-till management under a predominantly wheat-based crop rotation ten years ago. The dominant soil series at the Rockford site is also Thatuna. Average annual precipitation at the PCFS site is 518 mm while the Rockford site annually averages 380 mm (Washington State University, Ag Weather Net stations). Both sites follow the Mediterranean rainfall pattern, typical to the iPNW, with the majority of precipitation occurring during the winter months (Chi et al., 2016). Research plots were 5.49 m (18') wide by 12.19 m (40') long at the PCFS. At the Rockford site, plot size was adjusted to 4.88 m (16') by 9.14 m (30') to target the most homogenous location of the field. Both studies were established using a randomized complete block design with four replications.

Treatments

Two liming materials were applied to each site during the first week of November, 2013, following a winter wheat crop. The first was an ultra-fine (1-2 micron) particle size fluid lime (trade

name "NuCal" or "HydroCal", produced by Columbia River Carbonates™, Woodland, WA) applied using a plot sprayer at calcium carbonate equivalent rates of 224 kg ha⁻¹ (FL224), 448 kg ha⁻¹ (FL448), 1120 kg ha⁻¹ (FL1120), and 2240 kg ha⁻¹ (FL2240), to the plots at both sites. Sugar Lime was sieved through a 2 mm mesh sieve to diminish clumping resulting from product moisture. A sub-sample of the material was oven dried at 48.8°C to obtain moisture content and determine the appropriate application rate. The Sugar Lime was applied uniformly by hand to plots at calcium carbonate equivalent rates of 448 kg ha⁻¹ (SL448) and 2240 kg ha⁻¹ (SL2240). No lime material was applied to the zero-rate control plots.

Soil Sampling and Analysis

Spring soil samples were taken from all plots within each site in April 2014. Samples were collected to a depth of 10 cm using 1.8-cm diameter hand probes by 2-cm depth increments. Composite samples of each depth increment were made from 30 soil cores taken randomly throughout each plot. In November 2014, soil sampling was repeated at each site using a 2.8-cm diameter Giddings (Machine Company[™]) probe to penetrate dry and frozen conditions. Nine soil cores, to a depth of 10 cm, were taken from each plot, divided into 2-cm increments, and composited. Spring soil sampling at the end of March, 2015 was repeated using hand-operated soil probes following the same protocol as in April, 2014. All soil samples were kept chilled until reaching the lab, where they were stored at 4°C until processing.

Soil samples were passed through a 2-mm sieve and air-dried at room temperature (24°C). Soil pH was measured with 1:1 soil and water slurry. The protocol used was an initial stirring with the addition of water and 30 minutes later, while stirring, the measurement was taken with a Denver Instrument model 250 pH ISE conductivity benchtop meter and an Accumet #13-62-631 saturated KClfilled, glass electrode (VanLierop, 1990). Exchangeable bases (Ca, Mg, K, Na) and cation exchange

capacity (CEC) were measured using NH₄OAC extraction (Gavlak et al., 2005), and atomic absorption spectrophotometry. Base saturation was calculated by dividing the sum of the exchangeable bases by the CEC. Extractable Mn was measured using the DTPA extraction method (Gavlak et al., 2005). Extractable Al was measured using 1.0 N KCl (Bertsch and Bloom, 1996).

Crop sampling and analysis

The PCFS site was seeded to chickpea (*Cicer arietinum* var. Billy Beans) at a rate of 157 kg ha⁻¹ with a Horsch-Anderson drill at a depth of 5 cm on April 30, 2014. The Rockford site was planted with canola (*Brassica napus* var. HyClass 930) on May 20, 2014, at a rate of 3.5 kg ha⁻¹ to a depth of 1.3-cm using a Flexi-coil air drill with Cross-Slot™ openers on a 25.4-cm spacing and an 11-52-0 fertilizer blend. At anthesis, above-ground crop biomass of chickpea (PCFS) and canola (Rockford) was collected in each plot. Two sampling points of one meter by one-half meter were used, each included two one-meter length rows. For a total area sampled of one square meter. All crop plants were at ground level with rice knives. Samples were put into paper bags and air dried. The dried biomass was weighed and then ground with a Model 4 Wiley Mill, to pass through a 2-mm mesh in preparation for analysis. Tissue Al and Mn were subjected to a nitric acid digest and the samples were analyzed using ICP-OES spectrometry. In 2015 the PCFS site was rotated to spring wheat (*Triticum aestivum* var. Louise). The Rockford site was planted to lentil (*Lens culinaris*). No fertilizer was applied at the time of lentil seeding. A foliar application of NuTran Micronutrients (10% N, 1% K, 1.33% S, 0.17% B, 0.17% Cu, 0.1% Fe, 1.3% Mn, 1.3% Zn) was applied on June 4th at a rate of 747.52 mL ha⁻¹.

Yield data was collected for chickpea and spring wheat at the PCFS site using a research plot-sized combine and harvesting a strip 1.52 m x 9.14 m from the center of each plot. The grain was dried,

cleaned using air-flow, and weighed to record yield data. Yield data were not collected at the Rockford site.

Statistical analysis

Analysis of variance was performed for soil and crop data using PROC GLM (SAS v. 9.3, 2010) independently for each site, sampling time or crop, and depth for the soils data (P<0.1). The model included the soil or crop response to factors treatment and block. A Pearson correlation (PROC CORR, SAS v. 9.3, 2010) analysis (P<0.1) was used on the analysis of plant tissue elements and biomass and yield. A stepwise multivariate analysis (P<0.15) using PROC REG (SAS v. 9.3, 2010) was performed with crop response to the soil properties of pH, KCl extractable Al, DTPA extractable Mn, and base saturation, all depths were included in the model.

Results and Discussion

Soil response to surface application of lime: Results

Soil pH

At the PCFS site, in the spring of 2014, the pH of the unlimed soil, including all sampled depth increments, ranged from 5.46 at the 0-2 cm depth, to 4.69 at the 2-4 cm depth (Fig. 1.1 a,c,e,g). In the fall of 2014, the range was from 5.84 (0 to 2 cm) to 4.74 (4 to 6 cm), and at the third sampling point in Spring 2015, soil pH ranged from 5.65 at 0-2 cm to 4.61 at the 8 to 10 cm depth (Figure 1.1 a,c,e,g). The data indicate a trend of organic matter ranging from 8.12% at 0-2 cm to 2.92% at 8-10 cm, and pH demonstrating a positive linear relationship, in unlimed soil across all depths (Spring 2015) (Figure 1.1g).

In spring of 2014, treatment effects were seen only at the 0-2 cm depth. The 2240 kg ha⁻¹ rate of both lime materials were significantly higher than all other treatments except FL1120 (Table 1.1a). The FL2240 increased soil pH from 5.19 in controls to 6.53, while SL224 increased soil pH to 6.57 compared

to the control. The FL1120 treatment increased pH compared to the control and FL224, but not from the 448 kg ha⁻¹ rate of either material. The 448 kg ha⁻¹ rate of both materials was different than the control and FL224. The FL224 treatment and the unlimed treatment were not different. No differences were seen between materials.

In Fall 2014, increases of 1.32, 1.18 and 0.55 pH units were seen with the FL2240 treatment at the 0-2 cm, 2-4 cm, and 4-6 cm depths compared to the control, which had pH values of 5.62, 5.00, and 4.90, respectively (Table 1.1a). The SL2240 was significantly higher than the control at depths 0-2 and 2-4 cm with respective increases of 1.44 and 1.03 pH units. The SL2240 and FL2240 treatments were not different from each other at any depth. The FL1120 treatment also had higher pH (6.77 at 0-2 cm, and 5.66 at 2-4 cm) than the control from 0-4 cm resulting in an increase of 1.16 and 0.66 units in the two depth increments. The FL1120 treatment and was not different than the 2240 kg ha⁻¹ treatments at any depth. The FL448 (pH 6.22) increased pH compared to the control at the 0-2 cm depth by 0.60 units; the other 448 kg ha⁻¹ treatment, SL448, was not different than the control at that depth. For all other depths, neither treatment was significantly different than the control, and the materials showed no differences between each other (Table 1.1a).

In Spring of 2015, treatment effects were not seen below the 4-6 cm depth. The SL2240 was the only treatment to have higher pH than the unlimed control from 0-6 cm. The treatments increased soil pH by 1.29, 1.11, and 0.47 units from 5.36, 5.03, and 4.84, respectively, at 0-2 cm, 2-4 cm, and 4-6 cm, in the surface depths. The same rate of fluid lime increased soil pH from 0-4 cm by a magnitude of 1.32 units at 0-2 cm, and 0.99 units at 2-4 cm. No differences in pH were seen between the two treatments at the 2240 kg ha⁻¹ rate. The FL1120 treatment also had higher pH (6.23, 5.63) than the control (5.36, 5.03) at depths from 0-4 cm by 0.87 units and 0.60 units at the 0-2 cm and 2-4 cm depths, respectively. At the 0-2 cm depth, this treatment was not different than the 2240 kg ha⁻¹ treatments, but was significantly

lower at the 2-4 cm depth with a difference of 0.39 units between FL1120 and the FL2240 treatment and a difference of 0.51 pH units with the SL2240 treatment. There was no difference between the FL1120 treatment and the 448 kg ha⁻¹ rates of either material. The SL448 treatment had higher pH (5.30) than the control (reference pH of control) at the 2-4 cm depth, but was not different than the control at any other depth. The FL448 treatment (pH 5.89) was not different from the control at any depth, and the materials were not different from each other. The FL224 treatment was never different from the unlimed control (Table 1.1a).

In Spring 2014 at the Rockford field site, soil pH ranged from 5.06 (8-10 cm) to 4.19 (0-2 cm) in unlimed soil across all depths (Figure 1.1 b,d,f,g). In Fall 2014 a soil pH range of 5.50 (0-2 cm) to 4.20 (4-6 cm), and in Spring 2015 soil pH range was from 5.33 (0-2 cm) to 4.30 (6-8 cm) (Figure 1.1 b,d,f,g). A relationship between soil organic matter, ranging from 7.96% at 0-2 cm to 3.02% at 8-10 cm for unlimed soil across all depths (Spring 2015), and soil pH was not seen at the Rockford site (Figure 1.1h).

At the Rockford site, pH showed treatment effects only at the 0-2cm depth in the spring and Fall of 2014 (Table 1.2a). In the spring of 2014, the FL2240 treatment (pH 4.98) was higher than the control (pH 4.41). The SL2240, FL1120, and FL448 treatments were not different than FL2240 or the unlimed control. The SL448 and FL224 treatments were not different from the control. The FL448 and the SL448 treatments were not different from each other. In the Fall of 2014, both 2240 kg ha⁻¹ treatments significantly increased pH at the 0-2 cm depth compared to all other treatments with an increase of 1.24 and 1.24 pH units attributed to FL2240 (pH 6.52), and SL2240 (6.53) respectively. The FL448 treatment had significantly higher pH (5.63) than the unlimed control (pH 5.28) by 0.27 units. The SL448 and the FL1120 were not different than the FL448 treatment, or the control. The FL224 was not different than the control. By spring 2015 the FL2240 increased pH compared to the unlimed control and all other treatments except SL2240 from 0-6 cm increasing pH by 1.14 (0-2 cm), 0.50 (2-4 cm), and 0.23 (4-6 cm)

pH units compared to the control (pH 5.12, 4.55, 4.40). The SL2240 had significantly higher pH (pH 6.40, 4.99) than all other treatments from 0-4 cm by 1.28 (0-2 cm) and 0.44 (2-4 cm) pH units, compared to the control, at the 4-6 cm depth the treatment was not different than any other treatment, including the SL2240. The FL1120 also had higher pH (5.78 at 0-2 cm and 4.80 at 2-4 cm) than the unlimed control from 0-4 cm by a magnitude of 0.65 (0-2 cm) and 0.24 (2-4 cm) pH units, and at the 4-6 cm depth, did not change pH compared to other treatments. At the 0-2 cm depth, the FL448 treatment had higher pH (5.47) than the control by 0.35 pH units, but they were not different at the 2-4 or 4-6 cm depth. The FL448 and SL448 treatments were not different. The SL448 and FL224 treatments were not different than the control at any depth (Table 1.2a).

Base Saturation

Base saturation at the PCFS site in Spring 2014 ranged from 73.5% (6-8 cm) to 56.4% (4-6 cm) (Figure 1.1a, Figure 1.3a). In Fall of 2014, the range of base saturation values was from 74.2% (8-10 cm) to 59.5% (6-8 cm), and in the spring of 2015 the range was 74% (0-2 cm) to 54.9% (6-8 cm) base saturation for all depths (Figure 1.1a, Figure 1.3a). Base saturation did not exhibit a strong relationship with soil pH at this site (Figure 1.1a). A distinct relationship was also not seen between base saturation and soil Al (Figure 1.3a).

At the PCFS site in the spring of 2014, the FL2240 treatment (base saturation 77.5%) increased base saturation by 12.7% at the 0-2 cm depth compared to the control (64.8%) and was significantly higher than all other treatments except the SL2240 treatment. The SL2240 treatment was higher (base saturation 75.4) than treatments SL448 (by 11.6%), FL224 (by 11.6%), and the unlimed control (by 10.7%) at the 0-2 cm depth. The FL1120 and FL448 treatments were also higher than the SL448, FL224,

and unlimed control treatments, but not different than the SL2240 treatment. No treatment effects on base saturation were seen at any other depths at the Spring 2014 sampling point (Table 1.1a).

By Fall 2014, increased base saturation was seen from 0-8 cm with the FL2240 treatment (base saturation: 85.3%, 82.6%, 70.5%, 66.93%) compared to the unlimed control (base saturation: 69.0%, 65.3%, 63.8%, 64.7%), by 16.3%, 17.3%, 6.76% and 2.27% at the 0-2 cm, 2-4 cm, 4-6 cm, and 6-8 cm depths, respectively. The FL2240 treatment was not different than SL2240, which increased base saturation by 20.44% compared to the control, and had higher base saturation (89.4%) than all other treatments at the 0-2 cm depth, except FL2240. At the 2-4 cm depth the SL2240 had significantly higher base saturation (78.0%) than the unlimed control by 12.7%, and was not different than FL1120 or FL448. The FL1120 (79.4%) and FL448 (77.4%) treatments had higher base saturation than the control by 10.4% and 8.4% respectively, at the 0-2 cm depth but the treatments were not different at depths below that level. The treatment SL448 and the FL224 were not different from the unlimed control from 0-4 cm. At the 4-6 cm depth the base saturation of the SL448 treatment (62.3%) is lower than the control, and at the 6-8 cm depth the FL2240 (70.5%) is the only treatment that is significantly higher than the low SL448 value (Table 1.1a).

In Spring 2015 both the FL2240 (80.3%) and SL2240 (83.3%) treatments had higher base saturation than all others at the 0-2 cm depth, at the 2-4 cm depth both treatments were significantly higher (75.0%, 74.7%), respectively, than all others except FL1120. The FL2240 treatment increased base saturation by 12.1%, compared to the control (base saturation of 68.2%) at 0-2 cm, and 12.7% at 2-4 cm (base saturation of 62.2%). The SL2240 increased base saturation at 0-2 cm by 15.1% and 12.4% at 2-4 cm compared to the unlimed control. At 0-2 cm, the FL1120 treatment (75.0%) was different than all treatments except FL448, at the 2-4 cm depth the FL1120 treatment (70.1%) was not different than any

other. The FL448, SL448, and FL224 treatments were all the same as the unlimed control and each other (Table 1.1a).

Base saturation on unlimed soil at the Rockford site ranged from 47.8 (8-10 cm) to 32.9 (4-6 cm) % across all depths in the spring of 2014. In Fall 2014, the values ranged from 63.2 (0-2 cm) to 31.2 (4-6 cm) percent. In Spring 2015, base saturation values ranged from 60.1% (0-2 cm) to 30.6% (8-10 cm) on unlimed soil across all depths (Figure 1.1b, Figure 1.3b). Decreasing pH was associated with decreasing base saturation at this site (Figure 1.1b). The trends also indicated that base saturation decreased with increasing soil KCl Al (Figure 1.3b).

At the Rockford site, in Spring 2014, the 0-2 cm depth was the only level where differences were seen between treatments. The base saturation of the FL2240 (73.2%) and SL2240 (71.6%) treatments were both higher than the unlimed control (43.0%) by 30.2% and 28.7% respectively, as well as the FL224, FL448, and the SL448 treatments. The FL2240 was higher than the FL1120 (by 14.7%), but the SL2240 was not. The FL1120 treatment was also not different than the control (Table 1.2a).

By Fall 2014, treatment effects on base saturation were seen at the 0-2 and 2-4 cm depths with both the FL2240 (74.3% and 51.3%) and SL2240 (76.6% and 45.7%) treatments having higher base saturation than the control, by 19.8% and 22.1% respectively at 0-2 cm and 16.4% and 10.0% at 2-4 cm, and all other treatments except FL1120 (base saturation of 71.6% and 47.9%). The FL1120 treatment was also higher than the control (by 17.1% at 0-2 cm and 6.8% at 2-4 cm) and FL224 treatments and, at the 2-4 cm depth, higher than the SL448 treatment. The SL448 and FL448 treatments were not different than each other, at any depth. At the 0-2 cm depth the SL448 treatment (62.2%) was higher than the control (54.5%) and FL224 (57.4%) treatments, while the FL448 was not different than the control or the FL224 treatment (Table 1.2a).

At the Spring 2015 sampling point, treatment effects were seen to a depth of 6 cm. The FL2240 treatment (78.9% 0-2 cm and 56.6% 2-4 cm) was significantly higher than the unlimed control (53.7% and 40.2%) a difference of 25.3% and 16.4% higher at the 0-2 cm and 2-4 cm depths. The FL2240 treatment was also higher than the FL224 treatment (54.8% and 40.8%), from 0-4cm. At 4-6 cm the FL2240 treatment had higher base saturation (46.0%) than the SL448 (35.4%) and FL224 treatments (35.3%). The SL2240 treatment had higher base saturation (77.6%) than the unlimed control (53.7%), the FL224 (54.8%), FL448 (63.2%), and SL448 (58.4%) treatments at the 0-2 cm depth. At the 2-4 and 4-6 cm depths, the SL2240 treatment (50.24% and 39.2%) was not different than any other. The FL1120 treatment (base saturation of 66.0%) was higher than the unlimed control (by 12.3%) treatments and FL224 (by 11.2%), but not different than any others at the 0-2 cm depth. The FL1120 treatment was not different than any other treatment at any other depth. Both of the 448 kg ha⁻¹ treatment rates were higher than the unlimed control at the 0-2 cm depth by 9.6% and 4.7% for FL448 (base saturation 63.2%) and SL448 respectively (58.4%), they were not different from each other at any depth. At the 2-4 and 4-6 cm depths both FL224 (40.8% and 35.3%) and SL448 treatments (40.9% and 35.4%) had lower base saturation than the FL2240 treatment (Table 1.2a).

KCI Extractable Al

The KCl extractable Al at the PCFS measured in spring 2014 ranged from 41 (4-6 cm) to 2 (0-2 cm) mg kg⁻¹. In fall 2014, Al levels ranged from 70 (6-8 cm) to 1 (0-2 cm) mg kg⁻¹. At the final sampling point (spring 2015), KCl Al ranged from 68 (6-8 cm) to 0 (0-2 cm) mg kg⁻¹ within the top ten cm of unlimed soil (Figure 1.1c, Figure 1.2a, Figure 1.3a). A trend of KCl Al increasing with declining soil pH, particularly below pH 5, was seen at this site (Figure 1.1c). The data trends indicate that KCl Al decreased with increasing levels of organic matter at PCFS (Figure 1.2a).

Extractable AI was affected by treatment at the PCFS site in the spring of 2014, at the 0-2 cm depth. The unlimed control (5.25 mg kg⁻¹) and FL224 (1.75 mg kg⁻¹) had higher levels of AI than all other treatments. Lime treatments above 224 kg ha⁻¹ reduced KCI AI to levels between 0.50 and 1 mg kg⁻¹ with an average of 4.45 mg kg⁻¹. The other treatments did not have different AI levels from each other. In Fall 2014, the same pattern was seen at the 0-2 cm depth with an average reduction of 1.55 mg kg⁻¹. No significant differences were seen at any other depth. Trends at the Fall 2014 sampling point indicate lower levels of AI with increasing levels of lime application at the 2-4 and 4-6 cm depths, compared to the unlimed control, with a maximum reduction of 16.25 mg kg⁻¹ where the FL2240 treatment reduced AI to 0 mg kg⁻¹ at the 2-4 cm depth and by 28.75 mg kg⁻¹ at the 4-6 cm depth. No significant differences in KCI extractable AI were seen at any depth in the spring of 2015. However, trends again, indicate lower levels of extractable soil AI with higher rates of surface-applied lime. The largest difference occurred between the FL2240 treatment and the control at the 4-6 cm depth, where AI was lower with treatment than the control by 26.5 mg kg⁻¹ (Table 1.1b).

At the Rockford site, the range of KCl Al in unlimed soil across all soil depths in Spring 2014 was 216 (4-6 cm) to 27 (0-2 cm) mg kg⁻¹. In Fall 2014, the range was from 226 (4-6 cm) to 2 (0-2 cm) mg kg⁻¹, and in Spring 2015 KCl Al ranged from 205 (8-10 cm) to 3 (0-2 cm) mg kg⁻¹ (Figure 1.1d, Figure 1.2b, Figure 1.3b). At this site, data trends reflect KCl Al increasing as soil pH decreases, particularly below pH 5 (Figure 1.1d). Conversely, the data trends indicate that KCl Al decreases with increasing soil organic matter (Figure 1.2b).

Extractable AI at the Rockford site was affected by treatment at the 0-2 cm depth in Spring 2014. The three highest rate treatments, FL2240 (2.00 mg kg⁻¹), SL2240 (3.25 mg kg⁻¹), and FL1120 (12.00 mg kg⁻¹), all had significantly lower KCI AI than the unlimed control by 63.5, 62.25, and 53.5 mg kg⁻¹ respectively. Levels of AI in those treatments were not different than the 0-2 cm levels in the FL448 (28

mg kg⁻¹), SL448 (32.75 mg kg⁻¹), and FL224 (42.75 mg kg⁻¹) treatments, which were also not different than the levels of Al in the unlimed control (65.50 mg kg⁻¹). At the Fall 2014 sampling point no significant differences were seen at the 0-2 cm depth, though trends indicate decreasing levels of Al with surfaceapplied lime. At the 2-4 cm depth, the FL2240 treatment had lower KCl Al than the unlimed control by 85.8 mg kg⁻¹, and the FL224 treatment by 66.5 mg kg⁻¹, differences were not see between the other treatments. By spring of 2015, treatment effects were seen from the 0-6 cm depth. The FL2240 treatment had lower extractable AI than the unlimed control from 0-6 cm with differences of 9.5, 67.3, and 67.8 mg kg⁻¹ at 0-2 cm, 2-4 cm, and 4-6 cm respectively. The SL2240 treatment had lower extractable AI at the 0-2 cm (by 8 mg kg⁻¹), and 2-4 cm (by 64.8 mg kg⁻¹), depths compared to the control (11 and 82.25 mg kg⁻¹ respectively). At the 4-6cm depth the SL2240 level of Al was not different from the control or from the FL2240 treatment. At the 0-2 and 2-4cm depths, KCl Al was reduced by the FL1120 (by 8.5, 43.8 mg kg⁻¹), and FL448 (by 8.3, 25.5 mg kg⁻¹) treatments, compared to the control. The impact of the FL1120 treatment was not different than the 2240 kg ha⁻¹ rate treatments at either depth, and the FL448 was not different at 0-2 cm, but had higher Al at the 2-4 cm depth. The SL448 and FL224 treatments were not different, at the 0-2 cm depth, than any of the other treatments. At the 2-4cm depth, levels of Al were higher with treatments SL448 (83.00 mg kg⁻¹), and FL224 (77.50 mg kg⁻¹) than all other limed treatments and were not different than the unlimed control. At the 4-6 cm depth, KCI Al levels seen in treatments SL2240, FL1120, and FL448 were the same as treatment with FL2240, and the control. Treatments SL448 (142.50 mg kg⁻¹) and FL224 (135.25 mg kg⁻¹), had higher levels of Al than FL2240 (69.00 mg kg⁻¹) and were the same as the unlimed control (136.75 mg kg⁻¹) (Table 1.2b).

DTPA extractable Mn

Soil DTPA extractable Mn levels on unlimed soils at the PCFS site in Spring 2014, ranged from 84.8 (4-6 cm) to 30.7 (8-10 cm) mg kg⁻¹, in Fall 2014, values ranged from 54 (2-4 cm) to 18.8 (2-4 cm) mg

kg⁻¹. In the spring of 2015, DTPA extractable Mn levels over all depths ranged from 35.3 (0-2 cm) to 14 (6-8 cm) mg kg⁻¹ in unlimed soil (Figure 1.1e). A correlation was not seen between soil pH and DTPA extractable Mn (Figure 1.1e).

At the PCFS site in the spring of 2014, treatment differences were seen in DTPA extractable Mn at the 0-2 cm depth, where both 2240 kg ha⁻¹ treatments had lower soil Mn than all treatments except FL1120 with a difference of 2.35 mg kg⁻¹ (FL2240) and 1.87 mg kg⁻¹ (SL2240) compared to the control (53.70 mg kg⁻¹Mn). Soil Mn under the FL1120 treatment was not different than any other treatment, including the unlimed control. The SL448 treatment had lower Mn levels (48.85 mg kg⁻¹) than the control by 4.85 mg kg⁻¹, but was not different than the FL448 (55.35 mg kg⁻¹) or FL224 treatments (58.10 mg kg⁻¹ ¹). The FL448 and FL224 treatments were not different than Mn levels of the control. In the fall of 2014, no significant differences were seen at the 0-2 cm depth, trends indicate that the highest rate of surface-applied lime reduced levels of Mn compared to the control with the FL2240 showing a 5.25 mg kg⁻¹ reduction in soil Mn. At the 2-4 cm-depth, all limed treatments except FL224 had lower Mn levels than the control (37.95 mg kg⁻¹ Mn). The SL448 decreased soil Mn by 15.6 mg kg⁻¹ which was the biggest difference from the unlimed control. The FL224 treatment (36.05 mg kg⁻¹ Mn) was not different than any of the other treatments, including the control. By the Spring 2015 sampling point, treatment effects on soil Mn were seen from 0-2 cm to the 4-6 cm depth. The 2240 kg ha⁻¹ rate of both materials showed increased Mn levels compared to all other treatments except FL1120. The FL2240 treatment increased Mn by 5.8, 2.3, and 0.23 mg kg⁻¹ and the SL2240 treatment increased Mn by 2.25 and 3.9 mg kg⁻¹, and decreased Mn by 1.22 mg kg⁻¹, at 0-2 cm, 2-4 cm, and 4-6 cm respectively compared to the control Mn levels (24.05, 21.78, 26.35 mg kg⁻¹). At the 0-2 cm depth the FL448 (26.03 mg kg⁻¹), SL448 (28.73 mg kg⁻ ¹), and FL224 (26.65⁻¹) treatments were not different from the unlimed control. The FL1120 and SL448 treatments did not have significantly different effects on soil Mn at the 0-2 cm depth. The two

treatments were also not different at the 2-4 cm depth, where they both reduced soil Mn by 3.97 and 0.45 mg kg⁻¹ respectively, compared to the unlimed control. The FL448 treatment was not different than the SL448 treatment, and did not decrease soil Mn compared to FL224 or the unlimed control. The FL224 and unlimed control had the same effects on soil Mn across all soil depths in the spring of 2015 (Table 1.1b).

Unlimed soil Mn across all depths, at the Rockford site in Spring 2014 ranged from 148.7 (6-8 cm) to 41.5 mg kg⁻¹ (6-8 cm), in the fall of 2014 the range was 75.2 (4-6 cm) to 27.5 (0-2 cm) mg kg⁻¹, and in Spring 2015 soil Mn levels ranged from 16.2 (6-8 cm) to 79 (4-6 cm) mg kg⁻¹, on unlimed soil. Trends did not indicate a relationship between pH and soil Mn (Figure 1.1f).

At the Rockford site, in the spring of 2014, at the 0-2 cm depth, the FL448 treatment expressed the highest levels of soil Mn (79.9 mg kg⁻¹, Table 1.2b), the FL2240 treatment had the lowest level of Mn (70.2 mg kg⁻¹). No treatment differences were seen at the 2-4 cm depth. Differences were seen at the 4-6 cm depth, where the SL448 treatment had the lowest level of Mn (68.03 mg kg⁻¹) and FL2240, SL2240 showed a significantly higher levels (73.5 and 69.3 mg kg⁻¹). No significant differences were seen in the levels of DTPA extractable Mn, at the Fall 2014 sampling point. By Spring 2015, trends indicated a reduction of soil Mn with higher levels of lime treatment, but there were no significant treatment differences at the 0-2cm depth. At the 2-4 and 4-6 cm depths, the FL2240 treatment (45.03, 53.75 mg kg⁻¹) significantly reduced Mn compared to the unlimed control by 12.9 and 11.7 mg kg⁻¹, respectively. At the 4-6cm depth FL2240 was also significantly lower than the FL224 treatment by 4.22 mg kg⁻¹. All other treatments were the same as both the FL2240 and the control from 2-6cm (Table 1.2b).

Soil response to surface application of lime: Discussion

Predominant effects often associated with declining soil pH are: decreases in base saturation and concurrent increases in soil solution Al and phytotoxic Mn²⁺ (Mahli et al., 1998; Conyers, 1990; Bouman et al., 1995; Blake et al., 1999; Li and Mahler, 1993). Some of these effects were seen at the field sites and some were not. Differences in the expression of soil acidity and associated trends are most likely attributable to pedological factors such as native vegetation, management history, and the topographical heterogeneity common to agricultural field sites of the Palouse region.

The difference in where the range of pH values found at the two sites fall on the pH scale is most likely attributable to pedological factors and the nitrogen-intensive management legacy of the Rockford site, leading to higher concentrations of hydrogen ions and lower pH values. The absence of base saturation trends with pH and Al, at the PCFS site, can be explained by a cluster of unusual base saturation data from one of the sampling points. At the PCFS site, the landscape factor of an eroded protuberance with sub-soil close to the surface, and having a higher clay content (>16%, data not shown), appears to have maintained relatively high base saturation levels simultaneous with high levels of KCl extractable Al, compared with the data reflected at the other sampling points. At the Rockford site, there was a sharp increase in KCl Al levels below base saturation values of 45%, a trend that is more typical of acidic soils (Blake et al., 1999). These values may begin to indicate critical thresholds for problematic levels of phytotoxic Al.

The trends shown in unlimed soil at both sites characterize a relationship between organic matter and soil pH, and organic matter and KCl extractable Al. These are relationships that are also often seen as characteristic of acidic soils, as exchange sites on soil organic matter are able to adsorb both positively charged hydrogen ions and Al³⁺, contributing to the ability of soil to buffer changes in pH. Higher levels of soil organic matter, such as that found in no-till systems, can potentially help offset Al toxicitiy (Brown, 2008; Berggren and Mulder, 1995, Conyers, 1990). No relationship was seen between

soil pH and DTPA Mn at either site, despite the commonly identified negative association between the two soil properties (Edwards and Beegle, 1988; Li and Mahler, 1993; Blake et al., 1999). It is likely that the lack of relationship seen between these soil characteristics was the result of non-representative soil testing. The redox phase changes of Mn increase the challenge of obtaining representative values of the phytotoxic Mn²⁺ in soil that is plant available, particularly because during common soil sampling, handling, storage, and testing procedures, the soil is often wetted and dried, altering the native values of the original samples (Menzies, 2003; Gambrell, 1996). Complex relationships with microbes and other soil elements, such as Fe and Al, increase the challenge of identifying Mn toxicity through conventional soil testing (Menzies, 2003; Foy, 1984). Obtaining representative phytoxic values of soil Mn depends on methods of soil sampling, handling, and testing (Menzies, 2003; Hoyt and Nyborg, 1972).

Treatment with lime increased soil pH, and demonstrated ameliorative effects on soil properties associated with acidity, at both sites. Increasing pH corresponded to increases in base saturation and a reduction in KCl Al. Treatment differences were seen with soil Mn, however, a relationship between increased soil pH from application of lime and reduction in soil Mn was again less evident. This phenomenon may be attributed to weaknesses in the soil sampling, handling, and testing for Mn (Menzies, 2003). Inconsistent seasonal differences in expression of soil properties were most likely attributable to the Mediterranean climate patterns of the Palouse. Where lower soil moisture for fall sampling likely impacted the expression of pH and associated properties, compared to the spring sampling times. Soil pH is known to express seasonal fluctuations, which also may have an impact on the associated soil properties. Because of the susceptibility of Mn to redox processes, that also reflect soil moisture, it is expected that seasonal changes would also be seen with soil Mn.

The magnitude and depth of effect increased with increasing lime rate. Edwards and Beegle (1988) recommend a half-rate of lime, with the expectation that the limit of effectiveness is 5 cm within

two growing seasons. Soil sampling in their study was done in 5-cm depth increments, which could have led to a more pronounced response for the 0 to 5-cm depth after analysis than may be reflected in the field, due to sample mixing during collection and analysis. Conversely, in an Australian study, Conyers et al. (2003) recommended that an increased rate of lime should be applied with surface application than with conventional tillage. This practice would generate a stronger concentration gradient of the base material and facilitate more rapid movement to deeper depths, particularly in low rainfall cropping systems. The Wagga Wagga experimental station, where the study was conducted, receives 570mm of annual average precipitation, which is about 50 mm more than the rainfall at the higher-precipitation PCFS study site (Conyers, 2003). The same study found that surface-applied lime did not affect soil properties below the 10 cm depth after eight years.

Treatment effects were different between the sites. The differences are likely attributable to site differences between the soils and climate. Though the two sites are classified as the same series, their pedological and management history has resulted in the two soils reflecting different characteristics that influence their susceptibility to the ameliorative effects of liming. The Rockford site receives less rainfall than the PCFS site, but historic vegetative cover and management practices are probable contributors to the higher acidity at the site. The magnitude of lime impact at the Rockford site was greater than at PCFS (Table 1.1a, Table 1.1b, Table 1.2a, and Table 1.2b), suggesting that the pedology and management history have also resulted in a reduced buffering capacity at that site.

Because liming has not been standard practice on the Palouse, determining a recommended rate for lime application in either conventional or no-till systems has been a challenge because a reliable theoretical basis to base recommendations on has been absent for this cropping system. Lime rates used in this study reflected a cultural practice-based gradient of what local producers have been applying to their no-till systems if they are experimenting with a lime product for the first time (448 kg

ha⁻¹) and is largely based on the perceived economic trade-offs for the producer (Wegner, personal communication). Similar economic constraints were considered in the Conyers et al. (2003) study, which suggested weighing the benefits of quicker economic return and higher impact results gained from incorporating lime, versus the drawbacks of soil disturbance within a no-till system.

Impact of rate, material, and depth of effectiveness on remediating acidic soil properties, within two growing seasons, was inconsistent. Conventional liming programs associate smaller lime particle size and high purity with more effective soil response, which may help offset the higher costs associated with the product (Barber, 1984). At these field sites, we did not see a consistent difference between the fluid lime material compared to the sugar lime when equivalent rates of CaCO₃ were applied, during the two years of the study. Several cases showed one of the materials, applied at the same rate, being different than the control, while the same rate of the other material was not different than the control, or the other material. This phenomenon frequently occurred with the 2240 kg ha⁻¹ rate of both materials, and increased with depth. The most notable examples are from the spring of 2015 at PCFS with soil pH and Mn (Table 1.1a, Table 1.1b) and Spring 2015 at the Rockford site for soil pH, base saturation, Al and Mn. Looking at the lowest depth demonstrating treatment effect, at PCFS in Spring 2015, the 4 to 6-cm depth shows that the SL2240 treatment impact soil pH and Mn in a way that was statistically different than the control, but not from the FL2240 treatment, which was not different than the control at that depth. With all of the properties from that sampling point at the Rockford site, significant differences were seen at the 4 to 6-cm depth between FL2240 and the control, no difference was seen at that depth between the SL2240 treatment and the control, or from the FL2240 treatment. In a study to determine the influence of lime material on ameliorative effectiveness, Convers et al. (1996), found the biggest influence on liming reaction was lime particle surface area, the source of lime materials applied at comparable CCE levels, was less important in governing effectiveness of lime than

the material's solubility. However, the study acknowledged that after the first growing season the influence of type of material was minimal.

Godsey at al. (2007) found that the pH of surface soil to 7.5-cm depth was increased with a 1120 kg ha⁻¹ lime application after four years. The study was conducted in Kansas. The site was considered a low-rainfall cropping system because of receiving less than 1000mm of average annual precipitation. It is important to note that the Kansas study site (Godsey et al., 2007) receives more than double the rainfall of either Palouse study sites and is subject to different annual patterns. The Godsey et al. (2007) study compared pelletized lime to limestone and noted that material did not result in significant differences and concurred that lime movement downward from the soil surface is most affected by lime rate. Other studies of surface liming in no-till systems have found it to be a viable method of ameliorating soil acidity (Blevins et al., 1978; Caires et al., 2005). The studies where surface liming has been most effective are in no-till systems where the nitrogen-based fertilizers have historically been broadcast on the soil surface (Moschler et al., 1973; Godsey, 2007; Blevins, 1978) rather than a deep band application, as is common in the Palouse (Brown et al., 2008). The magnitude of acidification is determined by depth of placement of nitrogen fertilizers (Mahler and Harder, 1984), thus where nitrogen fertilizers have been broadcast applied to the soil surface, the most significant impacts of acidity were reflected on the soil surface. Studies conducted in no-till systems where fertilizer is broadcast applied to the soil surface do report the impact of acidity on soil characteristics throughout the surface 15-20cm of the soil profile (Moschler et al., 1973; Convers et al., 2003; Godsey et al., 2007; Caires et al., 2005; Blevins et al., 1978). One of the benefits of no-till systems is the organic matter deposition and accumulation, particularly at the soil surface. Organic matter increases the ability of soil to buffer changes in pH. Systems where nitrogen fertilizers are applied to the soil surface, will experience the benefits of this buffering layer in decreasing the rate of acidification experienced. In systems where the fertilizer is deep banded, and lime

is surface applied, the material must first encounter the high buffer capacity surface layer, then continue moving downward before ameliorative impact is seen at the acidic zone where the fertilizer has been continuously applied.

Reactivity of CaCO₃ is slow, driven not only by particle size, but also soil moisture and temperature (Havlin et al., 2013). Another suggestion by Conyers et al. (2003) to increase the effectiveness of lime application in low-input, low-precipitation, wheat-based systems, was to apply lime as early, before it is "needed" in rotation, as possible, to allow it ample time to react and penetrate to critical soil zones. This is particularly true in the Palouse cropping system with its Mediterranean climatic pattern, that will largely limit reactivity and movement of lime material during the growing season, because of low moisture content in the soil.

Fall applied lime in the Palouse should have the most exposure to cooler temperatures and moisture, and time before it is needed. However, this study indicates that even with fall application, and fine particle size, surface lime treatment may take several years to impact the acidity produced by deepbanded fertilizers. The most significant impacts on soil pH, base saturation, Al, and Mn, in depth and magnitude, was seen in the Spring of 2015, almost one and a half years after the lime material had been applied. The number of years and the rates where this would be most effective are still unknown.

Crop response to surface application of lime: Results

No significant differences from surface lime treatment were seen on yield, above-ground biomass, Tissue AI, or Tissue Mn in 2014 or 2015 (Table 1.3). In the 2014 crop year, chickpea biomass at the PCFS site ranged from 305 (control) to 346 (FL224) g m⁻², and canola biomass ranged from 285 (control) to 385 (SL2240) g m⁻². Tissue concentrations of AI in the chickpea biomass measured from 91.5 (SL448) to 104.3 (FL224) μ g g⁻¹. Measured tissue AI concentrations from the canola biomass ranged from
24.5 (FL224) to 48.5 (SL224) μ g g⁻¹. Biomass concentrations of Mn in 2014 ranged between 103.5 and 175 μ g g⁻¹ in chickpea and 46.8 to 92 μ g g⁻¹ in canola. Chickpea yield at the PCFS site was lowest with the SL2240 treatment at 1118 kg ha⁻¹, and highest with the FL1120 at 1694 kg ha⁻¹ (Table 1.3).

In the 2015 crop year, spring wheat biomass at the PCFS site ranged from 37 (control) to 64 (SL448) g m⁻², and lentil biomass at the Rockford site ranged from 14 (control) to 27 (FL448) g m⁻². Tissue Al in spring wheat measured from 21 (FL448) to 31.3 (control) μ g g⁻¹, tissue Al in lentil ranged from 70 (SL448) to 112.8 (SL2240) μ g g⁻¹. Tissue concentrations of Mn in spring wheat biomass ranged from 49 (SL2240) to 55.3 (control) μ g g⁻¹; in lentil the range was from 63 (SL448) to 102.5 (control) μ g g⁻¹. Spring wheat yield in 2015 ranged from 2006 (control) kg ha⁻¹ to 3063 (FL448) kg ha⁻¹ (Table 1.3). Spring wheat protein measured from 126.0 (FL 448) to 147.5 (FL2240) g kg⁻¹, and test weight ranged from 68.69 (FL2240) to 72.56 (FL448) kg hL⁻¹ (data not shown).

Crop response to surface application of lime: Discussion

Mechanical incorporation of lime materials into Palouse soils has resulted in increased crop yield (Bezdicek et al., 2003). In 1985, Mahler and McDole found that incorporating 4400 kg ha⁻¹ of lime to a depth of 15 cm, increased crop yields of both cereal and pulse crops. However, to date, surface application of lime in no-till studies in the Palouse have not shown an increase in crop yield (Brown, 2008). Studies in other regions found that surface liming can remediate acidic soil conditions and increase crop yield. Moschler et al., (1973) found that surface application of lime to no-till soils increased crop yield beyond the yield increase attained by incorporating lime, the researchers attributed this outcome to increased water use efficiency resulting from lime application. Lollato et al., (2013), found drought conditions enhanced differences in wheat growth as a result of liming, with liming treatment increasing crop yield. Edwards and Beegle (1978) found corn yields increased numerically, but

values were not statistically significant in two crop years following lime application. In the same study a reduction in plant tissue Mn was found with lime treatment, but tissue Al was not affected. Caires et al., (2005) found that net grain yield of corn, soybean, and wheat was increased by surface liming, with wheat experiencing the most benefit from liming. The study indicates that the response of wheat to lime may have also been associated with precipitation patterns during the crop year.

Low precipitation and a hot summer in 2015 created drought conditions that reduced wheat yields throughout Whitman county (Washington State University- Ag Weather Net, 2015; Tweedy, 2015), particularly in the spring wheat crop. Drought conditions may have masked any potential treatment differences by enhancing the inherent heterogeneity of the field site. By spring of 2015, when the spring wheat was seeded, the deepest level of effect where the surface liming treatment was seen was 4-6 cm. A treatment effect was seen on soil pH and Mn. These effects and their magnitude may not have provided an ameliorative impact for increasing crop yield. This could be attributable to insufficient vertical movement or the properties affected not being the main drivers of crop response.

Phytotoxic elements in plant tissue and crop response: Results

Tissue Al was negatively correlated to Tissue Mn (R^2 =-0.3) (Table 1.4) in the 2014 garbanzo crop at PCFS. In the 2015 spring wheat crop at the PCFS site no significant relationship was seen between the two variables. At the Rockford site a positive correlation between Tissue Al and Tissue Mn was seen in both canola (R^2 =0.79), and lentil (R^2 =0.43) (Table 1.4). A negative correlation was seen between Tissue Mn and above ground biomass in chickpea (R^2 =-0.54), canola (R^2 =-0.63), and lentil (R^2 =-0.57) (Table 1.4), but no relationship was seen with spring wheat biomass. A positive relationship was seen between Tissue Al and above ground biomass in chickpea (R^2 =0.35) and spring wheat (R^2 = 0.86) (Table 1.4) at the PCFS site. At the Rockford site, Tissue Al showed a negative relationship with canola biomass (R^2 =-0.48)

and no significant relationship with biomass. In the 2015 spring wheat crop at PCFS, Tissue Mn (R^2 =-0.4) and Tissue AI (R^2 =-0.69), (Table 1.4) were shown to negatively affect crop yield. In the 2014 chickpea crop above-ground biomass had a positive correlation with yield (R^2 =0.34), however in the 2015 spring wheat crop, a negative correlation was seen between biomass and yield (R^2 =-0.48) (Table 1.4).

Phytotoxic elements in plant tissue and crop response: Discussion

The relationships seen between Tissue AI and above-ground biomass were distinctly different between the two sites. The Rockford site had much higher levels of soil AI than the PCFS site (Table 1.1b, Table 1.2b), increasing the amount of AI available to the plant. The canola and lentil crops may also be more sensitive to soil AI, especially compared to the spring wheat variety 'Louise' that was grown at the PCFS site in 2015, which has a medium level (3) AI tolerance rating (Koenig et al., 2011). There is a range of physiological differences in AI tolerance between plant species, and even cultivars within species (Foy, 1984; Menzies, 2003; Kochian et al., 2015). The mechanisms of tolerance also vary widely, with some plants excluding AI from their roots with excretions of organic acids, while others, sequester AI in root tissue, and sometimes in above ground tissues (Foy, 1984; Menzies, 2003; Kochian et al., 2015). However, in almost all plants, AI is not easily translocated within the above-ground tissue, because of its mechanisms of phytotoxicity (Marschner, 2012). Because AI is not readily translocated within the plant, Tissue AI testing is not the most common indicator of AI toxicity, which is most commonly diagnosed by assessing impact on root structures for thickened, stunted, and discolored characteristics (Menzies, 2003).

Aboveground Mn toxicity is more commonly visibly expressed than Al toxicity symptoms, which often affect the crop by affecting roots in a less discernable way. Mn toxicity is expressed by leaf chlorosis, necrosis, and puckering (Figure 1.4). Manganese is more mobile in plant tissue than Al

(Marschner, 2012), thus, analysis of tissue Mn has been shown to be a stronger indication of the presence of Mn toxicity issues than soil analysis of Mn. Manganese toxicity is expressed in many crops as soil pH decreases below 5.5; while both Mn and Al toxicity often occur at soil pH below 5.0 (Menzies, 2003). Higher concentrations of Tissue Mn, was correlated to reduced biomass production in all crops except spring wheat. The reduction in above-ground biomass corresponding to increasing levels of Tissue Mn, could also correspond to yield reduction. However, levels of Mn in the plant tissue were below indication of toxicity (>250 μ g g⁻¹) for wheat or soybean (*Glycine max*) (Schulte and Kelling, 1999). Higher biomass resulted in higher yield in chickpeas in 2014. Precipitation patterns during the 2015 crop year may have resulted in a "haying-off" effect in the spring wheat crop, explaining the negative relationship seen between biomass and yield for that crop year (Brown et al., 2015). The complexity of interaction between soil factors that influence Mn availability and the genetic factors across crops and cultivars that influence a plant's susceptibility to Mn toxicity, have made it challenging for researchers to determine absolute values for Mn toxicity thresholds (Fernando and Lynch, 2015). Manganese toxicity in plants depends on total soil Mn, soil pH, organic matter, temperature, redox conditions that can increase availability of the phytotoxic form Mn²⁺, and competing elements in the soil (Fernando and Lynch, 2015; Foy, 1984). Like Al, a crop's susceptibility to Mn toxicity is dependent on crop species, tolerance mechanisms, and a range of tolerance between cultivars of the same species (Fernando and Lynch, 2015; Moroni et al., 2003). Toxic levels of soil Mn can also be detrimental to the rhizobia symbionts of legume crops, inhibiting nutrient uptake and thereby crop performance (Foy, 1984). Mn toxicity has been identified in other parts of Washington state (Jackson, 1984), though studies regarding soil acidity impacts in the Palouse region have largely overlooked the relationship between soil and tissue Mn and crop response. Reducing conditions that may be brought on by the wet conditions of the spring moisture regime of the Palouse, could contribute to Mn toxicity early in crop development when

a crop might be more susceptible to the negative impacts of the element and have less robust root structure to overcome the toxicant. In Palouse soils, Mn concentrations have been shown to increase with decreasing pH (Li and Mahler, 1993). Because of the complex relationships that can buffer the impact of phytotoxic Al in the soil, in some situations, Mn can surpass Al as the primary plant toxicant in soil (Bouman et al., 1995). Surface application of lime has been shown to reduce soil (Table 1.1b, Table 1.2b) and tissue concentrations of Mn within three years of application (Mahli et al., 1998).

Soil characteristics and crop response: Results

PCFS site

In 2014, chickpea tissue Mn was explained (R²=0.68) by Mn at 2-4 cm, base saturation and soil pH at the 8 to 10-cm depth, and pH at the 0 to 2-cm depth (Table 1.5). Tissue Al in chickpea is related (R²=0.24) to pH at depth 2-4 cm and Al at depth 0-2 cm. Chickpea biomass was explained (R²=0.82) by KCl Al from 0 to 6 cm, soil pH from 2 to 6-cm, and base saturation from 0-4 cm. Chickpea yield can be explained (R²=0.56) by KCl Al at the 2-4 and 6-8 cm depths, base saturation at the 0-2 and 6-8 cm depths, and soil pH at 6-8 cm.

In 2015, spring wheat tissue Mn was explained (R^2 =0.35) by soil pH and KCl extractable Al at the 8-10 cm depth. Tissue Al was explained (R^2 =0.90) by soil pH from 0-4 cm and 8-10 cm, base saturation from 0-8 cm, and soil Mn at the 6-8 cm depth. Spring wheat biomass was explained (R^2 =0.42) by soil Mn and pH at the 8-10 cm depth. Spring wheat yield was explained (R^2 =0.69) by soil pH from 6-10 cm, base saturation and soil Mn at 8-10 cm.

Rockford site

In 2014, canola tissue Mn can be explained (R²=0.45) by base saturation at depths 4-6 and 8-10 cm, KCl Al at 2-4 cm, and soil Mn at 4-6 cm (Table 1.6). Tissue Al in canola for 2014 had no significant results from the stepwise multi-variate analysis. Canola biomass in 2014 was explained (R²=0.39) by Al at the 0-2 cm depth and Mn at the 6-8 cm depth.

In 2015, lentil tissue Mn was explained (R²=0.85) by soil pH at depths 0-2 and 8-10cm, KCl Al from 0-4 cm, base saturation from 0-4 cm, and soil Mn at 2-4 cm. Lentil tissue Al was described (R²=0.96) by base saturation at 0-4 and 6-10 cm, soil Mn from 2-6 cm and 8-10 cm, KCl Al at 2-4 and 8-10 cm, and soil pH at 0-2 cm. Lentil biomass was explained (R²=0.85) by KCl Al from 0-4 cm, base saturation from 0-4 cm, soil pH at 0-2 and 8-10 cm, and soil Mn at 2-4 cm.

Soil characteristics and crop response: Discussion

Yield is often used as a prominent metric of crop performance; however, crop biomass, tissue Mn, and tissue AI can be related to yield (Table 1.4). Using a stepwise multivariate analysis on this dataset contributes to an increased understanding of which soil attributes and at which depths, are driving various crop responses. This information can then be used to inform further soil sampling and testing for key soil acidity attributes that affect crop performance in the iPNW. Stratified soil sampling, to capture the influence of soil acidity on key soil attributes likely has more significant implications within no-till systems where nutrients and acidity are known to be stratified (Neugschwandtner et al., 2014; Karlen et al., 1991; Brown et al., 2008).

The results indicate that crop performance indicators are affected by various soil attributes at different depths, and each one demonstrates different levels of predictive capability. The predictive variables, depths, and capacity, also varies by crop. With surface application of lime, the surficial

variables expressed, may serve as a proxy for treatment effects, or an explanation of why treatment effects may not have been seen. In the case of this study, spring wheat yield variability was best explained by soil pH at the 6 to 10-cm depth, and soil Mn at the 8-10-cm depth. No significant effects from the surface application of lime materials were seen on soil properties at these depths, two years after application (Table 1.1a, Table 1.1b). These factors are likely contributors to why no treatment effect was measured on crop yield within the two years of the study (Table 1.3).

This method of analysis could be combined with studies of root structure, microbial communities, and nutrient uptake, leading to an increased understanding of the impact on crop performance by nutrients, phytotoxicants, and other soil properties, at key points in the rooting zone of the soil profile. Understanding the relationship between these key zones where acidic properties influence crop responses, could inform future modeling and precision liming or fertility management strategies. The practice of deep-band fertilizer placement common in the region alters the pH and nutrient stratification patterns under no-till systems compared to those that apply nutrients to the soil surface. Remediation of stratified soil acidity in the no-till systems of the iPNW may be best addressed by lime placement below the soil surface to target key affected zones that are most impacting crop production. Understanding trends of where these zones may be, for particular crops, and crop response parameters, may improve the effectiveness of regional soil acidity remediation strategies.

Conclusions

With appropriate lime rates and more time, an ameliorative effect from the surface application of lime materials may be seen throughout the top 10 cm of the soil profile. No effects were seen from the treatment on crop response. Analysis suggests the lack of crop response in the two years of the study, may be a result of the ameliorative effects from lime not reaching zones of key influence on crop

performance as indicated by multivariate analysis. The lack of crop response could also be attributed to tolerance by crops grown, uncharacteristic crop years, and high variability within the field sites. Crop limiting aluminum toxicity remains a challenge to identify, both in soil solution and from tissue samples. Manganese phytotoxicity may be a stronger limiting factor in Palouse systems than has previously been recognized. Understanding which soil properties are driving crop responses, and that they are different for each crop, as well as which parts of the root zone have the biggest impact on crop response can be a useful next step in understanding soil acidity and liming on Palouse soils.

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		PCFS Soil	рН				PCFS Site	e Base Satu	ration	
		Spring 20	14				Sp	oring 2014		
		D	epth (cm)				D	epth (cm)		
Treatment ⁺	0-2	2-4	4-6	6-8	8-10	0-2	2-4	4-6	6-8	8-10
0	5.19c	4.78	4.82	4.94	5.05	64.78c	60.21	63.13	68.18	65.20
FL224	5.33c	4.89	4.90	5.00	5.13	63.89c	61.09	64.08	65.08	66.70
FL448	5.73b	5.07	4.93	5.07	5.17	69.34b	61.28	62.03	62.48	62.28
SL448	5.57b	5.03	4.92	4.99	5.17	63.82c	59.87	56.59	61.81	62.33
FL1120	6.01ab	5.13	5.05	5.15	5.22	72.32b	62.89	63.62	65.09	65.40
FL2240	6.53a	5.12	4.90	5.07	5.24	77.51a	64.39	64.39	67.68	66.88
SL2240	6.57a	5.04	4.90	5.06	5.16	75.44ab	61.97	59.98	62.57	64.46
		Fall 201	4					Fall 2014		
0	5.62c	5.00c	4.90b	4.85	4.95	68.98c	65.29c	63.74b	64.66ab	67.65
FL224	5.86c	5.21c	4.98ab	4.88	4.98	70.07c	65.29c	65.13b	62.73ab	67.00
FL448	6.22b	5.42c	5.14ab	4.97	4.98	77.37b	70.75bc	65.45b	63.60ab	65.71
SL448	6.34bc	5.40c	5.06ab	4.90	4.95	75.95bc	68.50c	62.30c	60.66b	63.96
FL1120	6.77ab	5.66ab	5.21ab	5.03	5.04	79.37b	71.33bc	65.19b	65.23ab	64.20
FL2240	6.91a	6.18a	5.44a	4.99	5.05	85.29ab	82.56a	70.50a	66.93a	68.30
SL2240	7.06a	6.03ab	5.37ab	4.99	4.93	89.42a	77.97ab	69.30ab	66.98a	67.04
		Spring 20	15				Sp	oring 2015		
0	5.36c	5.03c	4.84b	4.77	4.77	68.18c	62.24b	61.21	62.80	64.43
FL224	5.45c	5.08c	4.87ab	4.74	4.84	67.55c	62.87b	60.71	62.62	66.34
FL448	5.89bc	5.27bc	5.08ab	4.90	4.91	70.17bc	64.12b	62.40	60.31	62.72
SL448	5.79bc	5.30b	4.94ab	4.83	4.84	68.33c	65.16b	59.26	58.27	62.86
FL1120	6.23ab	5.63b	5.09ab	4.90	4.93	75.01b	70.06ab	65.14	63.27	64.85
FL2240	6.68a	6.02a	5.22ab	4.91	4.89	80.28a	74.96a	65.96	63.32	65.97
SL2240	6.65a	6.14a	5.31a	4.94	4.90	83.26a	74.67a	66.93	62.12	64.28

Table 1.1a. Response of soil properties, soil pH and base saturation to surface-applied lime treatments (Fall 2013) at PCFS site (Pullman, WA).

		PCF	S Site KCl	Al		Ē	PCFS S	ite DTPA N	In	
		Sp	oring 2014	Ļ			Spi	ring 2014		
		D	epth (cm)				De	pth (cm)		
Treatment ⁺	0-2	2-4	4-6	6-8	8-10	0-2	2-4	4-6	6-8	8-10
0	5.25b	21.75	26.00	14.50	6.50	53.70c	58.15	49.98	47.18	44.18
FL224	1.75ab	20.00	20.50	11.50	6.25	58.10bc	58.35	46.28	55.03	46.78
FL448	1.00a	8.75	14.25	7.50	2.50	55.35bc	51.63	58.00	36.98	26.73
SL448	0.75a	7.75	15.50	11.25	4.50	48.85b	44.53	50.70	43.78	47.83
FL1120	0.75a	6.50	11.00	8.25	4.25	47.10abc	53.45	50.10	48.80	44.05
FL2240	0.50a	7.50	15.75	8.00	3.75	56.05a	42.05	56.38	42.33	51.20
SL2240	1.00a	5.75	12.75	8.50	3.50	51.83a	61.28	50.33	48.18	57.18
		l	all 2014				F	all 2014		
0	2.25b	16.25	35.50	46.50	32.00	33.83	37.95b	31.30	32.00	41.43
FL224	1.00ab	11.00	24.25	33.75	20.25	37.55	36.05ab	30.18	32.93	41.28
FL448	0.75a	1.50	9.50	23.25	21.25	36.93	36.10a	31.05	24.45	29.65
SL448	0.50a	1.50	12.00	25.75	19.25	34.93	22.40a	37.30	26.73	32.00
FL1120	0.50a	1.25	8.25	13.75	14.50	30.90	38.38a	32.65	28.75	41.58
FL2240	1.00a	0.00	6.75	29.25	20.00	39.08	28.08a	33.18	28.73	29.65
SL2240	0.75a	0.75	7.25	23.25	22.25	32.28	32.80a	33.95	30.75	27.65
_		Sp	oring 2015	5			Spi	ring 2015		
0	2.00	10.50	31.50	45.00	34.50	24.05c	21.78c	26.35b	18.43	23.95
FL224	6.50	18.00	28.00	39.25	25.75	26.65c	26.75c	22.80ab	24.40	24.38
FL448	1.00	2.75	13.00	27.75	21.75	26.03c	20.05bc	24.20ab	21.50	20.13
SL448	0.75	1.75	15.00	27.75	21.50	28.73bc	22.23b	23.20ab	24.38	22.70
FL1120	0.75	0.75	8.00	18.25	16.25	23.35ab	25.75ab	20.53ab	22.98	22.45
FL2240	1.00	0.00	5.00	23.25	24.75	29.85a	24.03a	26.58ab	22.43	21.70
SL2240	1.00	0.25	5.25	21.00	19.25	26.30a	25.68a	25.13a	21.78	21.20

Table 1.1b.	Response of soil properties, KCl Al and DTPA Mn, to surface-applied lime treatments
	(Fall 2013) at PCFS site (Pullman, WA).

	Rockf	ord Site S	oil pH			R	ockford Sit	e Base Sat	uration	
	S	pring 201	4				Spi	ring 2014		
		De	oth (cm)				De	pth (cm)		
$Treatment^{\dagger}$	0-2	2-4	4-6	6-8	8-10	0-2	2-4	4-6	6-8	8-10
0	4.41b	4.33	4.41	4.54	4.83	42.98c	38.03	35.64	38.23	44.56
FL224	4.50b	4.31	4.27	4.36	4.59	47.20c	38.88	33.70	36.46	41.30
FL448	4.64ab	4.33	4.33	4.48	4.66	54.38c	44.79	40.54	42.11	51.28
SL448	4.57b	4.27	4.28	4.38	4.50	53.10c	41.02	36.58	35.36	41.21
FL1120	4.81ab	4.29	4.30	4.39	n.a.	58.48bc	37.89	32.20	29.33	38.87
FL2240	4.98a	4.50	4.45	4.58	4.51	73.21a	46.80	44.19	46.92	54.12
SL2240	4.93ab	4.34	4.28	4.39	4.47	71.63ab	39.11	34.94	35.57	40.55
		Fall 2014					Fa	all 2014		
0	5.28c	4.53	4.29	4.29	4.33	54.52c	41.04c	37.21	37.40	40.14
FL224	5.25c	4.54	4.23	4.22	4.28	57.38c	42.75c	38.71	40.03	41.79
FL448	5.63b	4.74	4.32	4.29	4.38	62.93bc	47.10bc	41.27	40.34	40.35
SL448	5.55bc	4.58	4.42	4.19	4.25	62.22b	45.87c	38.14	36.83	39.01
FL1120	5.93bc	4.68	4.26	4.19	4.25	71.60ab	47.88ab	39.66	37.71	40.29
FL2240	6.52a	4.89	4.47	4.35	4.42	74.28a	51.25a	46.70	43.83	46.86
SL2240	6.53a	4.70	4.30	4.22	4.24	76.63a	45.73a	38.53	33.32	35.28
	S	pring 201	5				Spi	ring 2015		
0	5.12d	4.55c	4.40b	4.35	4.36	53.66c	40.21b	36.29ab	36.37	38.01
FL224	5.18d	4.58bc	4.39b	4.31	4.31	54.77c	40.77b	35.33b	33.86	35.66
FL448	5.47c	4.67bc	4.45ab	4.38	4.42	63.24b	45.32ab	40.96ab	39.77	39.37
SL448	5.25cd	4.53c	4.33b	4.27	4.31	58.35b	40.89b	35.39b	33.71	34.89
FL1120	5.78b	4.80b	4.47ab	4.37	4.34	65.98ab	47.18ab	39.68ab	35.44	34.88
FL2240	6.26a	5.05a	4.63a	4.45	4.42	78.91a	56.61a	45.95a	41.74	41.54
SL2240	6.40a	4.99a	4.49ab	4.33	4.30	77.63a	50.24ab	39.17ab	33.83	34.80

Table 1.2a. Response of soil properties, pH and base saturation, to surface-applied lime treatments (Fall 2013) at Rockford site (Rockford, WA).

	R	ockford Sit	e KCI Al				Rock	ford DTPA	Mn	
		S	pring 2014				S	pring 2014		
		[Depth (cm)				0	Depth (cm)		
Treatment ⁺	0-2	2-4	4-6	6-8	8-10	0-2	2-4	4-6	6-8	8-10
0	65.50c	137.25	156.50	141.75	115.50	79.45	67.10	78.10ab	76.85	64.38
FL224	42.75bc	117.50	170.25	165.50	125.00	80.50	78.45	69.53ab	69.88	55.68
FL448	28.00bc	101.75	134.25	131.00	108.00	79.90	74.53	75.88ab	59.25	73.28
SL448	32.75bc	133.75	173.25	176.25	144.00	75.00	66.93	68.03b	69.18	64.88
FL1120	12.00ab	114.75	159.50	172.50	137.75	75.38	55.40	73.78ab	64.58	54.33
FL2240	2.00ab	69.75	119.00	107.25	72.50	70.20	62.73	73.53a	57.35	66.30
SL2240	3.25ab	108.75	177.00	180.25	145.50	76.23	79.58	69.33a	70.78	68.95
			Fall 2014							
0	16.50	115.75b	160.00	171.25	171.00	48.78	50.38	63.88	48.45	52.50
FL224	14.25	96.50b	132.00	151.00	138.50	59.28	66.30	53.23	57.18	40.78
FL448	2.50	59.75ab	99.25	118.75	105.00	51.18	53.23	66.33	49.43	47.38
SL448	3.00	82.50ab	114.25	164.75	160.00	54.15	73.03	56.63	56.00	47.95
FL1120	2.50	58.50ab	128.25	161.75	145.00	54.18	62.95	52.65	64.35	41.68
FL2240	12.25	30.00a	85.50	118.00	115.75	47.65	50.80	55.90	50.73	54.78
SL2240	1.25	62.25ab	125.50	161.75	167.50	50.35	85.08	94.35	33.08	56.45
		S	pring 2015				S	pring 2015		
0	11.00b	82.25c	136.75b	162.25	158.25	39.60	57.93b	65.48b	35.35	50.18
FL224	6.50ab	77.50c	135.25b	162.00	156.75	49.75	48.08ab	49.53b	62.68	58.48
FL448	2.75a	56.75b	108.50ab	138.75	126.25	49.25	45.90ab	55.28ab	49.50	53.23
SL448	5.25ab	83.00c	142.50b	176.50	167.75	53.20	34.73ab	47.73ab	65.78	56.08
FL1120	2.50a	38.50ab	111.50ab	152.00	160.50	48.55	38.03ab	57.73ab	43.20	53.98
FL2240	1.50a	15.00a	69.00a	116.25	116.75	40.00	45.03a	53.75a	45.73	51.53
SL2240	3.00a	17.50a	103.00ab	162.75	181.50	42.10	57.60ab	52.60ab	71.63	51.85

Table 1.2b. Response of soil properties, KCl Al and DTPA Mn, to surface-applied lime treatments (Fall 2013) at Rockford site (Rockford, WA).



Figure 1.1a,b,c,d,e,f,g,h. Relationships between soil pH and key soil properties associated with acidity across all depths of the unlimed control treatments (soil organic matter, KCl extractable Al, DTPA extractable Mn, base saturation (BS))



Figure 1.2a,b. Relationship between KCI Extractable AI and soil organic matter at two sites in the spring of 2015.



Figure 1.3a,b. Relationship between KCl Extractable Al and base saturation at two sites in the spring of 2015

$Treatment^{\dagger}$	Above Ground Tissue Mn	Above Ground Tissue Al	Above Ground Biomass	Grain Yield
		ug g ⁻¹	g m ⁻²	kg ha⁻¹
	(Chickpea 2014, PCF	-S	
0	175.0	92.0	305	1350
FL224	139.8	104.3	346	1354
FL448	120.3	92.8	336	1527
FL1120	137.3	94.8	324	1694
FL2240	132.3	93.0	344	1369
SL448	120.0	91.5	342	1437
SL2240	103.5	97.3	330	1118
	Spi	ring Wheat 2015, P	PCFS	
0	55.3	31.3	37	2006
FL448	49.8	21.0	59	3063
FL2240	49.3	24.3	63	2337
SL448	49.8	22.8	64	2574
SL2240	49.0	30.3	50	2505
	Can	ola 2014, Rockford	l site	
0	69.0	35.3	285	n.a.
FL224	64.0	24.5	352	n.a.
FL448	52.8	30.3	381	n.a.
SL448	92.0	48.5	312	n.a.
FL1120	77.8	35.5	358	n.a.
FL2240	58.0	31.8	346	n.a.
SL2240	46.8	25.3	385	n.a.
	Ler	ntil 2015, Rockford	site	
0	102.5	104.8	14	n.a.
FL448	64.3	101.3	27	n.a.
SL448	63.0	70.0	24	n.a.
FL2240	70.8	80.5	26	n.a.
SL2240	90.0	112.8	16	n.a.

Table 1.3. Crop response to treatment with surface applied lime (Fall 2013) at two sites over two crop years.

		Chickpe	as 2014			Spring Whe	eat 2015	
			Above				Above	
	Tissue		Ground	Grain			Ground	Grain
	Mn	Tissue Al	Biomass	Yield	Tissue Mn	Tissue Al	Biomass	Yield
Tissue Mn		1 -0.3*	-0.54**	ns	1	ns	ns	-0.4*
Tissue Al		1	0.35*	ns		1	0.86***	-0.69**
Biomass			1	0.34***			1	-0.48**
Yield				1				1
		Canola 2014	1			Lentil 2015		
			Above				Above	
	Tissue		Ground	Grain			Ground	Grain
	Mn	Tissue Al	Biomass	Yield	Tissue Mn	Tissue Al	Biomass	Yield
Tissue Mn		1 0.79***	-0.63**	n.a.	1	0.43*	-0.57**	n.a.
Tissue Al		1	-0.48**	n.a.		1	ns	n.a.
Biomass			1	n.a.			1	n.a.
*** ~0 0001					•			

Table 1.4. Pearson correlations among tissue Al, tissue Mn, biomass and yield.

** <0.05

*<0.1

							Chickpe	eas 2014							
	Tissu	e Mn			Tissu	ie Al			Bion	nass			Yie	ld	
Variable	Depth	Model	P-	Variable	Depth	Model	P-	Variable	Depth	Model	P-	Variable	Depth	Model	P-
		R ²	value			R ²	value			R ²	value			R ²	value
Al	4-6	0.51	<.0001	рН	2-4	0.13	0.046	Al	4-6	0.49	<.0001	Al	6-8	0.27	0.0023
Mn	2-4	0.59	0.0274	Al	0-2	0.24	0.042	Al	2-4	0.56	0.051	BS	0-2	0.36	0.0540
BS	8-10	0.63	0.0925					рН	2-4	0.67	0.004	Al	2-4	0.43	0.0737
рН	8-10	0.67	0.0731					рН	4-6	0.74	0.0145	BS	6-8	0.51	0.0525
-Al	4-6	0.65	0.1725					BS	0-2	0.77	0.0676	рН	6-8	0.56	0.0829
рН	0-2	0.68	0.1393					Al	0-2	0.8	0.0920				
								BS	2-4	0.82	0.0925				
								L				L			

 Table 1.5. Stepwise multiple regression for crop response and soil variables at PCFS site (Pullman, WA).

 Chickness 2014

Spring Wheat 2015

	Tissu	e Mn			Tissu	ie Al			Bion	nass		Yield			
Variable	Depth	Model	P-												
		R ²	value												
рН	8-10	0.26	0.0221	рН	8-10	0.21	0.0443	AI	2-4	0.16	0.0776	рН	8-10	0.44	0.0014
Al	8-10	0.35	0.1374	BS	0-2	0.43	0.0205	Mn	8-10	0.28	0.1192	BS	8-10	0.62	0.0106
				рН	0-2	0.57	0.0374	рН	8-10	0.45	0.0424	Mn	8-10	0.69	0.0918
				Mn	8-10	0.63	0.1466	-Al	2-4	0.42	0.3779	рН	6-8	0.73	0.1420
				рН	2-4	0.7	0.0851					-BS	8-10	0.69	0.1773
				BS	2-4	0.76	0.0896								
				BS	4-6	0.83	0.0396								
				BS	6-8	0.87	0.0983								
				Mn	6-8	0.9	0.1297								
				Mn	8-10	0.9	0.8945								

				Canola	2014					
Tissu	e Mn			Tissu	e Al			Bior	mass	
Depth	Model R ²	P-value	Variable	Depth	Model R ²	P-value	Variable	Depth	Model R ²	P-value
2-4	0.18	0.0466		n	S		Al	0-2	0.22	0.0245
4-6	0.26	0.1452					Mn	6-8	0.39	0.0272
4-6	0.38	0.0727								
8-10	0.45	0.1319								
				Lentil	2015					
Tissu	e Mn			Tissu	e Al			Bior	nass	
Depth	Model R ²	P-value	Variable	Depth	Model R²	P-value	Variable	Depth	Model R²	P-value
8-10	0.34	0.0075	Mn	2-4	0.17	0.0731	рН	8-10	0.34	0.0075
0-2	0.46	0.0698	BS	0-2	0.45	0.0082	Al	0-2	0.46	0.0698
2-4	0.59	0.0401	рН	0-2	0.62	0.0202	Al	2-4	0.58	0.0401
0-2	0.69	0.0379	Mn	8-10	0.77	0.0055	рН	0-2	0.69	0.0379
0-2	0.75	0.0923	Al	2-4	0.83	0.0443	BS	0-2	0.75	0.0923
2-4	0.81	0.0701	Mn	4-6	0.87	0.0840	BS	2-4	0.81	0.7010
2-4	0.85	0.0834	BS	6-8	0.89	0.1486	Mn	2-4	0.85	0.0834
			BS	8-10	0.91	0.1306				
			Al	8-10	0.94	0.0884				
			-BS	6-8	0.92	0.1785				
			BS	2-4	0.96	0.0086				
	Tissue Depth 2-4 4-6 8-10 Tissue Depth 8-10 0-2 2-4 0-2 0-2 2-4 2-4 2-4	Tissue Mn Depth Model R ² 0.18 2-4 0.18 4-6 0.26 4-6 0.38 8-10 0.45 Tissue Mn Depth Model R ² 0.34 0-2 0.34 0-2 0.46 2-4 0.59 0-2 0.69 0-2 0.75 2-4 0.81 2-4 0.85	Issue Mn Depth Model P-value R ² 0.18 0.0466 4-6 0.26 0.1452 4-6 0.38 0.0727 8-10 0.45 0.1319 Provide Margina Model Bepth Model P-value R ² 0.45 0.1319 Bepth Model R ² 0.45 0.00751 O-2 0.34 0.00751 0-2 0.46 0.0401 0-2 0.69 0.0379 0-2 0.69 0.0379 0-2 0.75 0.0923 2-4 0.85 0.0834	Tissue Wn Variable Depth Model P-value Variable R ² 0.18 0.0466 Image: Constraint of the second	Canola Tissue Mn Tissue Depth Model P-value Variable Depth R ² 0.18 0.0466 n 4-6 0.26 0.1452 n 4-6 0.38 0.0727 n 8-10 0.45 0.1319 n Etentil Tissue Depth Model P-value Variable Depth Model P-value Variable Depth Besto 0.34 0.00755 Mn 2-4 0-2 0.46 0.0698 BS 0-2 0-2 0.69 0.0379 Mn 2-4 0-2 0.0923 Al 2-4 0-2 0.0923 Al 2-4 0-2 0.0923 Al 2-4 0-2 0.0923 Al 2-4 0-2 0.0834 BS 6-8 BS 8-10 <td>Canola 2014 Tissue Mn Fvalue Variable Depth Model R² 2-4 0.18 0.0466 R² ns R² 4-6 0.26 0.1452 ns ns 4-6 0.38 0.0727 ns ns 8-10 0.45 0.1319 ns ns Entert 100 Section 1000727 8-10 0.45 0.1319 ns ns Tissue Mn Entert 1015 Depth Model P-value Variable Depth Model R² ns ns ns ns Depth Model P-value Variable Depth Model R² </td> <td>Canola 2014 Tissue Mn rissue Al Depth Model P-value Depth Model P-value R^2 0.0466 Depth R² P-value 4-6 0.18 0.0466 ns R² 4-6 0.38 0.0727 ns ns 8-10 0.45 0.1319 </td> <td>Canola 2014 Tissue Wn Tissue Al Depth Model P-value Variable Depth Model P-value Variable 2-4 0.18 0.0466 ns</td> <td>Canola 2014 Tissue AI Bior Depth Model P-value Variable Depth Model P-value Rain 0.26 4-6 0.26 0.1452 0.1452 ns</td> <td>Canola 2014 Tissue AI Biomassi Model R² Simalization R² 2-4 0.18 0.0466 $Pertee R^2$ Al 0-2 0.22 4-6 0.26 0.1452 $Pertee R^2$ Al 0-2 0.22 4-6 0.38 0.0727 $Pertee R^2$ Mn 6-8 0.39 4-6 0.45 0.1319 $Pertee R^2$ Mn 6-8 0.39 Tissue N Tissue N Biomassi R² Depth Model Pervalue Model R² Depth Model Pervalue Pervalue Model R² 0.24 0.46 0.0075 Mn 2-4 0.17 0.0731 pH 8-10 0.34 0.24 0.46 0.0698 BS 0-2 0.622 Al 0.22 0.69 0.24 0.59 0.0401 pH 0-2 0.69</td>	Canola 2014 Tissue Mn Fvalue Variable Depth Model R ² 2-4 0.18 0.0466 R ² ns R ² 4-6 0.26 0.1452 ns ns 4-6 0.38 0.0727 ns ns 8-10 0.45 0.1319 ns ns Entert 100 Section 1000727 8-10 0.45 0.1319 ns ns Tissue Mn Entert 1015 Depth Model P-value Variable Depth Model R ² ns ns ns ns Depth Model P-value Variable Depth Model R ²	Canola 2014 Tissue Mn rissue Al Depth Model P-value Depth Model P-value R^2 0.0466 Depth R ² P-value 4-6 0.18 0.0466 ns R ² 4-6 0.38 0.0727 ns ns 8-10 0.45 0.1319	Canola 2014 Tissue Wn Tissue Al Depth Model P-value Variable Depth Model P-value Variable 2-4 0.18 0.0466 ns	Canola 2014 Tissue AI Bior Depth Model P-value Variable Depth Model P-value Rain 0.26 4-6 0.26 0.1452 0.1452 ns	Canola 2014 Tissue AI Biomassi Model R ² Simalization R ² 2-4 0.18 0.0466 $Pertee R^2$ Al 0-2 0.22 4-6 0.26 0.1452 $Pertee R^2$ Al 0-2 0.22 4-6 0.38 0.0727 $Pertee R^2$ Mn 6-8 0.39 4-6 0.45 0.1319 $Pertee R^2$ Mn 6-8 0.39 Tissue N Tissue N Biomassi R ² Depth Model Pervalue Model R ² Depth Model Pervalue Pervalue Model R ² 0.24 0.46 0.0075 Mn 2-4 0.17 0.0731 pH 8-10 0.34 0.24 0.46 0.0698 BS 0-2 0.622 Al 0.22 0.69 0.24 0.59 0.0401 pH 0-2 0.69

Table 1.6. Stepwise multiple regression for crop response and soil variables at the Rockford site (Rockford, WA).



Figure 1.4. Photo of canola from Rockford site, 2014. Leaf puckering is a symptom of Mn toxicity.

CHAPTER TWO: EVALUATION OF BUFFER TEST METHODS FOR ESTIMATING LIME REQUIREMENT ON PALOUSE REGION SOILS

Abstract

Anthropogenically accelerated soil acidification is an issue of increasing concern in the Palouse region of Eastern Washington and Northern Idaho. Interest in amelioration of acidic soil conditions is also increasing. Buffer tests can provide lime requirement estimates; however, appropriate tests and calibrations for the Palouse region are lacking. The objective of this study was to determine the buffer tests and calibrations that are most suitable for the agricultural soils of the Palouse. Ten major Palouse agricultural soils (0- to 15-cm composite; initial pH < 5.33) were incubated with nine levels of CaCO₃ for 90 days in the laboratory to assess changes in pH. The data indicated that achieving a target pH of 6 in the top 15 cm of the soil profile required 3.36 to 8.36 Mg ha⁻¹ of CaCO₃. Laboratory incubations were compared with conventional buffers: Shoemaker, McLean, and Pratt (SMP), Adams and Evans, Woodruff, and Woodruff 6 buffer tests, and two that do not require the use of hazardous materials, Sikora and Modified Mehlich. The Modified Mehlich (R²=0.90), Woodruff 6 (R²=0.78) and Woodruff (R²=0.75) buffers produced the strongest correlation between test results and the lime requirement produced by the incubation. The SMP (R²=0.47) and Adams and Evans (R²=0.56) demonstrated the lowest correlation with observed lime requirement. Palouse calibrations for each test were proposed. An alternative method for determining lime requirement of Palouse soils without buffer tests, was developed based on a multivariate analysis of soil test properties. Here, electrical conductivity, organic matter, KCl extractable Al, and base saturation explained a significant amount of the variability ($R^2=0.98$) in lime requirement. Evidence from this study demonstrates that the SMP and Adams and Evans buffers tests do not produce reliable lime requirement estimates for Palouse region soils. Suitable estimates can be provided by the Modified Mehlich and the Woodruff tests using regionally appropriate calibrations. Options that circumvent the need for buffer testing by using soil characteristics as the basis for

recommendation warrant further examination, particularly as their predictive capability may be better than buffer tests.

Introduction

Soil acidification, anthropogenically accelerated by application of ammoniacal fertilizers, and loss of base cations through leaching and removal with harvest, is an issue of increasing concern in the Palouse region of the Inland Pacific Northwest (iPNW). The Palouse region is often delineated as the Palouse River watershed, and is typified by rolling hills with deep soil profiles of wind-deposited silt loam loess (McDaniel and Hipple, 2010). Historically, the pH of Palouse soils was near neutral, having developed on the transition zone of the north-western Rocky Mountain front under native forest or prairie cover and xeric conditions (Daubenmier, 1970; Mahler et al., 1985; Bezdicek et al., 2003; Brown et al., 2008). Acidic conditions are found in this region on soils that largely reflect the characteristics of the Mollisol and Alfisol orders, rather than the properties associated with the typically acidic Ultisol and Oxisol soils. Management strategies commonly used to remediate acidic soil are applicable, but require locally relevant research and adaptation to increase relevancy for the Palouse region because of the difference in soil properties (Doerge and Gardner, 1988; Gavlak et al., 2005).

Lime application is the most common strategy for raising soil pH, increasing base saturation and neutralizing phytotoxic elements in soil (Sims, 1996). Identifying the ideal quantity of lime to apply can be a challenge for land managers. Each soil, even those with the same initial pH, will often have a unique lime requirement. McLean (1973) defines lime requirement (LR) as "the amount of liming material which must be applied to a soil to raise its pH from an initial acid condition to a level selected for near optimum plant growth." Crops have different soil pH requirements, and land managers have varying nutrient management goals; both are factors in determining an ideal target pH. A soil's buffering

capacity and acidity characteristics determine the quantity of lime required to move from the initial pH to an optimum pH.

Methods for determining soil lime requirement can be resource intensive and may include field testing, titration, laboratory incubations, or using measured soil properties to determine lime requirement (Sims, 1996). Often methods are combined for validation purposes. More commonly, a lime requirement estimate (LRE) is determined using a buffer test. Buffer tests are easier, cheaper, and allow high throughput testing, using buffered solutions designed to respond in a predictable way to acidity present in a soil. When mixed with an acidic soil, the pH of the buffer solution declines. Using the final buffer pH, LRE is calculated with formulas calibrated for the target pH and region.

Buffer tests common in the United States are the Shoemaker, McLean, and Pratt (SMP) (Shoemaker et al. 1961); Adams and Evans (Adams and Evans, 1962); Woodruff (Woodruff, 1948); and Mehlich (Mehlich, 1976) tests (Sims, 1996; Gavlak et al., 2005; Dietzel, 2009). The tests are best suited to the soils where they were developed. To produce the most effective LREs for use in alternate locations, regional screening of buffer tests and recalibration to local conditions are necessary (Dietzel et al, 2009; Doerge and Gardner, 1988). Regionally appropriate tests and calibrations are often determined by the soil pH response on local soils in laboratory incubations with calcium carbonate (CaCO₃) or calcium hydroxide (Ca(OH)₂). Often, this testing is performed on a statewide basis.

The pedology of Washington state is highly variable, ten of the twelve soil orders are represented throughout the state. With coastline, desert, rain forest, glaciers, plains and a prominent mountain range bisecting the state, affecting every component of soil formation; selecting a buffer test for the entire state is not an effective strategy. Eastern Washington shares the regionally characteristic

pedology of the Palouse across state lines with northern Idaho and northeastern Oregon (McDaniel and Hipple, 2010). In this case, it may be more appropriate to evaluate the applicability of buffer test procedures and produce local calibrations for the Palouse region than for the entirety of Washington state.

In a 1977 WSU technical bulletin, Baker and Chae recommended their modification to the SMP test as the most effective way to determine LREs for western Washington soils. In 1988, Mohebbi and Mahler published results from their evaluation of lime requirement tests recommending the Woodruff buffer test adjusted to pH 6, this work remains as the basis of lime requirement testing and recommendations in Northern Idaho. However, in practice, regional soil test labs use the SMP or the Adams and Evans method to determine LRE if it is requested. Increasing soil acidity in the Palouse region, development of new buffer tests and their success elsewhere, lack of adoption of Mohebbi and Mahler's (1988) recommendation, and increasing interest by land managers for LREs as they recognize soil pH decline, make it necessary to reassess the procedures for producing LREs for unique soils of the Palouse region.

One concern surrounding the use of buffer tests is that many contain hazardous materials. The commonly used SMP buffer contains both p-nitrophenol and chromate. These materials are a concern because of worker safety, excess wear on lab equipment and proper hazardous waste disposal. Alternative buffers that successfully mimic well established tests have been emerging. Alternative tests should minimize hazardous waste while maintaining or improving test accuracy. The Mehlich test developed by Hoskins and Erich (2008) replaces BaCl₂ with CaCl₂, and Sikora (2006) effectively replaces the p-nitrophenol and potassium chromate in the SMP method, with non-hazardous reagents while producing buffer pH values that consistently correlate with the original SMP test. Studies in several states including NY, MO, and WI have founs that these "green" buffer test options successfully replace

historically used hazardous buffer test methods (Dietzel et al.; 2009, Nathan et al., 2012; Laboski and Peters, 2006).

Researchers have used other soil properties such as base saturation (Canterella et al., 1998), CEC (Lemire et al., 2005), and soil texture (Miller et al., 2005) as a basis for predicting LR. Using these characteristics instead of a buffer test has the potential to eliminate additional hazardous waste, reduce the need for additional tests, and even predict LR more effectively than buffer tests.

The primary objective of this study was to determine the buffer test that provides the best estimate of lime requirement for Palouse soils. Completing the primary objective required the implementation of four subobjectives: i) determine pH response by ten prominent Palouse agricultural soils to increasing levels of calcium carbonate (CaCO₃) by performing a laboratory incubation; ii) generate LRE values using common buffer test methods and calibrations for comparison of best fit to the incubation LR values; iii) use values generated by the first two subobjectives to determine locallybased LRE calibrations; and iv) combine other measured soil characteristics to produce a LRE to determine if other analytical tests can produce accurate LRE values and bypass the necessity of buffer tests.

Materials and Methods

Soil Selection and Field Sampling

Ten agricultural soils from the Palouse region of Eastern Washington and Northern Idaho were selected from the USDA NRCS soil surveys of Spokane (1968), Whitman (1980), Columbia (1973), Latah area (1981) and Lewis (2004) counties. The selection was based on the extent and representative nature of mineral soils used for crop production in the region. Sites were selected for sample collection that were known to have soil pH values below 5.35 and from the soil series: Athena, Joel, Larkin, Naff, Palouse, Santa, Southwick, Taney, Thatuna and Walla Walla (Table 2.1). All sampling sites were in managed agricultural fields that had not been fertilized since the previous year. Collection occurred during late April and early May of 2014. Global positioning system (GPS) coordinates were recorded (Google Maps) for each of the sampled locations.

A hand-operated mud auger of 6.5-cm diameter and 30-cm length, was used to take 25 cores to a depth of 15 cm at the recorded GPS point. The cores were composited and kept cool until they reached the laboratory, where they were stored at 4°C. The samples were then passed through a 2-mm sieve and air dried.

Soil Characterization

The soils were characterized for: 1:1 water pH (Thomas, 1996), EC (Gavlak et al., 2005), KCl extractable AI (Bertsch and Bloomlm, 1996) and Walkley Black organic matter (Nelson and Sommers, 1996). Exchangeable base-forming cations (Ca, Mg, Na, K) and cation exchange capacity (CEC), were measured using NH₄OAc extraction (Gavlak et al., 2005). Base saturation was calculated by dividing the sum of the exchangeable bases by the measured CEC. Soil particle size was determined using the Malvern Mastersizer (1994).

Laboratory Incubation

Eight increasing levels of reagent-grade calcium carbonate (CaCO₃) and a control (0 applied CaCO₃) were used in a laboratory incubation: 0 Mg ha⁻¹, 0.448 Mg ha⁻¹, 1.12 Mg ha⁻¹, 2.24 Mg ha⁻¹, 4.48 Mg ha⁻¹, 6.72 Mg ha⁻¹, 8.96 Mg ha⁻¹, 11.2 Mg ha⁻¹, 22.4 Mg ha⁻¹. Soil (125 g) was weighed into clean, labeled, wide-mouth mason jars. Pre-weighed CaCO₃ representing each level, was added to each jar and mixed on a roller grinder (Purakayastha et al., 2009) for ten minutes. Ultra-pure deionized water was mixed mechanically with a spatula until the complete sample was wetted to achieve gravimetric field capacity, as determined by the 3.33 kPa designation in the soil survey for each series (USDA NRCS county soil survey: Spokane, 1968; Whitman, 1980; Columbia, 1973; Latah area, 1981; and Lewis, 2004).

Each sample was uniformly tamped to approximate a bulk density of 1.3 g cm⁻³, a typical value for Palouse soils. This procedure was replicated four times for each soil by rate combination. Each jar was then weighed to obtain a total weight of the jar and wetted sample and field capacity was maintained throughout the incubation. The jars of soil were incubated without lids, in covered plastic tubs, at 21°C for 90 days. At the end of 90 days, the incubation was terminated by each sample being passed through a 2-mm sieve and air dried at 24°C. Five grams of soil was weighed and 5 mL of ultra-pure water was added to the soil with a syringe, the sample was stirred for ten seconds and then allowed to stand for 30 minutes. Final soil pH was measured while stirring with a Denver Instrument model 250 pH ISE conductivity benchtop meter and an Accumet #13-62-631 saturated KCl-filled, glass electrode.

Lime Requirement Buffer Tests

Seven unique tests of buffer pH were performed. Four buffer test solutions were mixed following established protocols: Shoemaker McLean and Pratt (SMP) (Shoemaker et al., 1961), Adams and Evans (Adams and Evans, 1962), Modified Mehlich (Hoskins, 2008) and Sikora (Sikora, 2006). Solutions of the original Woodruff 7 buffer test (Woodruff, 1948) were also prepared, with two additional modified versions of the test. The analytics guide to the Western Region recommends that if the Woodruff 7 buffer pH is below 6, the test should be re-run, using a half-quantity of soil (Gavlak et al., 2005), and this variation was performed as an additional test. The second modification to the Woodruff test was for the Woodruff 6, where the buffer solution pH was adjusted from 7 to 6, and then followed the standard Woodruff test protocol (Mohebbi and Mahler, 1988). Using the buffer pH values from each of the seven tests, ten LREs were derived from existing test calibrations, if a target pH was used in the calibration, the value for target pH 6 was calculated. Three calibrations for the SMP test were evaluated, McLean (1982, from Sims, 1996), VanLierop (1990, from Sims, 1996), and the Western Region calibration (Gavlak et al., 2005). For the Adams and Evans test, the original calibration was used (Adams and Evans, 1962). The LRE for the Modified Mehlich buffer test was determined using two different calibrations for the standard Mehlich test, the VanLierop calibration (1990, from Sims 1996) and from the Western Region Analysis Manual (Gavlak et al., 2005). The LRE for the Sikora test was calculated using the calibration from Wisconsin (Laboski and Peters, 2006). The Woodruff test LRE, for all adaptations, was calculated using the formula for the Western Region (Gavlak et al., 2005), and represents the original Woodruff calibration (Woodruff, 1948).

Statistical Analyses

The incubation pH values measured for each increasing level of CaCO₃, on the ten soils, were used to generate unique linear regressions, between rates 0 and 11.2 Mg ha⁻¹ for each soil, using PROC REG (SAS v. 9.3, 2010). The regression equations were then used to determine the laboratory lime requirement for each soil to target pH values of 5.5, 6.0, and 6.5. The CaCO₃ rates determined by the incubation to target pH 6 were regressed with those estimated for each buffer test calibration using PROC REG (SAS v. 9.3, 2010). The buffer pH values were then regressed directly with the CaCO₃ requirement from the incubation to provide a local calibration for estimating lime requirement. Multivariate regression, using PROC REG (SAS v. 9.3, 2010), was performed with the measured soil characteristics to estimate the incubation lime requirement to pH 6.

Results and Discussion

Soil Characterization

Characterization of ten regionally prominent agricultural soils demonstrated that all of the soils analyzed were a silt loam texture with clay ranging from 11 to 20% (Table 2.2). Soil pH values ranged from 4.4 to 5.3, EC from 0.3 to 0.8 dS m⁻¹ and organic matter (OM) from 2.8 to 5%. The KCl extractable Al levels ranged from 5 to 139 mg kg⁻¹ (Table 2.2) and were negatively correlated to soil pH (R²=-0.93, Pvalue=<.0001). The soils had a range of exchangeable Ca from 4.0 to 9.5 cmol_c kg⁻¹, exchangeable Mg of

0.9 to 2.3 cmol_c kg⁻¹, and cation exchange capacity (CEC) values from 14.1 to 23.3 cmol_c kg⁻¹. Base saturation values ranged from 41.6 to 66.6% (Table 2.2) and was positively correlated with soil pH (R²=0.89, P-value=.0012). The characteristics of Palouse soils largely reflect the properties of the Mollisol soil order, rather than those of Ultisols, Oxisols, or Spodosols that tend to be acidic in their natural state. However, the anthropogenically induced acidification occurring in the region is contributing to common indicators of soil acidity problems, like low pH, high levels of exchangeable AI, and decreasing base saturation.

Incubation Response

The pH response of each soil to incrementally increasing rates of CaCO₃ (0 to 11.2 Mg ha⁻¹) was linear (R² 0.92 to 0.98) (Fig. 2.1, Table 2.3). A plateau was observed at neutral soil pH. For most soils this occurred between CaCO₃ rates of 11.2 and 22.4 Mg ha⁻¹ (Fig. 2.1). Equations describing the soil pH response to incubation with CaCO₃ produced lime requirement (LR) values from 3.4 to 8.4 Mg of CaCO₃ ha⁻¹ to obtain a target pH of 6. The slopes of the regression equations ranged from 0.20 to 0.29 (Table 2.3). Significant negative relationships (below α =0.05) were seen between the OM, CEC, and exchangeable Ca and the soil pH response slopes (data not shown). These are key properties in determining the buffering capacity of a soil (Brady and Weil, 2004). The Joel series sample had the highest OM, CEC, and exchangeable Ca (Table 2.2), the linear response of the Joel soil to CaCO₃ had the highest R² value, and the lowest slope value of all ten soils (Table 2.3). These factors indicate that the Joel soil has the highest buffering capacity, which is also reflected in that soil having the highest lime requirement of the group.

Buffer Tests

Correlations between LRE values using existing buffer test calibrations and the LR from the laboratory incubation values ranged from 0.02 to 0.90 (Table 2.4, Figure 2.2). The Modified Mehlich (MM) buffer test had the highest R² value of all buffer tests screened (Table 2.4) using either the Western Region (WR) (Gavlak et al., 2005) Mehlich calibration (0.90) or the Van Lierop (VL) Mehlich calibration (0.87) (Sparks, 1996). The lowest correlation was seen for the WR protocol for adapting the Woodruff 7 test if the buffer reads below pH 6. All of the correlations tested were significant with p-values less than α =0.05 except for the adaptation to the Woodruff test.

The differences in LRE produced by the WR calibration of the MM buffer test ranged from an over-prediction of 1.09 Mg ha⁻¹ on the Taney soil, to an under-prediction of 0.85 Mg ha⁻¹ for the Athena soil, with a mean over-prediction on all ten soils of 0.28 Mg ha⁻¹ (Table 2.3, Table 2.5). The WR calibration of the MM test had the smallest difference between the buffer test LRE using the existing WR calibration and the incubation LR. The Van Lierop (VL) calibration also had a high R² value of R² = 0.87; however, the test over-predicted at all LR levels (Table 2.4, Figure 2.2a).

Within the the North American Proficiency Testing Program (NAPT, 2016), six analytical labs use the Mehlich or Modified Mehlich buffer test, eight labs use the Adams and Evans buffer test, 22 use the Woodruff test, 24 use the Sikora buffer test, and 25 labs use the SMP buffer test for providing LRE. This indicates that, despite studies demonstrating the effectiveness of the Mehlich test at predicting LR (Sims and Dennis, 1989; Hoskins and Erich, 2008; Wolf et al., 2008; Dietzel et al., 2009; Manjula, et al., 2013) it is not in common usage. The original Mehlich buffer test was developed using Coastal Plain, Piedmont, and Mountain soils from NC, soils from ten other states in the southeastern United States, as well as soils from the country of Columbia (Mehlich, 1976). The soils represented were primarily Ultisols, and

included Spodosols, Alfisols, Entisols, and Histosols. The objective for the development of the Mehlich procedure was to produce a test suited to large scale soil analysis programs, where the buffer is wellcalibrated to the soils' exchangeable acidity (Mehlich, 1976). The breadth of different soils in the development of the test suggests that it is broadly suitable for a range of soils.

The modification to the Mehlich test was developed as an alternative to standard use of the hazardous waste-generating SMP test (Hoskins and Erich, 2008). The MM test has been found to perform well on a diversity of soils (Dietzel et al., 2009; Wolf et al., 2008). The original Mehlich test does not contain the hazardous reagent p-nitrophenol found in other commonly used buffer tests, or potassium chromate, which is an addition to the SMP test. Instead, the original Mehlich test uses BaCl₂ to displace exchangeable acidity, and as a preservative for the buffer solution. The MM test effectively substitutes CaCl₂ for displacing acidity; however, it does not function as a preservative. The short shelf-life of the MM buffer, ranging from one week (Dietzel et al., 2009) to one month (Hoskins, 2008), has been cited (Manjula et al., 2013) as a prohibitive drawback when considering its routine use in soil test labs. Dietzel et al. (2009) suggests substituting a half quantity of BaCl₂ from the original buffer, with CaCl₂ to achieve both a longer shelf life and a reduced concentration of barium that is not considered toxic waste.

The original Mehlich test was designed to offset salt exchangeable acidity in the soil detrimental to optimum crop yield, rather than to achieve a particular target pH (Mehlich, 1976; Van Lierop, 1990; Sims, 1996). The optimum pH for the Palouse cropping systems is still unknown. An approach to lime requirement testing that neutralizes exchangeable acidity and optimizes crop performance could be a more effective approach in the development of regional liming programs, than determining LR to meet a particular target pH. For the group of Palouse soils analyzed, rates given by the MM were closely matched with those from the incubation target pH 6 values with an R² of 0.9 (Table 2.4). Manjula et al.
(2012) found that the MM test performed comparably well to the Woodruff buffer on Missouri soils, where use of the Woodruff buffer has been well established for decades since its development. Mohebbi and Mahler (1988) did not test the performance of the Mehlich buffer on northern Idaho soils, but the replacement of the Woodruff test by the MM where it originated, suggests that the performance of the two buffers should be comparable in other regions as well.

Both Woodruff 6 and Woodruff 7 tests had a strong correlation to the incubation LR with R² values of 0.78 and 0.75 respectively (Table 2.4). The measured buffer pH values for Woodruff 6 ranged from 5.41 on the Joel soil to 5.66 on the Walla Walla soil. Using the standard Woodruff calibration for deriving LRE (Gavlak et al., 2005), the greatest under-prediction of LR by the Woodruff 6 test was on the Athena soil by 3.2 Mg ha⁻¹ and the lowest under-prediction was 0.31 Mg ha⁻¹ on the Southwick soil. The Woodruff 6 test had an average under-prediction of 1.84 Mg ha⁻¹ (Table 2.3, Table 2.5, Figure 2.2b).

Buffer pH values for the Woodruff 7 test ranged from 5.75 to 6.22 on the Joel and the Walla Walla soils, respectively. The Woodruff 7 over-predicted LR across all soils by 3.07 Mg ha⁻¹, the most by 4.4 Mg ha⁻¹ for the Larkin series sample, and the least by 1.9 Mg ha⁻¹ on the Athena soil (Table 2.3, Table 2.5).

The Woodruff buffer was the first test to be used for determining LREs. It was developed in 1948 on Missouri soils (Woodruff, 1948). Havlin et al. (2014) describes the Woodruff test to be effective on Mollisol soils. The LRE from Woodruff (7) test was well correlated to and the LR determined by the incubation (Table 2.4, Figure 2.2b). Results support that the buffer test maintained a linear relationship between LR and buffer pH on Palouse soils below buffer pH 6. The linear relationship between soil acidity and buffer response is reputed to become compromised when buffer pH values drop below 6 (Woodruff, 1948). The Soil Testing Manual for the Western Region (Gavlak et al., 2005) recommends

compensating for this by reducing the mass of soil used for the test by half, and re-testing, then doubling the lime requirement estimate to compensate for the adjustment. On Palouse soils, this adjustment to the protocol produced the lowest correlation (R²=0.02) and the biggest discrepancy between LRE values and LR determined by the incubation and all of the compared tests (Table 2.3, Table 2.4, Table 2.5).

Mohebbi and Mahler (1988) found that the Woodruff buffer test adjusted to pH 6 was the most effective predictor of LR for northern Idaho soils. The current study corroborates that there is a strong correlation between the Woodruff 6 buffer test results and lime requirement for Palouse soils (Table 2.4). Using the existing WR calibration, the Woodruff 6 test underestimated LR, particularly for soils with high LR (Figure 2.2b). The pH range of the soils tested by Mohebbi and Mahler (1988) was between 5.0 and 5.6, a pH range with higher pH values than the soils from the current study where soil pH values ranged from pH 4.4 to 5.3. The Woodruff 6 test buffer solution starts at pH 6 and the buffer pH decreases with the addition of acidic soil. The strong correlation of this test with LR found in this study as well as Mohebbi and Mahler's work (1988) suggests that the relationship between Woodruff buffer pH values below 6 and LRE stays consistent within the bounds of buffer pH values, with the lowest being 5.41 found in these studies. The Woodruff 6 test, using the existing calibration, was not as effective at estimating higher lime rates than lower rates. This could be an artifact of the beginning of deterioration in the linear relationship between buffer pH, soil acidity, and lime requirement at lower buffer pH values. Using the standard Woodruff 7 buffer test produced buffer pH values as low as 5.75 that maintained a high correlation with LR of Palouse soils. The threshold where the linear relationship between buffer pH and useful LRE values is no longer maintained, is currently unknown.

The Adams and Evans (AE) test had an R² value of 0.56 (Table 2.4, Figure 2.2d). The AE test produced a maximum LR over-estimate on the Taney soil of 1.88 Mg ha⁻¹, and largest under-prediction

was by 2.06 Mg ha⁻¹ on the Joel soil. The average Adams and Evans estimate using the existing calibration, under-estimated LR by 0.43 Mg ha⁻¹ (Table 2.3, Table 2.5).

The AE test was developed in Alabama for Red-Yellow Podzol soils, characterized by few 2:1 clays, low CEC, and low organic matter (Adams and Evans, 1962). Cation exchange capacity values of soils from the original study ranged from 0.8 to 13.0 mg kg⁻¹. One of the objectives of the AE test is to capture small differences in LR and reduce potential for over-liming soils with low buffer capacity (Sims, 1996). Mehlich et al. (1976) found that the buffer pH values for the AE test correlated more closely with total soil acidity than exchangeable acidity on 114 soils used to develop the Mehlich buffer test. Which fraction of soil acidity is measured by a buffer test, and the soil characteristics it is best suited for, are two essential components of determining acceptable lime requirement estimates.

The AE test was designed for use on soils with different properties than Palouse soils. The AE test is intended for soils with small amounts of 2:1 clays, and the soils of the Palouse are dominated by mica, vermiculite, and smectite (McDaniel and Hipple, 2010). The lowest CEC value from the group of Palouse soils used in this study, is higher than the highest used by Adams and Evans when developing the buffer test. Additionally, the organic matter content of Palouse soils tends to be high, compared to highly-weathered, naturally acidic soils associated with the southeastern U.S., and is a characteristic common to the Mollisol soil order. The wide range of soil orders and characteristics does not preclude the use of the AE buffer test in other parts of Washington state, where soil properties may share similar characteristics with soils where the test was developed.

Using the WI calibration developed by Laboski and Peters (2006) for the Sikora buffer test produced an R² value of 0.73 compared to the LR (Table 2.4, Figure 2.2c). The test over-predicted by 4.4 Mg ha⁻¹ on the Santa and Thatuna soils and under-predicted by 2.2 Mg ha⁻¹ on the Walla Walla soil

(Table 2.3, Table 2.5). The buffer pH values for the Sikora test had a significant (*p*=0.0003) R² correlation value of 0.82 with the buffer pH values of the SMP test it was designed to mimic (Fig. 2.3). The Sikora buffer test was designed to replace the SMP test without using hazardous chemicals. The significant correlation suggests that the Sikora test could be used interchangeably, for a greener chemistry option, where test labs or clients prefer LREs based on the SMP test. The Sikora test demonstrated a higher correlation with the group of Palouse soils than the SMP test. Using the WI calibration for the Sikora test, Laboski and Peters (2006) produced more favorable LRE values for the Palouse soils than using the other common SMP calibrations.

The SMP test, using the WR calibration, had an R² value of 0.47 (Table 2.4, Figure 2.2d). The McLean and Van Lierop calibrations (Sims, 1996) produced lower R² values of 0.43 and 0.41, though all R² values were significant below α=0.05 (Table 2.4). The calibration recommended for the WR ranged from an over-estimate of 0.37 Mg ha⁻¹ on the Larkin soil to an under-estimate of 2.82 Mg ha⁻¹ on the Joel soil (Table 2.5, Figure 2.2d). The SMP buffer test was developed on Ohio soils in response to perceived inadequacy of the Woodruff buffer test to compensate for soil acidity contributed by Al (Shoemaker et al., 1961). Acidity contributed by H⁺ was the only form of acidity considered in the development of the original Woodruff test (Woodruff, 1948). Shoemaker et al. (1961) developed their test on soils with an upper limit of NH₄OAc extractable Al of 19.8 mg kg⁻¹ (McLean et al., 1958). Now, the SMP buffer test is the most commonly used throughout the United States. The SMP test is currently the recommended buffer test to provide LREs for the states of Washington and Oregon, particularly for soils found on the Western side of the Cascade mountain range (Sparks, 1996; Baker and Chae, 1977; Peterson and Jackson, 1971). The test is known to be broadly effective and performs well on soils with high lime requirements

above 4.48 Mg ha⁻¹ (Havlin et al., 2014; McLean, 1973). Most of the LR values for Palouse soils in this study were above this guideline for using the SMP buffer (Table 2.3).

The SMP buffer test is currently the prevailing test used to determine lime requirement for Palouse region soils (Western Laboratories, 2016; Soil Test Consultants, 2016; Best Test Analytical Services, 2016). The data presented in this study indicate that SMP has the lowest correlation of the buffer tests analyzed, apart from the adapted Woodruff protocol for buffer pH values below 6. Mohebbi and Mahler (1988) also found that the single-buffer SMP test did not effectively represent LREs for a group of northern Idaho soils. The soils used by Mohebbi and Mahler (1988) were from the same region and had characteristics similar to those investigated in the current study. The similarity between the regional soils used and the results of the buffer test performance indicate that the SMP test does not provide consistently accurate LREs for the soils of the Palouse region.

Buffer tests are presumed to be the most suitably applied to soils with similar characteristics to the soils where the test was developed (Sims and Dennis, 1989). Most of the buffer tests in common use were developed on Ultisols, and similar highly-weathered, low buffering capacity soils, while the soils of the Palouse region are predominantly Mollisols with high buffering capacity. This presents a challenge for the acidified soils of the Palouse region because the buffer tests in current usage were not developed for anthropogenically acidified Mollisol soils. Consequently, the tests may not be as effective at providing accurate estimates because of the differences in soil characteristics. Utility of buffer test LREs depends on two primary factors: (1) LRE values provided by the tests should be a close representation of actual lime requirement (LR) values; and (2) the tests should perform consistently on the target group of soils. The indication of consistent test performance is a high correlation between buffer test results and LR values. The proximity of the LRE to the LR is less critical than consistent performance. Consistent test performance allows for the use of a more accurate regional calibration to

be developed based on local experimental data. Regional calibration of buffer tests improves the utility of LRE values (Gavlak et al., 2005; Doerge and Gardner, 1988). Local calibration of the buffer tests to laboratory incubation LR is an essential step in meeting this regional need. In regions with highly weathered soils, it is a bigger concern for buffer tests to not under-estimate a need for high lime requirement because of the negative impact of low pH on crop performance (Fox, 1980). However, as liming programs are still being developed in the Palouse region, and lime is commonly viewed as an input with economic limitations within the dominant dryland-wheat system, it may be less of a concern for land managers to under-apply lime, than to over-apply and incur extra expense.

Direct correlations between the buffer test pH values and the incubation results to target pH 6 from the group of Palouse soils tested can provide the foundation for local buffer test calibrations (Figure 2.4). The highest R² values observed from the derived correlations (Palouse calibrations), were for the MM test (R²=0.90), Woodruff 6 (R²=0.78), and Woodruff 7 (R²=0.75). Lower correlations were seen for Adams and Evans (R²=0.58), Sikora (R²=0.48), with SMP being the lowest (R²=0.33). Despite generating a new calibration, the correlation for the SMP test remains low and undermines the ability of the test to consistently predict useful LRE values for Palouse soils. The steep slope of the Woodruff 6 test, with the Palouse calibration (-18.55, Figure 2.4a) relies on a two tenths pH unit change, spanning LR values of 3.36 to 8.36 Mg ha⁻¹. The wider range of buffer pH values, observed with the MM and the Woodruff 7 test, allows for a greater range in the pH measurement and provides opportunity to produce better LREs.

Lime response in the field is different than what is seen under ideal laboratory conditions (Baker and Chae, 1977; Dietzel et al., 2008). Further field testing is required to validate the calibrations from this study. Another unknown component to the regional calibration is the geographical boundaries of where these test results and calibrations can most successfully be applied.

Multivariate Analysis

The multivariate analysis of soil characteristics to predict lime requirement to target pH 6, indicated that EC explains LR with a partial R^2 of 0.82 (Table 2.6). Further explanation of lime requirement combines EC with organic matter, KCl extractable Al, and base saturation to estimate lime requirement on Palouse soils with an R² of 0.98 (Figure 2.5). In some regions, using methods alternative to buffer tests, such as base saturation (Canterella et al., 1998), soil texture (Miller et al., 2005), or CEC (Lemire, 2005) to determine lime requirement is becoming common practice. However, a connection between EC and LR is not well-established. Smith and Doran (1996) found a significant negative relationship between pH and EC, which was also seen in this study (R²=0.50, data not shown). Smith and Doran suggested the relationship may be attributed to the effect of acidity associated with nitrification. Data from this study indicate a strong positive relationship between EC and NO_3^- (R²=0.87, data not shown). The effects of recent nitrogen fertilization or existing issues with other salts may obfuscate a relationship between EC and LR. It should be noted that the strong correlation between EC measured in the laboratory for this study will correlate differently with LR than apparent EC measured in the field. The relationship between organic matter and lime requirement can be attributed to the role of organic matter in a soil's buffering capacity (Brady and Weil, 2004). The buffering capacity of a soil is a key component in a soil's susceptibility pH changes, including with addition of lime materials. Soil Al contributes to soil acidity, neutralizing phytotoxic Al is one of the goals of liming programs. Base saturation is an indicator of soil acidity with lower base saturation values associated with greater soil acidification. In some regions achieving a certain threshold of base saturation is the primary goal of liming programs. For some acidic soils, lime requirement recommendations are derived primarily from base saturation (Canterella et al., 1998)

Using standard soil analyses metrics streamlines the soil testing process for lime requirement and bypasses a need for tests using hazardous or perishable materials. Measuring LREs based on EC, exchangeable AI, organic matter, and base saturation provides a good opportunity to monitor these other key attributes of soil health. Additionally, the multivariate analysis of soil characteristics performed on these soils suggests a higher predictive capacity for LRE than buffer tests can provide (Table 2.6, Figure 2.5). However, more materials, equipment, labor and time, would be required to run four soil tests, rather than one, as in the case of buffer tests. Soil test labs would likely respond by charging a higher price in order to receive adequate compensation for the additional tests, while a higher cost may disincentivize comprehensive soil testing by land managers in the Palouse region.

Conclusions

This study demonstrates that though buffer tests can be used to predict lime requirement for Palouse soils, the SMP and Adams and Evans buffer tests are not suitable for generating appropriate lime requirement estimates in the Palouse region, and evidence supports the use of the Modified Mehlich and Woodruff tests with locally appropriate calibrations for more reliable lime requirement estimates. There is an indication that other key soil properties can be used to increase the predictive capacity of lime requirement testing for the region's soils and preclude the need for buffer tests to be performed. Soil and crop responses can vary in the field, particularly with implementation of different tillage systems and methods of incorporation. It is essential that these results from controlled laboratory conditions be contextualized with follow-up under field conditions.

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Soil Series	Classification	Extent	Longitude	Latitude
	Suborder	Hectares	Degrees	
Athena	Haploxeroll	2,052,841	46.3393	-117.993
Joel	Argixeroll	107,865	46.2577	-116.576
Larkin	Argixeroll	372,271	46.7022	-116.807
Naff	Argixeroll	827,676	46.7502	-117.205
Palouse	Haploxeroll	1,871,224	46.7474	-117.210
Santa	Fragixeralf	381,519	46.9315	-116.771
Southwick	Argixeroll	332,230	46.7060	-116.826
Taney	Argixeroll	453,693	46.9690	-116.851
Thatuna	Argixeroll	590,963	47.5209	-117.172
Walla Walla	Haploxeroll	3,263,513	46.3545	-118.021

Table 2.1. Soil series, classification, extent, and location of samples.

Soil Series	рН	\mathbf{EC}^{\dagger}	Са	Mg	CEC [‡]	AI	Base saturation	OM§	Sand	Silt	Clay
		dS m ⁻¹		cmol _c	kg ^{-1 -}	mg kg ⁻¹			%		
Athena	4.5	0.5	4.0	0.9	15.8	46	48.0	4.0	29	60	11
Joel	4.7	0.7	9.5	1.6	23.3	68	50.1	5.0	28	52	20
Larkin	5.2	0.8	8.9	1.4	20.6	8	54.6	5.0	27	55	18
Naff	4.5	0.6	5.8	2.0	15.5	104	55.5	3.7	27	56	17
Palouse	5.0	0.8	6.0	1.3	18.1	18	49.5	5.1	29	55	16
Santa	4.4	0.5	4.1	1.2	14.1	139	41.6	3.6	26	58	16
Southwick	5.3	0.5	7.4	1.7	17.3	5	56.4	3.3	25	56	19
Taney	4.7	0.4	5.8	1.2	16.8	51	46.1	3.6	24	57	19
Thatuna	4.5	0.4	4.6	0.9	15.0	64	45.2	4.2	27	57	16
Walla Walla	5.3	0.3	6.3	2.3	15.4	6	66.6	2.8	30	56	14

Table 2.2. Characterization of ten Palouse soils.

+ - Electrical Conductivity

‡ - Cation Exchange Capacity

§ - Organic matter



Figure 2.1. Soil pH response of ten Palouse soils to a 90-day incubation with CaCO₃.

	Incubation	Incubation				
Soil	LR equation [†]	response	Incubation lime requirement to 15 cm			
Series			Target pH 5.5	Target pH 6	Target pH 6.5	
		R ²		Mg ha ⁻¹		
Athena	y=0.23x+4.42	0.97	4.80	7.01	9.23	
Joel	y=0.20x+4.36	0.98	5.82	8.36	10.90	
Larkin	y=0.21x+4.91	0.94	2.79	5.17	7.55	
Naff	y=0.26x+4.12	0.97	5.39	7.34	9.29	
Palouse	y=0.25x+4.45	0.96	4.18	6.17	8.17	
Santa	y=0.29x+4.12	0.94	4.70	6.40	8.10	
Southwick	y=0.24x+5.18	0.95	1.31	3.36	5.41	
Taney	y=0.26x+4.85	0.92	2.49	4.42	6.35	
Thatuna	y=0.24x+4.48	0.94	4.27	6.36	8.44	
WallaWalla	y=0.27x+4.98	0.93	1.88	3.71	5.53	

 Table 2.3. Lime requirement (LR) for ten Palouse soils at three target pH values.

⁺- Where x=CaCO₃ (Mg ha⁻¹) and y=pH response

Table 2.4. Correlation between lime requirement estimates (LRE) provided by common buffer test (BT) calibrations and lime requirement (LR) values determined by a 90-day laboratory incubation with CaCO₃.

			Relationship
			between BT LRE
Buffer test	R ²	P-value	and incubation LR
WR Mehlich ⁺	0.90	<0.0001	y=1.33x-2.29
VL Mehlich [‡]	0.87	<0.0001	y=0.79x-2.40
Woodruff 6 ⁺	0.78	0.0008	y=2.21x-2.98
Woodruff 7^{+}	0.75	0.0012	y=1.15x-4.39
WI Sikora [¶]	0.73	0.0016	y=0.45x+2.25
Adams and Evans ⁺	0.56	0.0131	y=1.05x+0.16
$WR SMP^{\dagger}$	0.47	0.0276	y=0.85x+1.54
ML SMP [§]	0.43	0.0390	y=0.59x+1.75
VL SMP [§]	0.41	0.0452	y=0.27x+0.87
WS Woodruff7 ^{†‡}	0.02	0.7474	y=0.13x+5.30

⁺ Calibration from Soil, Plant, and Water Reference Methods for the Western Region, 3rd edition, Gavlak et al., 2005.
[‡] Protocol following the modification for buffer pH values below 6.

§ Calibration from Methods of Soil Analysis: Part 3. Sims, 1996.

¶ Calibration from Laboski and Peters, 2006.

Soil Series	Modified Mehlich [†]	Woodruff 6 [†]	Woodruff 7 [†]	Sikora [‡]	Adams and Evans [†]	WR SMP⁺
					Target pH 6	
			Mg ł	าa ⁻¹		
Athena	6.16	3.84	8.95	8.24	5.29	4.7
Joel	8.12	4.98	10.46	11.04	6.3	5.54
Larkin	6.01	4.28	9.61	6.49	5.12	5.54
Naff	6.94	4.43	9.85	9.94	6.3	5.54
Palouse	6.33	4.31	9.41	8.96	5.96	6.22
Santa	6.5	4.33	9.10	10.81	6.3	6.22
Southwick	4.4	3.05	6.97	4.63	3.36	3.53
Taney	5.51	3.65	8.63	7.09	6.3	4.7
Thatuna	6.86	4.16	9.41	10.76	5.71	6.22
WallaWalla	4.29	2.86	6.58	1.55	3.36	2.18

Table 2.5. Comparison of lime requirement estimates (0-15cm depth) provided by common buffer test calibrations.

⁺ Calibration from Soil, Plant, and Water Reference Methods for the Western Region, 3rd edition, Gavlak et al., 2005.

‡ Calibration from Laboski and Peters, 2006.



Figure 2.2a,b,c,d. Correlations between lime requirement estimates (LRE) from common buffer tests and the lime requirement (LR) to target pH 6, determined by the response of ten Palouse agricultural soils to a 90-day incubation with CaCO₃. The WR Mehlich, both Woodruff tests, and WR SMP calibrations are from Soil, Plant, and Water Reference Methods for the Western Region, 3rd edition, Gavlak et al., 2005. The Modified Mehlich (MM) Van Lierop (VL) calibration is from Methods of Soil Analysis: Part 3, Sims, 1996. The Sikora test calibration is from Laboski and Peters, 2006.







Figure 2.4 a,b,c,d. Lime requirement estimate (LRE) calibrations for Palouse soils.



Figure 2.5. Multivariate lime requirement estimate (LRE) determined using Electrical Conductivity (EC), Soil Organic Matter (OM), Base Saturation (BS), and KCl extractable AI (AI), correlates (R²=0.98; P=<.0001) with lime requirement (LR) on Palouse soils.

Table 2.6. Multivariate analysis of measured soil properties indicates that lime requirement, to target pH 6, can be estimated based on Electrical Conductivity (EC), Soil Organic Matter (OM), Base Saturation (BS), and KCI extractable AI (AI).

Variable	Partial R ²	Model R ²	P-value
EC	0.82	0.82	0.0003
OM	0.06	0.95	0.0397
KCI AI	0.03	0.97	0.0931
BS	0.02	0.98	0.0871

CHAPTER 3: SOIL ACIDIFICATION IMPLICATIONS FOR MANAGEMENT EXTENSION PROJECT Introduction

As interest and awareness of soil acidification in the Palouse increases, it has been important to recognize the need for evidence-based information on the topic to be made available to growers and industry personnel. There are two ways this project sought to meet the needs of the community served. One was through a collaborative effort to generate a series of specialized Extension fact sheets, and the second was to produce a short video series paralleling the information available in the fact sheets.

Sub-project i) Extension fact sheet collaboration:

The issue of soil acidification in the Palouse region has been emerging as a topic of regional interest. Because soil pH affects many components of the cropping system, a range of expertise is required to adequately address the complexities faced in managing the system. In an effort to support the need for specialized information, decrease redundancy of materials produced, identify knowledge gaps on the topic, and facilitate collaboration between experts, an extension team was formed. Experts known to be working on or interested in soil pH and acidification from Washington State University (WSU), University of Idaho (UI), and the USDA- Agricultural Research Service (ARS) at WSU, were invited to participate. First steps in the process were to determine the key topic areas to address. From there, micro-teams (each with a designated "team leader") from within the group were formed to address each of the topic areas. The topics were addressed by producing a short Fact Sheet through WSU Extension that supports and links to other documents in the collection. Each document in the collection is submitted using the standard protocol through the WSU Fast Track peer-review publishing system. As each document is published, it joins the collection housed on the WSU Wheat and Small Grains website and is marketed through that platform. Team communication was primarily done through email or in-

person meetings two to four times a year. A survey was sent to the team to monitor the process. It is

too early to evaluate user benefits and feedback.

A summary of the survey results:

Project implementation:

- Purpose
 - Majority of respondents felt the team is accomplishing its goals
 - Mixed opinions on how well they were initially defined and how well everyone was represented when they were formed
- Communication
 - Has happened by email and meetings, respondents felt the frequency and quality of both was neutral to above average
- Leadership
 - Comments indicated that there is room for improvement with leadership clarity and concern for who will push the project forward once I have graduated
- Procedures
 - Publication has been slow, both within micro-teams and through the two-step process of university publication channels
- Evaluation
 - 50% response from the team

Benefits

- Group perceives that stakeholders will find this information
 - Valuable
 - Accessible
 - Split opinions on whether more information should be added and how much it should be promoted
 - Highly relevant topic with research needs
- Collaborative work important on emerging issue
- Possible model for future extension projects

Challenges

- Publication channels
- Time conflicts
- Team members offering their unique expertise need to be recognized
- Evaluating impact on user end
- Trying to move closer to what users might prefer not there yet

Project Outcomes:

Fact sheets

- Soil pH Implications for Management: An Introduction- FS170E: Carol R. McFarland, David R. Huggins, Richard T. Koenig. 2015.
- Recommended Crop Species and Wheat Varieties for Acidic Soils FS169E: Paul S. Froese, Aaron
 H. Carter, Michael O. Pumphrey. 2015.
- How Soil pH Affects the Persistence and Activity of Herbicides FS189E: Alan J. Raeder, Drew Lyon, James B. Harsh, Ian Burke. 2015.
- Using a pH Meter for In-Field Soil pH Sampling FS205E: Paul Carter
- Agricultural Lime and Liming: Part 1, Part 2, Part 3 (In progress): Wayne Thompson, Carol
 McFarland, Tabitha Brown, David R. Huggins

Acidification in the inland Pacific Northwest. Crops and Soils Magazine. March – April 2015.

Delivering relevant extension education using a collaborative model:

a case study on soil acidification in the iPNW. Paper presented at the 2015 ASA, SSSA, CSSA, ESA meeting

Supported the hosting of an internal research symposium on soil acidification hosted by Dr. Haying Tao

Extension sub-project ii) Soil Acidification: Implications for Management Video Series

The video series was an effort to deliver Extension information on a regionally relevant topic using a non-traditional platform. The systems-based nature of soil acidification and management of low pH lends itself to a visual platform. Some of the complex chemistry associated with the topic was able to be animated, a presentation that may be more accessible by the target audience. The conversational interview style, with both farmers and experts, provides an opportunity for the user to connect more with the material. These factors are the justification for the initiation of the project.

The first steps in developing the project were about defining the scope, creating buy-in, and exploring resources. A short proposal was created, and available resources were determined, along with what the resource investment required for the project, would be. The next steps involved project development. During this phase a script/outline and story board were proposed and discussed. The script included not only the topics to be covered, but also how and by who, and what visual imagery would come along with it and what inputs would be required to get the desired materials. This included people, time, travel, and equipment. After the script and inputs were determined, the next phase was coordinating, developing interview questions, and actively filming. For this series we interviewed two local farmers, who have experienced issues with soil acidity on their farm, and four experts with experience on various topics related to soil acidification. To complement the interviews, "b-roll" footage of native prairie cover, native forest cover, liming, and direct drilling, was filmed.

Additionally, two animations were developed to elucidate key concepts within the video. The first animation describes and illustrates what pH is, while the second describes and illustrates the process of soil acidification. The scripts for both animations were written and reviewed for content. The animations were co-developed with the WSU extension videographer and a contracted graphics animator. Drafts of the animations were reviewed for flow and accuracy of content. The next step was to pull the key content from the collection of video interviews and put them together in a cohesive way, following the storyboard. Rough drafts of the three videos were compiled and reviewed for content, by a committee of experts. A final cut was completed after the review. The draft then proceeded to the

final stages of editing, matching the complementary footage and images to the interviews, covering editing splices, as well as making aesthetic corrections. Titles for the videos, interviewees, and credits are then added along with music to make the final products.

The project resulted in three short videos with a total length of under 25 minutes. Each of the videos was developed focusing on a theme: the first was identifying the symptoms of low pH in the field, the second was how the process of soil acidification happens, and the third centered on management considerations for low pH soils. A farmer-focused narrative carries throughout each video.

Video 1 - Soil Acidity: What it looks like

Abstract

This short video interviews two area farmers who have experienced issues with low soil pH on their farms. University experts are also interviewed to give further insight into identifying low soil pH issues on farms of the Palouse region.

Video 2 - Soil Acidity: How it happens

Abstract

This short video interviews two area farmers who have experienced issues with low soil pH on their farms. University experts are also interviewed to give further insight into common questions on how the process of soil acidification is happening in the Palouse region.

Video 3 – Soil Acidity: Managing it on the farm

Abstract

This short video interviews two area farmers who have experienced issues with low soil pH on their farms. University experts are also interviewed to give further insight into common questions relevant to managing low soil pH on local farms.

Interview questions:

Development of open-ended interview questions were guided by the script.

Josh Jones on-farm experience:

How did you become aware of the issue both in the region and on your farm?

Can you describe what your crops looked like in the field, and how they were yielding - were there

certain crops that should have been doing better but just weren't?

What did you think it when you first saw the symptoms and how were you able to connect them to low pH soil?

What have you done to address the issue on your farm? How did you decide to make the management decisions that you did? Have you noticed a difference?

Randy Emtman on-farm experience:

Please tell me about yourself, and your family's farm – how long have you been farming, how many

acres, what crops you grow, tillage system and other pertinent background

Can you describe what your crops looked like that suggested to you there might be a problem

undermining your crop vigor

What did you first attribute the symptoms to when you first saw them?

How were you able to connect them to low pH soil?

I understand that you have worked with a lot of the WSU research and extension people, can you talk about some of that work and the process that you went through with support of researchers, industry

and your farm managers to, identify the various components of the pH complex

Are there crops that you can't grow on your lowest pH fields?

What have you done to address pH issues on your farm?

How did you decide to make the management decisions that you have in response to low pH soil conditions?

Have you noticed differences in crops and soil response to the management changes that you have made?

How do you foresee management of low pH soils impacting the way you farm in the future?

Many farmers tell me that acidification isn't a problem in their area - do you think this is an issue limited

to the Rockford area?

Drew Lyon on herbicides:

Why and how does soil pH affect the way that herbicides work?

Which herbicides are most affected by changes in soil pH?

Are there ways to differentiate damage from herbicide carryover from Al toxicity – especially in

legumes?

How can herbicide applications be managed to avoid crop damage and herbicide effectiveness if low pH conditions are suspected?

Tim Paulitz on pathogens:

What factors determine if a pathogen is going to be a problem in a field?

You were one of the first researchers at WSU to start to see low pH as an issue, how did that happen?

One issue with identifying an Al toxicity problem has been that it presents in a similar way as several

pathogens, how can a farmer distinguish a pathogen issue from Al toxicity?

Does low pH soil encourage a higher prevalence of pathogens in crops?

If so which are the pathogens most likely to be problematic under low pH conditions?

What can be done to positively identify and manage the pathogens that are problematic under low pH conditions?

Are there pathogens that are unlikely to be a problem under low pH conditions?

Rich Koenig on acidification and soil fertility:

Is there a relationship between soil erosion and acidification?

Can you speak to the effect of pH on the soil's ability to retain and release essential plant nutrients?

Is it possible to offset annual N fertilization with lime applications and what would that take?

Are there fertilizers that don't acidify?

Does growing legumes acidify soil?

Is there a difference between lime materials?

How and when to apply lime?

I applied lime and there was no yield response, why not?

Is there an optimum pH for soil?

How does low pH affect nutrient availability and loss?

What do you see as the long-term consequences for the region if pH issues go un-addressed?

When we talk about low pH, Al toxicity usually comes up - where does the Al come from?

How do you see the bigger picture with anthropogenic acidification from both an agronomic impact and

soil health standpoint?

What do you think are the most important points in the conversation surrounding soil acidification in

the Palouse?

Tabitha Brown on acidification trends and patterns:

When did you start working on the pH issues of the Palouse?

Has there been a lot of work done in the region looking at pH changes?

In your experience, how is soil pH in the Palouse changing over time?

Where are issues with low pH being seen in the region? Does there seem to be boundaries?

You do some work looking at field-scale variability of pH, what are you seeing there? How about variability within the soil profile? What effects have you been seeing on the crops planted in low pH soil? What symptoms would you see in the crops that would lead you to look more at the soil pH? Have you seen any management strategies that seem to be working?

Further resource access:

These resources are currently being housed and can be accessed on the CAHNRS and WSU Wheat and Small Grains Website on the Soil Acidification in the inland Pacific Northwest website: http://smallgrains.wsu.edu/soil-and-water-resources/soil-acidification-in-the-inland-northwest/