LIMING FOR IMPROVED NUTRIENT UTILIZATION AND WEED MANAGEMENT

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Abstract

Major yield setbacks due to invasive weed species population and soil acidity have been recorded in various regions of the United States. Estimated yield loss due to weed competition was approximately 12.3% in the Pacific Northwest. Similarly, it is estimated that there is a 40 to 70% reduction in yield when small grains are grown on acidic soils worldwide. One way to simultaneously improve the productivity of Idaho soils while increasing crop competitiveness is through liming. Agricultural lime applications increase soil pH which may improve crop competitiveness and make soil conditions unsuitable for certain weed species. Lime requirement (LR) analyses can be performed by reacting varying concentrations of lime with soil to provide calibrated equations for estimating how much lime is required to increase the pH of that soil to the desired level. Unfortunately, no known calibration testing has been conducted using soils from southern Idaho. The current University of Idaho and soil testing lab lime recommendations are based on testing mostly done in the 1980s on soils from Midwestern states, Washington, and northern Idaho. These calibrations do not reflect the climate or chemical and physical properties of acidic and trending acidic soils in southern Idaho. The overall aim for this paper was to evaluate the effect of liming acidic soils on soil properties, crop growth, and weed density, and b) to develop lime requirement equations for Idaho soils using lab incubations and field trial results. Generally, linear soil pH and Al responses were observed to lime rates, but there were no recorded significant effects on grain quality metrics or weed growth. Sikora (R^2=0.99) and the Adams-Evans buffer (R^2=0.92 to 0.97) methods were best suited for predicting the LR for Idaho soils compared to the calcium hydroxide buffer method (R^2=0.02 to 0.11). The insights gained from this thesis on the potential benefits of lime application can be of great value to farmers and other stakeholders in Idaho's agricultural industry who seek to optimize crop yield and improve soil health.

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Dedication

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Statement of Contribution

Dr. Jared Spackman assisted with the initial conceptualization, funding acquisition, resources (Chapters 1, 3, and 4), data collection and curation, investigation, supervision, writing, reviewing, and editing for all chapters. Dr. Albert Adjesiwor assisted with the data curation, formal analysis, investigation, reviewing, and editing for all chapters. Dr. Kurtis Schroeder and Dr. Daniel Strawn assisted with supervision, writing, reviewing, and editing for all chapters. Dr. David Tarkalson assisted with initial conceptualization, funding acquisition, resources, data curation, formal analysis, investigation, supervision, writing, reviewing, and editing for Chapter 2.

Chapter 1: First-Year Evaluation of Precipitated Calcium Carbonate As A Lime Amendment In Eastern Idaho

Abstract

While most of eastern Idaho's soils are alkaline with a pH of 7.0 to 8.5, there are several regions with acidic soils. Periodic applications of locally available precipitated calcium carbonate can help neutralize soil acidity and maintain the productivity of acidic soils in eastern Idaho. Precipitated calcium carbonate is a byproduct of sucrose extraction during the processing of sugar beet roots, primarily produced in Idaho and Oregon. However, there is limited information about the specific effect of precipitated calcium carbonate on Idaho soils. Four on-farm field trials were conducted in south-eastern Idaho to assess the effect of precipitated calcium carbonate lime rates (0, 2.2, 4.5, and 9.0 Mg ha-1) on the modification of soil pH across different soil depths. Soil samples were collected at 0–5, 5–10, 10–15, 15–20 and 20–30 cm depths in the fall of 2022 immediately before lime application and in May-June of 2023 and post-harvest 2023. Following liming, soil pH increased at all soil depths, but the greatest increase occurred in the top 10 cm of the soil profile. Across the four sites, the 9.0 Mg ha-1 lime rate increased soil pH by 0.7 to 1.5 pH units by the May-June sampling event relative to the non-limed check. With the exception of grain protein and test weight at Site B, there were no significant differences between treatments in terms of yield and quality parameters. Out of all grain and straw nutrient parameters tested, only phosphorus (average straw tissue concentration; 0.39%), and potassium (average straw tissue concentration; 0.42%) at site B and potassium (average tissue concentration; 0.50%) at Site C were significantly increased. These sites will continuously be monitored to evaluate how long a lime application lasts before soils revert to pre-lime application soil pH levels.

Introduction

Western United States (US) arid and semi-arid soils are slightly acidic to alkaline (e.g., pH of 6.0 – 8.5; Brown et al., 2008). However, there are several regions in northern and south-eastern Idaho where soil may have pH as low as 4.3 (Stukenholtz Laboratories Inc., Personal communication, (2023); Mahler, 1994). Soil acidification is becoming increasingly problematic in surficial soil layers, negatively impacting crop production in the US (McFarland, 2015). While soil acidification is a natural process, it is accelerated by acidic rainfall, excess irrigation, nutrient cycling, ammonium fertilizer application, root exudates, soil mineral exchange, and hydrolysis reactions (Msimbira et al., 2020; Havlin et al. 2016; Tang et al., 2003; Bolan et al., 1991). In agricultural soils, acidification is promoted when tillage accelerates soil mineralization and as elemental sulfur and ammonium (NH_4^+)-based fertilizers are oxidized (Msimbira et al., 2020).

Precipitation is naturally acidic as carbon dioxide combines with water vapor to produce carbonic acid (pH ~ 5.7; Oshunsanya, 2018). Likewise, plants exude chelates, organic acids, and H^+ ions to improve nutrient availability (e.g., phosphate) and uptake, and to balance chemical charges as cations like K^+, Ca^{2+}, and Mg^{2+} are taken up (Tang et al., 2003; Havlin et al., 2016; Msimbira et al., 2020). Mineralization of organic residues also release carbon dioxide that combines with soil water to reduce soil pH (Msimbira et al., 2020; Gavlak et al., 2003). Excessive precipitation and/or irrigation events that leach base cations (K^+, Na^+, Ca^{2+}) down the soil profile can result in the accumulation of acidic cations (H^+, Al^{3+}) (Rowell, 1985). Hydrolysis also contributes to soil acidity by producing H^+ ions. For example, when aluminum (Al) species hydrolyze, they generate H^+, which lowers soil pH (Havlin et al., 2016; Coleman, 1957).

Generally, plants have adapted to grow in a wide range of soil pH conditions, but growth and development is optimized within a specific pH range unique to each species. For sugar beet, barley, potatoes, and wheat, the lower soil pH threshold is 6.0, 5.8, 5.5, and 5.4 (Anderson et al., 2013; Mahler, 1994), respectively. When grown outside these optimal pH ranges, water and nutrient accumulation may be reduced, symbiotic relationships with soil microbiology may not be formed (e.g., *Rhizobia* in alfalfa), or crop physiological development may be hindered (McFarland, 2016; McCauley, 2009). Bioavailable Al and Fe increases with increasing soil acidity and may become toxic to the developing crop. Excess Al can inhibit cell differentiation in the root apex, root cap, and vascular bundles preventing lateral root development and limiting cell membrane permeability to nutrients and water (Havlin et al., 2016; Silva, 2012; Kochian, 1995). Iron toxicity is evidenced by leaf bronzing where the leaves become covered with reddish-brown spots as oxidized polyphenols accumulate in plant tissues and free radicals are produced irreversibly damaging cell structural components (Figure 1.1) (Becker, et al., 2005).

Figure 1.1. Iron toxicity in rice evidenced as leaf bronzing where iron accumulates as brown to black colored spotting on plant tissues (Image Source: http://www.knowledgebank.irri.org/training/fact-sheets/nutrient-management/deficiencies-and-toxicities-fact-sheet/

Acidic soils may be amended with lime materials, which neutralizes H^+ ions by adding OH^- or CO_3^{2-} to the soil solution, displacing acid-forming cations (H^+, Al^{3+} & Mn^{2+}) on soil cation exchange sites with Ca^{2+} ions and forming insoluble $Al(OH)_x$ compounds (Havlin et al. 2016; Anderson et al. 2013; Collins 2012). As the soil pH and Ca^{2+} concentration increase, exchangeable H^+ and Al^{3+} desorb from soil cation exchange sites to buffer soil solution, undergo hydrolysis, and precipitate as aluminum hydroxide (Buni, 2014; Gavlak et al., 2003).

Liming materials include calcium and magnesium carbonates, fly ash, and precipitated calcium carbonate (PCC) (Havlin et al., 2016). Precipitated calcium carbonate is a byproduct of the sucrose extraction process of sugar beet roots (Tarkalson, 2023) and is formed when calcium oxide (CaO) and CO_2 are injected into the sucrose stream to remove impurities (e.g., Ca, K, and organic molecules). The Amalgamated Sugar Company processing factories in Paul, ID; Twin Falls, ID; and Nampa, ID produce approximately 351,081 Mg (387,000 tons) of PCC annually (USDA-NASS, 2022). This PCC has a $CaCO_3$ equivalency of 75% to 81% (Tarkalson, 2023). While the majority of the agricultural soils in southern Idaho do not need PCC lime additions to correct low pH, approximately 64,750 ha of agricultural land in eastern Idaho (Fremont, Bonneville, Caribou, and Oneida counties) could benefit from lime additions (Web Soil Survey, 2022).

There is limited information about the specific effect of PCC on acidic Idaho soils. Several liming studies in the western US have been conducted in Montana, northern Idaho, and Oregon soils that may or may not correlate well with the chemical and physical properties of eastern Idaho soils. To evaluate the impact of PCC lime rates on soil pH modification and small grain yield, on-farm field trials were conducted in eastern Idaho in 2021 and 2022. The study aimed to investigate how the application of PCC lime at different rates affected soil pH at various depths and ultimately, crop yield. The insights gained from this study on the potential benefits of PCC lime application can be of great value to farmers and other stakeholders in eastern Idaho's agricultural industry who seek to optimize crop yield and improve soil health.

Materials and methods

Site description and experimental study

Four on-farm field trials were conducted in Fremont and Bonneville counties in eastern Idaho. The soil series classification data for each farm site was retrieved from the Web Soil Survey (2022) database (Table 1.1). Treatments were arranged in a randomized complete block design with four replications. Treatment plots were 30 x 15 m and received 0, 4.5, 9.0 and 13.5 Mg ha^{-1} of PCC that was applied using a commercial applicator’s spreader in the fall of 2021. All treatment plots were tilled up to 10 cm soil depth immediately after surface lime application, except for Site D (Table 1.3). Similarly, all sites were irrigated, except for Site D in Bonneville County that receives annual precipitation of approximately 427 mm (AgriMet, 2023). The PCC used in this study was derived from Amalgamated Sugar, Co. in Paul, ID.

Other than liming, the plots were managed according to each collaborator’s individual practices. Field study management practices and activities for each field site from 2021 to 2022 are shown in Table 1.3. Different classes and varieties of spring wheat and barley were grown at each site. At Site A, our collaborating farmer planted "Explorer”, a hard white spring wheat that was released in 2001 by the Montana Agricultural Experiment Station and has excellent baking quality (Lanning et al., 2002). At Site B, our collaborating farmer planted Westbred 9668, a hard red spring wheat that was released by Bayer Crop Science. At Site C, our collaborating farmer planted Seahawk, a soft white spring wheat that was released by the Washington Agricultural Experiment Station in 2014. Lastly, our collaborating farmer planted ABI-Voyager, a two-row malting barley that was released in 2011 by Busch Agricultural Resources for use in adjunct brewing at Site D.

Soil sampling and pre-analysis

A summary of the initial soil chemical properties for four Idaho field sites is provided in Tables 1.4. All initial soil chemical properties were assessed by Stukenholtz Laboratories Inc, Twin Falls, ID, USA. Soil pH and electrical conductivity samples were collected at three different time points: immediately before the application of PCC lime in the fall of 2021 (October), during the summer (mid-June to early July) and fall (late September to early October) of 2022. The samples were taken at depths of 0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, and 20–30 cm. The samples were dried in a forced-air oven at 35 °C, and then ground to pass through a 2 mm sieve and analyzed for pH (1_{soil}:1_{water}), pH (1_{soil}:2_{water}), and pH (1_{soil}:$1_{\text{0.01 M CaCl2}}$:) (Gavlak et al., 2003; S-2.20; S-2.10; S-2.22) using an Orion ROSS Sure-Flow pH electrode interfaced with an Orion Star A215 pH/conductivity benchtop meter (Thermo Scientific Inc., Waltham, MA, US). The summer 2022 samples were collected as a 12-core (3.2-cm diameter) composite soil sample from within a 3 m radius of each plot's center. The fall 2022 samples were collected as a 3-core (5-cm diameter) composite soil sample from within a 3 m radius of each plot's center. Additional soil samples were collected at the 0–15 and 15–30 cm depths and analyzed for extractable aluminum (Gavlak et al., 2003; S-15.10) by collecting a 10-core (5-cm diameter) composite soil sample from each replicate at or before applying PCC in 2021 and a 3-core (5-cm diameter) composite soil sample collected within a 3 m radius of each plot's center following grain harvest in 2022. All extractable aluminum soil samples were submitted to Brookside Laboratories, New Bremen, OH, USA.

Other soil pre-analyses that were quantified were: cation exchange capacity (Gavlak et al., 2005; S-10.10), organic matter by loss on ignition (Gavlak et al., 2003; S-9.20) and the values were adjusted to Walkey-Black equivalent values (Gavlak et al., 2003; S-9.10), ammonium-N (Gavlak et al., 2003; S-3.50), nitrate-N (Gavlak et al, 2003; S-3.10), Bray P (Gavlak et al., 2003; S-4.20), ammonium-acetate exchangeable K with the values multiplied by a factor of 0.8 to convert to bicarbonate extractable K (Gavlak et al., 2003; S-5.10, S-4.10), ammonium-acetate exchangeable Ca and Mg (Gavlak et al, 2003; S-5.10) (Table 1.4).

Grain yield and quality

At maturity, a 1.5 x 1.5 m area was hand-harvested near the center of each plot except at Site A where the collaborating producer harvested before the plots could be sampled. Aboveground biomass was cut just above the soil surface using rice knives and the total biomass was weighed. The heads and straw were hand-fed into a small plot combine to separate the grain from the straw. All harvestable grain was collected, weighed, cleaned using an MLN deawner (Pfeuffer, Kitzingen, Germany), and measured for test weight (USDA, 2023) and plumps and thins (barley only, USDA, 2020, method 1.13). Grain protein and moisture content were assessed using a Brukker Tango Near Infrared Spectroscopy (NIRS). In addition to grain, a subsample of straw was collected from each plot and measured for moisture content. Straw samples were dried in a forced air oven at 60℃ until a constant mass and ground to pass through a 2 mm sieve. Both grain and straw samples were analyzed for nitrogen (Gavlak et al., 2003, method P2.02), phosphorus, potassium, aluminum, and sodium (Gavlak et al., 2003, method P-4.30) by Brookside Laboratories, New Bremen, OH, USA.

Data analysis

All data analyses were performed in R statistical language version 4.0.2 (R Core Team, 2023). Linear models were fitted using the lm function in R (Faraway, 2014; Sheather, 2009). Spring wheat and barley yield, grain quality, and nutrient metrics were assessed using analysis of variance (Park, 2009). PCC lime rate and soil depth were considered as fixed effects and replication was considered a random effect. For the main effect of lime rate, estimated marginal means were calculated, and *post-hoc* Tukey-adjusted pairwise treatment comparisons were performed at the alpha level of 0.05 using the *emmeans* and *multcomp* packages (Hothorn et al., 2008; Lenth, 2022).

Results and discussions

Initial Soil Physical and Chemical Conditions

Eastern Idaho lies within the Cordilleran fold and thrust belt, and in the Basin-and-Range province (Link et al., 1999). Geographical events over an extended period of time have contributed to different characteristics of eastern Idaho soils, physically as well as chemically (Francois et al., 2022). Soils within this region are dominated by diverse mineral deposits like potassium (K) (109.5-194.5 ppm; Table 1.4), which reflects a long history of volcanic activity deformity (Hughes 1999). However, in some regions, parent materials were subject to other soil-forming factors, including climate, microorganisms, and topography that interacted with one another at different rates of speed or efficiency (Hughes 1999). These soil-forming factors likely contributed to the trending acidic characteristic with some soils testing as low as 5.3. For example, Fremont County soil was glaciated and likely had overall more water flowing through the soil profile compared to Bonneville County. Water level differences between these areas likely contributed to more acidic surficial layers in Fremont County (Grow, 1993) due to loss of base cations and the accumulation of acidic cations in the top profile.

Of the four sites used in this study, the top surficial layers were the most acidic and became increasingly alkaline with deeper soil depths (Table 1.4). This is consistent with the soil pH profile of other acidic soils across the Pacific Northwest for northern Idaho (Mahler, et al., 1984) and for western Oregon soils (Anderson, et al., 2013). This suggests that leaching is a major loss pathway for the base cations (K^+, Na^+, Ca^{2+}), which results in the accumulation of acidic cations (H^+, Al^{3+}) in the top profile (Rowell, 1985). At site A and B where Al levels were slightly higher within the 15–30 cm profile (Table 1.4). Nonetheless, these Al concentrations do not seem to differ much by depth (Table 1.4).

PCC lime analysis

On a dry weight basis, the PCC Calcium Carbonate Equivalency (CCE) for all sites ranged from 71.2 to 80.1% (Table 1.2) and are similar to the values (75% CCE) reported by Tarkalson et al. (2023). This value is less than other lime products such as dolomitic limestone (85%; Clemson University, 2023). It is also important to note that not all plots received the full lime application. In fact, based on actual dry lime application rates and equivalent $CaCO_3$ rates of PCC utilized in field trials across all sites (Table 1.5), we can estimate that only 61%, 58% and 91% of the lime rate was applied at Site A and B, C and D respectively.

PCC lime effect on wheat and barley growth

Out of all the quality and yield parameters that were assessed, only grain protein (average 163 g kg^{-1}) and test weight (average 80 kg hL^{-1}) at site B displayed statistical differences between treatments due to lime application rates (Table 1.6). At Site B, the non-limed control had about 15 g kg^{-1} greater grain protein concentration and about 1 kg hL^{-1} lighter test weight values relative to the limed treatments that were not different from each other (Table 1.6). This response is similar to water and nutrient stress symptoms when wheat produces smaller, lighter kernels with less carbohydrates resulting in a higher measured grain protein concentration (Kumar et al., 2019). Stress conditions during the growing season have been found to increase protein content due to the reduced ratio of glutenins to gliadins and the proportion of unextractable polymeric proteins (UPP) (Kumar et al., 2019; Yang et al., 2018; Balla et al., 2011; Gupta et al., 1992; Blumenthal et al., 1995). These are elements of proteins that are associated with other polymers such as sucrose SRC, which differentiates flours with various water-soluble pentosans. Increased protein accumulation reduces starch in wheat, which results in increased dough strength but reduced bread volume (Rakszegi et al., 2019).

Averaged across treatments, grain yield and quality were typical to the region for each small grain variety grown, although Site D's yield (average 5,552 kg ha^{-1}; Table 1.6) was similar to ABI Voyager grown under irrigation (Marshall et al., 2023). Additionally, Site B's Westbred 9668 grain protein concentration was approximately 12 to 28 g kg^{-1} (Table 1.6) greater than that reported by Marshal et al. (2023) but were similar to the grain protein concentration reported by Thurgood (2020). Similar to grain yield and quality, PCC lime did not show any significant responses on any grain and straw nutrient parameters at all sites (Table 1.7 and 1.8). Only grain P (average; 0.39%) and grain K (average; 0.42%) at site B as well as grain K (average; 0.50%) and straw Al (average; 19.2%) at site C displayed were significantly increased by PCC lime rate (Table 1.7 and Table 1.8).

Similarly, it is possible that lack of observed differences in grain yield and quality parameters at all sites, except those already described, is because the soil pH (0-30 cm depth) was greater than the critical soil pH of 5.2 when small grain growth begins to be limited (Mahler and McDole, 1987). Within one week of emergence, small grain crop roots tend to have grown into the 20–30 cm and past the 30 cm soil depth after the second week of emergence (Gregory et al., 1992). Thus, soil acidity may have only negatively affected the roots for the first few weeks of growth and then the roots would have grown into less acidic soils and not been negatively affected. Since Site B had the lowest soil pH of all four sites, it was the most likely to have an agronomic response to lime applications.

Aluminum toxicity may occur in small grains when the soluble Al concentration is ≥ 5 mg kg^{-1} (Azam et al., 2020). At Sites B, C, and D soluble Al concentrations were up to 13.8 mg kg^{-1} which likely inhibited crop growth. However, small grain crop roots grow quickly, and unless severely restricted by physical (e.g., clay pans) or chemical barriers (e.g., Al toxicity).

PCC lime effect on Soil pH and Extractable Al

Linear regression analyses suggest that the soil pH intercepts were increasing with increasing soil depth, which suggests that south-eastern Idaho soil pH was becoming alkaline at deeper soil depths (Table 1.9 to Table 1.12). During the summer and fall of 2022, the intercepts were steeper at the top profile, which means that soil pH was rapidly increasing at the topsoil profile, and possibly why there were significant soil pH responses in the topsoil profile (Table 1.9 to Table 1.12; Appendix 1,5 to 2.6). This suggests that tillage is a big factor that can incorporate the PCC into the soil. However, it is common for tillage to incorporate lime only at the top 10 cm of the soil profile, which possibly resulted in the significant soil pH responses at the top profile. Caires et al. (2005) and Sumner (1995) also reported that lime incorporation with tillage usually distribute anions (HCO_3^- & OH^-) from lime dissolution at the topsoil profile. However, soil pH responses were not significant at some sites between the 10–15, 15–20, or the 20–30 cm depth (Table 1.9 to Table 1.12), because deeper profile soils are likely to receive less or no lime. This suggests that likely, there was no response of soil pH to PCC application.

Between soil pH methods, measured soil pH values were lower for pH 1:1$_{CaCl2}$ < pH 1:1$_{water}$ < pH 1 :2$_{water}$ (Table 1.9 to Table 1.12). At the highest PCC lime rate, the greatest soil pH 1:1$_{CaCl2}$ values ranged from 4.5 to 6.2, soil pH 1:1$_{water}$ values ranged from 4.9 to 6.6 and soil pH 1:2$_{water}$ values ranged from 5.0 to 6.8 one year after PCC application. These results are similar to reports by Miller et al. (2010), Sumner (1995), and Conyers et al. (1988) who reported that the salt effect with the addition of 0.01 M of $CaCl_2$ likely attributes to this response due to the exchange of Ca^{2+} and H^+ and possibly Al^{3+} on soil surfaces. Therefore, soil pH variations may have originated from the disparities in the pH methods, which all have a different or similar method in quantifying the pH of a soil. Soil pH 1:1$_{CaCl2}$ values were different from other pH methods because it quantifies the pH of the soil, while disregarding the relative buffering capacity of the soil. This method is more effective for soils with lower soluble soils (ECe < 0.4 dS m-1) as compared to the soil pH 1 :1_{water} or pH 1 :2_{water} methods (Gavlack et al., 2003). Changes in extractable Al were significant only in the top 15 cm profile (Table 1.13). These suggest that PCC lime rates reduced Al concentrations in the topsoil profile, which makes sense because the top acidic soil profile is prone to having more Al concentration as compared to the deeper soil profile. Flower et al., 2011 also reported that mitigation of Al by lime application below 10 cm is slow.

In general, liming effects can be limited by several factors, including soil texture and or the slow lime dissolution effect (Lierop et al., 1990; Anderson et al., 2019). Preliminary studies have reported that surface lime incorporation can mitigate soil acidity or Al effects on sandy clay loam soils at depths of 50, 55 and 60 cm depths, but only after 10 or 15 years (Caires et al., 2005; Tang 2003). However, our soils for this study are silt loam soils with high silt content of 65 to 75%, which likely increased resistance to lime movement at deeper soil depths (Barth et al., 2018; Conyers et al., 2003). Slow lime movement was also observed in other studies because lime can react with soil only at the depth that the lime was incorporated (Lierop et al., 1990; Anderson et al., 2019), which suggests that lime should be incorporated at deeper soil profile to neutralize soil pH beyond 10 cm soil depth.

Where linear models were not significant for the first 15 cm profile, but significant at the 15–20 or the 20–30 cm depth (Site D; Table 1.12), suggest some buffering activity. Dynamic changes in soil pH relative to soil depth are subject to the stratification of SOM, which makes soils vulnerable to biogeochemical reactions such as buffering reactions (Zheng et al., 2022). Increased crop residue inputs and rainfall or irrigation impacts are the primary predictors for the higher SOM pools above the 15 cm profile (Franzluebbers, 2002). In general, SOM contains a wide range of phenolic and carboxylic functional groups (Strawn, 2020; Hayes et al., 2001), which are binding sites for protons and cations. With larger SOM pools above the 15 cm profile, organic acids such as fulvic acids or humic acids of phenolic and carboxylic groups also increase, which highly buffers soils (Pertusatti et al., 2007).

Conclusion

PCC lime application did not significantly affect wheat and barley nutrient and quality parameters. Linear soil pH and Al responses were observed to PCC lime rates with the most significant response within the 10 cm soil depth. By conducting long term trials, a clearer understanding can be gained to assess the significant impact of lime application on both crop growth and soil properties.

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Table 1.1 Site locations, soil taxonomic descriptions, and soil textural analysis in the top 30 cm of agricultural fields in eastern Idaho, USA.

Site	County	Coordinates	Soil series	Sand	Clay	Silt
					———%——	
Site A	Fremont	44.0421611 °, -111.3975833°	Marystown (fine-silty, mixed, superactive, frigid Pachic Argixerolls) – Robinlee (fine-silty, mixed, superactive, frigid Calcic Pachic Argixerolls) – Rexburg (coarse-silty, mixed, superactive, frigid Calcic Haploxerolls), hardpan substratum silt loams, 1 to 4 percent slopes	19	11	70
Site B	Fremont	44.07132778 °, -111.39533333°	Marystown (fine-silty, mixed, superactive, frigid Pachic Argixerolls) – Robinlee (fine-silty, mixed, superactive, frigid Calcic Pachic Argixerolls) – Rexburg (coarse-silty, mixed, superactive, frigid Calcic Haploxerolls), hardpan substratum silt loams, 1 to 4 percent slopes	19	10	71
Site C	Fremont	44.08833333 °, -111.48666667°	Kucera (coarse-silty, mixed, superactive, frigid Calcic Pachic Haploxerolls) – Sarilda (coarse-silty, mixed, superactive, frigid Pachic Haploxerolls) silt loams, 2 to 6 percent slopes	26	9	65
Site D	Bonneville	44.49540833 °, -111.35486389°	Rin (coarse-silty, mixed, superactive Pachic Haplocryolls) silt loam, 4 to 12 percent slopes	17	6	77

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Table 1.2. Physical and chemical properties of precipitated calcium carbonate applied at four sites in Eastern Idaho, USA in 2021.

Property	Site A	Site B	Site C	Site D
Dry matter, (%)	76.5	76.6	76.5	95.8
CCE, (%) [a]	58.1, 76.0	61.4, 80.1	58.1, 76.0	68.2, 71.2
Total N, (%) [b]	0.44	0.37	0.44	0.35
Total C, (%) [b]	13.80	13.55	13.80	11.90
NO_3-N, (mg kg^{-1}) [b]	225.00	358.00	225.00	32.00
P_2O_5, (%) [b]	1.33	0.89	1.33	1.53
K_2O, (%) [b]	0.67	0.08	0.67	0.19
Ca, (%) [b]	31.02	32.04	31.02	32.54
Mg, % [b]	1.04	0.85	1.04	0.99
S, (%) [b]	0.80	0.21	0.80	0.65
Zn, (mg kg^{-1}) [b]	18.0	27.0	18.0	20.0
Fe, (mg kg^{-1}) [b]	1281.0	1094.0	1281.0	1356.0
Mn, (mg kg^{-1}) [b]	170.0	115.0	170.0	183.0
Cu, (mg kg^{-1}) [b]	11.0	24.0	11.0	11.0
B, (mg kg^{-1}) [b]	7.0	2.0	7.0	10.0
Na, (mg kg^{-1}) [b]	0.10	0.00	0.10	0.09
P, (mg kg^{-1}) [b]	0.59	0.39	0.59	0.67
K, (mg kg^{-1}) [b]	0.56	0.07	0.56	0.16
pH, as received	8.3	8.0	8.3	8.6
Salts, (mmhos cm^{-1}) [b]	2.6	1.2	2.6	1.2

[a] CCE: calcium carbonate equivalent on a “as applied” wet basis and oven dry basis.[b] dry weight basis.

Table 1.3. Field study management practices and activities for each field site from 2021 to 2022.

Year	Activity	Site A	Site B	Site C	Site D
2021	Previous crop	Potato	Potato	Potato	Canola
	Pre-lime application soil sampling (DOY) [a]	298	294	297	305
	Lime application (DOY) [a]	295	294	297	304
	Fall Tillage [b]	C	D, C	D	NT
2022	Spring tillage [b]	FC	FC	FC	NT
	N, P_2O_5, K_2O, S, Mg, B fertilizer rates (kg ha^{-1})	67/67, 17, 0, 17, 0, 0	157, 22, 22, 34, 0.6, 0.3	140, 28, 28, 45, 0, 0	
	N Source	Urea/UAN32			
	Crop [c]	HWSW	HRSW	SWSW	SB
	Variety	Explorer	Westbred 9668	Seahawk	Voyager
	Seed treatment [d]	Fv	Fcv	F, Ws	
	Seeding Rate (kg ha^{-1})	135	112	123	
	Seeding Depth (cm)	2.5	3	2.5	
	Weed control [e]	B, As	B, O	A	
	Summer soil sampling (DOY) [a]	160	159	161	174
	Hand harvest (DOY) [a]	NA	236	235	235
	Straw removal	Yes	Yes	Yes	
	Fall soil sampling (DOY) [a]	257	258	257	258
	Fall Tillage [b]	FC	D, C	C	NT

[a] DOY: day of the year

[b] Tillage method: D, disk; C, chisel/ripper; FC, field cultivator; NT, no-till

[c] HWSW: hard white spring wheat; SWSW: soft white spring wheat; SB: spring barley

[d] Fcv: fungicide, CruiserMaxx Vibrance, Syngenta, a.i. sedaxane, difenoconazole, mefenoxam, thiamethoxam; Fv: fungicide, Vibrance Extreme, Syngenta, a.i. sedaxane, difenoconazole, mefenoxam; Ws: wireworm, Senator 600 FS, Nufarm Americas Inc., a.i. imadacloprid;

[e] A: Axial XL (pinoxaden), Syngenta; As: Axial Star (pinoxaden + fluroxypyr), Syngenta, Greensboro, North Carolina, U.S.; B: Bronate (bromoxynil + MCPA), Bayer CropScience; O: OpenSky (fluroxypyr + pyroxsulam), Corteva,

Table 1.4. Initial soil chemical properties in the top 30 cm of the soil profile for four Idaho field sites.

Property	Depth	Site A	Site B	Site C	Site D
pH [a]	0 – 5 cm	4.8	4.6	5.0	5.6
	5 – 10 cm	4.7	4.6	5.1	5.1
	10 – 15 cm	4.9	4.8	5.3	5.4
	15 – 20 cm	5.2	5.2	5.6	5.9
	20 – 30 cm	6.1	5.7	6.1	6.2
Al, mg kg^{-1}	0 – 15 cm	6.2	13.8	3.1	2.1
	15 – 30 cm	6.3	14.2	2.6	1.8
Ca, meq 100 g^{-1}	0 – 30 cm	7.9	6.0	6.1	7.1
Mg, meq 100 g^{-1}	0 – 30 cm	1.7	1.3	1.6	1.2
Na, meq 100 g^{-1}	0 – 30 cm	0.2	0.2	0.2	0.1
CEC, meq 100 g^{-1} [b]	0 – 30 cm	11.8	9.4	9.5	10.2
K, mg kg^{-1}	0 – 30 cm	161.1	125.7	109.5	194.5
N, mg kg^{-1} [c]	0 – 30 cm	6.0	5.8	5.8	4.5
Fe, mg kg^{-1}	0 – 30 cm	47.9	57.3	50.4	56.7
OM [d]	0 – 30 cm	2.11	2.4	2.4	3.0

[a] Soil pH measured using $1{:}1_{water}$; [b] CEC: cation exchange capacity; [c] N: Nitrate; [d] OM: organic matter.

Table 1.5. Actual wet and dry lime application rates and equivalent $CaCO_3$ rates of PCC utilized in field trials across all sites in Eastern Idaho, USA.

Wet basis rate (Mg ha^{-1})	Dry basis rate (Mg ha^{-1})	Equivalent $CaCO_3$ rate (Mg ha^{-1})
Site A & B		
0	0	0
4.5	3.4	2.8
9	6.9	5.5
13.5	10.3	8.3
Site C		
0	0	0
4.5	3.4	2.6
9	6.9	5.2
13.5	10.3	7.8
Site D		
0	0	0
4.5	4.3	4.1
9	8.6	8.2
13.5	12.9	12.3

Table 1.6. Treatment means for grain yield, grain protein, grain test weight, kernel plumps, and straw biomass in response to the dry “equivalent $CaCO_3$ rates” of precipitated calcium carbonate at three different farm sites in eastern Idaho, USA.

Treatment	Yield (kg ha^{-1})	Protein (g kg^{-1})	Test Weight (kg hL^{-1})	Dry Biomass (Mg ha^{-1})	Plumps (%)
Equivalent $CaCO_3$ rate (Mg ha^{-1})			**Site B**		
0	6299[1]a	176a	79b	5a	-
2.8	6406a	160b	80a	5a	-
5.5	6460a	160b	80a	5a	-
8.3	7429a	162b	80a	6a	-
P-value	0.408	**0.001**	**0.001**	0.484	
			Site C		
0	7376a	100a	73a	7a	-
2.6	7106a	106a	73a	7a	-
5.2	6837a	105a	73a	6a	-
7.8	7430a	103a	73a	6a	-
P-value	0.799	0.458	0.573	0.796	
			Site D		
0	5317a	11.3a	64a	3a	99.6a
4.1	5586a	11.5a	64a	2a	99.6a
6.4	6192a	11.4a	66a	4a	99.6a
9.6	5115a	11.3a	67a	3a	99.8a
P-value	0.409	0.975	0.179	0.473	0.873

[1] Within the same column and site, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Table 1.7. Treatment means for straw nutrient in response to PCC rates at three different farm sites in eastern Idaho, USA.

Treatment	**N[1] (%)**	**P[1] (%)**	**K [1] (%)**	**Al[1] (%)**	**Na[1] (%)**
Equivalent $CaCO_3$ rate (Mg ha^{-1})			**SITE B**		
0	0.7a	0.03a	3.58a	24.3a	332a
2.8	0.7a	0.04a	3.61a	15.9a	376a
5.5	0.7a	0.04a	3.34a	15.1a	388a
8.3	0.7a	0.04a	3.44a	22.7a	386a
P-value	0.833	0.292	0.068	0.519	0.351
			SITE C		
0	0.7a	0.67a	2.36a	17.8b	505a
2.6	0.8a	0.61a	2.22a	17.1b	1443a
5.2	0.8a	0.59a	2.06a	16.8b	1054a
7.8	0.8a	0.66a	2.36a	25.0a	997a
P-value	0.501	0.539	0.284	**0.034**	0.103
			SITE D		
0	0.9a	0.10a	2.11a	339.1a	151a
4.1	0.8a	0.09a	2.12a	91.8a	148a
6.4	0.9a	0.11a	1.93a	85.8a	160a
9.6	0.8a	0.11a	1.93a	53.3a	195a
P-value	0.501	0.976	0.667	0.504	0.597

[1] Abbreviations: N; Nitrogen, P; Phosphorus, K; Potassium, Al; Aluminum, Na; Sodium.

[2] Within the same column and site, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Table 1.8. Treatment means for grain nutrient in response to PCC rates at three different farm sites in eastern Idaho, USA.

Treatment	**N[1] (%)**	**P[1] (%)**	**K [1] (%)**	**Al[1] (%)**	**Na[1] (%)**
Equivalent $CaCO_3$ rate (Mg ha^{-1})			**SITE B**		
0	3.1a	0.35b	0.38b	12.6a	48.9a
2.8	3.0a	0.37b	0.41a	12.9a	62.8a
5.5	3.0a	0.40a	0.41a	9.6a	55.5a
8.3	2.9a	0.42a	0.45a	11.2a	51.3a
P-value	0.833	**0.015**	**0.027**	0.774	0.518
			SITE C		
0	1.9a	0.35a	0.49b	10.9a	45.5a
2.6	1.9a	0.36a	0.48b	10.6a	57.0a
5.2	1.9a	0.38a	0.50a	11.5a	54.6a
7.8	1.8a	0.40a	0.53a	11.2a	52.3a
P-value	0.723	0.108	**0.045**	0.992	0.218
			SITE D		
0	1.9a	0.44a	0.54a	28.0a	51.4a
4.1	2.1a	0.42a	0.53a	29.7a	48.5a
6.4	2.0a	0.42a	0.53a	32.4a	52.5a
9.6	1.9a	0.44a	055a	27.5a	52.8a
P-value	0.292	0.292	0.878	0.504	0.695

[1] Abbreviations: N; Nitrogen, P; Phosphorus, K; Potassium, Al; Aluminum, Na; Sodium.

[2] Within the same column and site, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Table 1.9. Linear regression equations for soil pH 1:1 $_{\text{water}}$, soil pH 1:2 $_{\text{water}}$, and soil pH 1:1 $_{\text{0.01M CaCl2}}$ responses to "equivalent $CaCO_3$ rate" at Site A measured during the Summer and Fall of 2022.

Soil depth (cm)	Linear regression equation	*P-value*	R^2	Linear regression equation	*P-value*	R^2	Linear regression equation	*P-value*	R^2
				SUMMER 2022					
	A[1]			**B**			**C**		
	pH 1:1 $_{\text{water}}$			**pH 1:2 $_{\text{water}}$**			**pH 1:1 $_{\text{CaCl2}}$**		
0–5	$y=5.3 + 0.09x$	**<0.001**	0.32	$y=5.6 + 0.10x$	**<0.001**	0.66	$y=4.6 + 0.14x$	**<0.001**	0.52
5–10	$y=5.1 + 0.08x$	**<0.001**	0.25	$y=5.5 + 0.09x$	**<0.001**	0.56	$y=4.3 + 0.10x$	**<0.001**	0.53
10–15	$y=5.2 + 0.03x$	0.25	0.09	$y=5.5 + 0.04x$	0.11	0.16	$y=4.4 + 0.04x$	**0.03**	0.31
15–20	$y=5.4 + 0.03x$	0.20	0.11	$y=5.8 + 0.002x$	0.94	0.94	$y=4.6 + 0.10x$	0.24	0.10
20–30	$y=5.7 + 0.02x$	0.37	0.06	$y=6.2 - 0.0007x$	0.97	0.001	$y=5.0 + 0.03x$	0.07	0.01
				FALL 2022					
	D			**E**			**F**		
	pH 1:1 $_{\text{water}}$			**pH 1:2 $_{\text{water}}$**			**pH 1:1 $_{\text{CaCl2}}$**		
0–5	$y=5.2 + 0.15x$	**<0.001**	0.62	$y=5.4 + 0.15x$	**<0.001**	0.63	$y=4.6 + 0.17x$	**<0.001**	0.66
5–10	$y=5.0 + 0.12x$	**<0.001**	0.50	$y=5.3 + 0.10x$	**<0.001**	0.49	$y=4.4 + 0.10x$	**<0.001**	0.54
10–15	$y=5.2 + 0.03x$	**0.04**	0.25	$y=5.5 + 0.04x$	**0.01**	0.37	$y=4.3 + 0.06x$	**<0.001**	0.68
15–20	$y=5.3 + 0.32x$	**<0.001**	0.52	$y=5.6 + 0.03x$	**0.01**	0.38	$y=4.5 + 0.03x$	0.09	0.18
20–30	$y=5.5 + 0.05x$	**<0.001**	0.62	$y=5.8 + 0.03x$	**0.04**	0.25	$y=4.8 + 0.03x$	0.06	0.24

[1] See appendix 1.1 for regression graphs.

Table 1.10. Linear regression equations for soil pH 1:1 water, soil pH 1:2 water, and soil pH 1:1 0.01M CaCl2 responses to "equivalent CaCO3 rate" at Site B measured during the Summer and Fall of 2022.

Soil depth (cm)	**Linear regression equation**	***P-value***	**R^2**	**Linear regression equation**	***P-value***	**R^2**	**Linear regression equation**	***P-value***	**R^2**
SUMMER 2022									
	A[1]			**B**			**C**		
	pH 1:1 $_{\text{water}}$			**pH 1:2 $_{\text{water}}$**			**pH 1:1 $_{\text{CaCl2}}$**		
0–5	y=5.7 + 0.18x	**<0.001**	0.64	y=6.0 + 0.07x	**<0.001**	0.67	y=5.4 + 0.11x	**<0.001**	0.76
5–10	y=5.4 + 0.14x	**<0.001**	0.50	y=5.8 + 0.10x	**<0.001**	0.47	y=5.0 + 0.16x	**<0.001**	0.58
10–15	y=5.0 + 0.07x	**0.004**	0.44	y=5.1 + 0.10x	**<0.001**	0.61	y=4.4 + 0.11x	**<0.001**	0.59
15–20	y=5.4 +0.004x	0.81	0.004	y=5.7 + 0.02x	0.33	0.07	y=4.7 + 0.05x	0.08	0.40
20–30	y=6.2 - 0.06x	0.009	0.39	y=6.3 - 0.17x	0.11	0.17	y=5.2 + 0.01x	0.17	0.13
FALL 2022									
	D			**E**			**F**		
	pH 1:1 $_{\text{water}}$			**pH 1:2 $_{\text{water}}$**			**pH 1:1 $_{\text{CaCl2}}$**		
0–5	y=4.2 + 0.15x	**<0.001**	0.94	y=5.3 + 0.14x	**<0.001**	0.65	y=4.1 + 0.24x	**<0.001**	0.91
5–10	y=4.5 + 0.11x	**<0.001**	0.52	y=5.5 + 0.01x	0.85	0.002	y=4.3 + 0.01x	**<0.001**	0.53
10–15	y=4.9 + 0.05x	**0.01**	0.35	y=5.5 + 0.02x	0.56	0.03	y=4.5 + 0.03x	**0.005**	0.44
15–20	y=5.0 + 0.06x	**0.004**	0.45	y=5.6 + 0.01x	0.38	0.05	y=4.6 + 0.04x	0.007	0.41
20–30	y=5.5 + 0.03x	0.06	0.24	y=5.8 + 0.004x	0.83	0.003	y=5.2 + 0.03x	0.10	0.18

[1] See appendix 1.2 for regression graphs.

Table 1.11. Linear regression equations for soil pH 1:1 water, soil pH 1:2 water, and soil pH 1:1 0.01M CaCl2 responses to “equivalent CaCO3 rate” at Site C measured during the Summer and Fall of 2022.

Soil depth (cm)	**Linear regression equation**	***P-value***	**R^2**	**Linear regression equation**	***P-value***	**R^2**	**Linear regression equation**	***P-value***	**R^2**
				SUMMER 2022					
	A[1]			**B**			**C**		
	pH 1:1 $_{\text{water}}$			**pH 1:2 $_{\text{water}}$**			**pH 1:1 $_{\text{CaCl2}}$**		
0–5	y=4.8 + 0.24x	**<0.001**	0.93	y=5.4 + 0.19x	**<0.001**	0.94	y=4.3 + 0.26x	**<0.001**	0.98
5–10	y=5.2 + 0.16x	**<0.001**	0.82	y=5.4+ 0.15x	**<0.001**	0.56	y=4.8 + 0.18x	**<0.001**	0.64
10–15	y=5.4 + 0.12x	**<0.001**	0.80	y=5.8 + 0.09x	**<0.001**	0.58	y=5.0 + 0.09x	**0.004**	0.44
15–20	y=5.7 + 0.10x	**<0.001**	0.55	y=6.0 + 0.07x	**0.01**	0.36	y=5.0 + 0.08x	**0.04**	0.24
20–30	y=5.9 + 0.07x	**<0.001**	0.39	y=6.1 + 0.07x	**0.01**	0.36	y=5.3 + 0.08x	**0.05**	0.25
				FALL 2022					
	D			**E**			**F**		
	pH 1:1 $_{\text{water}}$			**pH 1:2 $_{\text{water}}$**			**pH 1:1 $_{\text{CaCl2}}$**		
0–5	y=5.3 + 0.08x	**0.04**	0.25	y=5.8 + 0.13x	**<0.001**	0.72	y=4.9 + 0.18x	**<0.001**	0.56
5–10	y=5.7 + 0.02x	0.75	0.007	y=5.8 + 0.13x	**<0.001**	0.60	y=5.2 + 0.008x	0.90	0.001
10–15	y=5.8 - 0.002x	0.97	0.0001	y=6.1 - 0.01x	0.63	0.01	y=5.1 - 0.0003x	0.98	0.001
15–20	y=6.0 - 0.03x	0.39	0.05	y=6.2 - 0.02x	0.44	0.04	y=5.2 - 0.02x	0.37	0.06
20–30	y=6.1 - 0.02x	0.44	0.04	y=6.4 - 0.03x	0.27	0.08	y=5.6 - 0.04x	0.37	0.06

[1] See appendix 1.3 for regression graphs.

Table 1.12. Linear regression equations for soil pH 1:1 water, soil pH 1:2 water, and soil pH 1:1 0.01M CaCl2 responses to "equivalent CaCO3 rate" at Site D measured during the Summer and Fall of 2022.

Soil depth (cm)	**Linear regression equation**	***P-value***	**R^2**	**Linear regression equation**	***P-value***	**R^2**	**Linear regression equation**	***P-value***	**R^2**
SUMMER 2022									
	A[1]			**B**			**C**		
	pH 1:1 $_{\text{water}}$			**pH 1:2 $_{\text{water}}$**			**pH 1:1 $_{\text{CaCl2}}$**		
0–5	y=5.3 + 0.13x	**<0.001**	0.58	y=5.9 + 0.08x	**0.007**	0.41	y=5.0 + 0.14x	**<0.001**	0.65
5–10	y=5.3 + 0.03x	0.07	0.21	y=5.6 + 0.03x	**0.009**	0.39	y=4.6 + 0.04x	**<0.001**	0.60
10–15	y=5.4 + 0.03x	0.06	0.22	y=5.7 + 0.02x	0.22	0.11	y=4.8 + 0.03x	**0.01**	0.38
15–20	y=5.6 + 0.06x	**0.004**	0.45	y=6.2 + 0.000006x	0.99	0.001	y=5.3 + 0.01x	0.51	0.03
20–30	y=6.2 + 0.001x	0.99	0.001	y=6.5 + 0.001x	0.89	0.001	y=5.5 + 0.01x	0.25	0.08
FALL 2022									
	D			**E**			**F**		
	pH 1:1 $_{\text{water}}$			**pH 1:2 $_{\text{water}}$**			**pH 1:1 $_{\text{CaCl2}}$**		
0–5	y=5.4 + 0.11x	**0.002**	0.50	y=5.7 + 0.10x	**0.002**	0.49	y=5.2 + 0.12x	**<0.001**	073
5–10	y=5.1 + 0.04x	0.08	0.19	y=5.2 + 0.06x	**0.004**	0.45	y=4.6 + 0.02x	0.09	0.19
10–15	y=5.0 + 0.06x	0.07	0.21	y=5.2 + 0.09x	**0.03**	0.32	y=4.6 + 0.05x	**0.05**	0.24
15–20	y=5.5 + 0.05x	**0.02**	0.33	y=5.8 + 0.05x	**0.01**	0.34	y=4.9 + 0.05x	**0.02**	0.31
20–30	y=5.9 + 0.03x	**0.04**	0.25	y=6.3 + 0.02x	0.10	0.18	y=5.4 + 0.05x	**0.004**	0.44

[1] See appendix 1.4 for regression graphs.

Table 1.13. Linear regression equations for KCl aluminum responses to "equivalent $CaCO_3$ rate" measured during Fall 2022 in eastern Idaho, USA.

Soil depth (cm)	Linear regression equation	*P-value*	R^2
	Site A		
0-15	$y=9.3 - 0.85x$	**<0.001**	0.27
15-30	$y=6.4 - 0.38x$	0.30	0.03
	Site B		
0-15	$y=33.9 - 4.24x$	**<0.001**	0.71
15-30	$y=8.7 - 0.01x$	0.99	0.001
	Site C		
0-15	$y=8.9 - 1.07x$	**<0.001**	0.15
15-30	$y=1.5 - 0.05x$	0.29	0.04
	Site D		
0-15	$y=8.7 - 0.86x$	**<0.001**	0.40
15-30	$y=1.0 + 0.0004x$	0.46	0.001

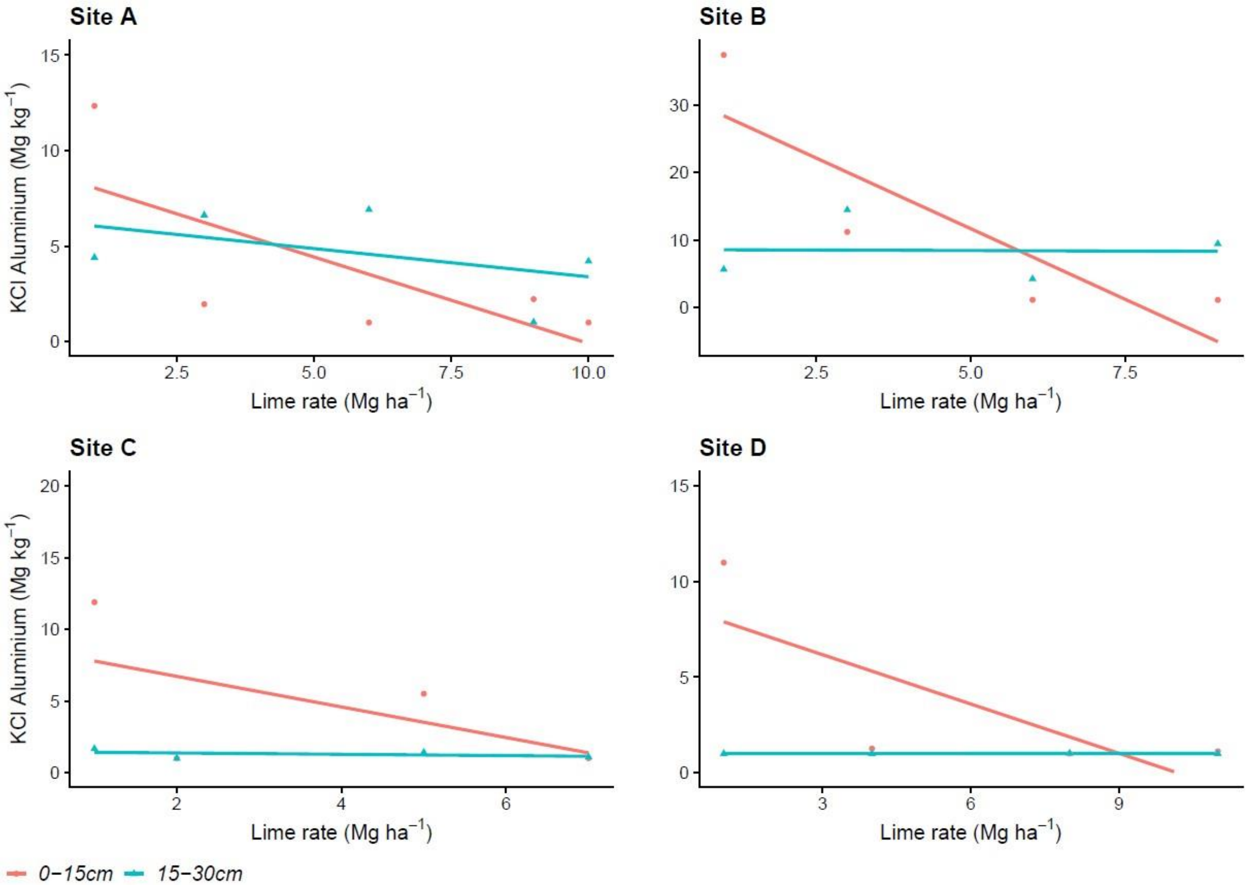

Figure 1.2. KCl aluminum responses to “equivalent CaCO3 rate” measured during Fall 2022 in eastern Idaho, USA.

Chapter 2: Precipitated Calcium Carbonate Effects on Soil Properties and Early Barley Development

Abstract

The extent of soil acidification is increasing in the surface soil layers, which weighs heavily on the crop producers in the United States. Even though most western arid soils are alkaline, some regional acidic agricultural acres in eastern Idaho could benefit from lime additions to correct lower soil pH issues in both no-till and conventional tillage systems. While these areas could benefit from PCC additions, most growers are wary of applying materials that may cause physical or chemical issues in soil that would negatively affect crop growth. This study was conducted to evaluate the effects of PCC rates on soils and early season barley growth. Generally, PCC rates did not negatively affect the early barley growth, soil pH and EC. There was no statistically significant effect of PCC on the barley shoot mass planted in Robana-Rin and Portneuf soils. PCC rates significantly increased soil pH for all soil types. Robana-Rin soil had the lowest initial pH of 4.1 and the greatest increase in pH when PCC was added, a 2.9 pH unit increase. The Portneuf and Wolverine soils had higher initial pH values and the pH increases from PCC additions were less than in the Robana-Rin soil. There were no effects of PCC applications on soil EC for the Portneuf and Wolverine soils except for Robana-Rin soil, which showed 0.72 dS m-1 soil EC increase with PCC addition. PCC can safely be added to improve soil pH on acidic soils without affecting barley growth.

Introduction

The natural process of soil acidification is accelerated by the application of ammonium- and elemental sulfur-containing fertilizers (Heylar, 1976), the removal of base cations (Ca, Mg, K, and Na) at harvest (Hart et al., 2013; Engel et al., 2020), and leaching of base cations and their conjugate bases such as nitrate (Patriquin et al., 1993). Even under intensively managed agricultural production systems, soil pH change is gradual (e.g., 0.1 pH unit per 91–100 kg of applied ammonium-based nitrogen fertilizer) and the effect on yield and crop quality is often not observed until a soil pH threshold is reached (Mahler and McDole, 1987). The critical pH threshold varies by crop and is approximately 6.0 for alfalfa, 5.6–5.7 for annual legumes like peas, 5.2 for wheat and barley (Mahler and McDole, 1987;

Koenig et al., 2009), and <5.0 for potato (Horneck et al., 2007). Mahler and McDole (1987) showed that most agronomic crops produce 75% of maximum yield when the soil pH is 0.3 pH units below the crop's critical pH threshold. Reductions in crop yield are due to Al and/or Mn toxicity; H^+ ion toxicity; decreased bioavailability of Ca, Mg, P, K, and Mo concentrations; and inhibition of root growth (Marschner, 1995).

While most arid and semi-arid western U.S. soils are alkaline, there are regional acidic areas that could benefit from periodic applications of liming materials are used to maintain the productivity of acidic soils (Brown et al., 1959). Liming materials include calcium and magnesium carbonates, fly ash, and precipitated calcium carbonate (PCC) (Havlin et al., 2013). In areas where conventional agricultural liming materials are either unavailable or uneconomical, locally produced liming materials could serve as a valuable asset for producers.

Southern Idaho and southeastern Oregon are primary producers of sugar beets harvesting 67,340 ha yr^{-1} on average from 2017 to 2021 (USDA-NASS, 2022). Precipitated calcium carbonate is a byproduct of sucrose extraction during the processing of sugar beet roots. In 2018, the Amalgamated Sugar Company processing factories (Paul, ID; Twin Falls, ID; and Nampa, ID) had PCC stockpiles totaling approximately 12.6 million tons (*ASCO, personal communication)*. These factories produce approximately 351,081 Mg (387,000 tons) of PCC annually. The PCC produced from the sugar beet processing factories in Idaho has been measured to have a $CaCO_3$ equivalency of between 75% and 81% (Tarkalson, per. Comm.). A majority of the agricultural land around these plants does not need lime (e.g. PCC) additions to correct low pH, thus the PCC accumulates over time. However, approximately 64,750 ha of agricultural land in eastern Idaho (Fremont, Bonneville, Caribou, and Oneida counties) could benefit from lime additions due to surface acidification from ammonium-based fertilizer applications in both no-till and conventional tillage systems (Tarkalson et al., 2006).

Although there are significant agricultural acres in Idaho that could benefit from local PCC inputs to correct low pH issues, growers are wary of applying materials that may contain toxic constituents or cause physical or chemical issue in soil that would negatively affect crop growth. Barley production is used for the malt and feed industries and with approximately 890,300 ha harvested in the U.S. with an average yield of 4.2 metric tonnes

ha^{-1} (NASS, 2020). Because soil acidity remains one of the constraints to barley production, the experiments reported in this paper were designed to examine the responses of barley growth and soil properties to PCC application rates.

Materials and Methods

Study site and soil sampling

This research study was conducted at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID. Three agricultural soil samples were collected at a depth of 0 to 30 cm from the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID [Portneuf silt loam (coarse-silty mixed mesic Durixerollic Caliciorthid)], an agricultural field near Firth, ID [Wolverine sand (Mixed, frigid Xeric Torripsamment)], and an agricultural field near Ashton, ID [Robana silt loam (Fine-silty, mixed, superactive Pachic Agricryolls)–Rin silt loam (Coarse-silty, mixed, superactive Pachic C Haplocryolls) complex (Robana-Rin silt loam)]. The Portneuf soil is primarily found in southern Idaho and occupies approximately 117,000 ha (NRCS, 2009a). The Wolverine soil is primarily found in southern Idaho and Oregon and occupies approximately 11,000 ha (NRCS, 2009a). Although the Wolverine soil does not occupy as large of an area as the Portneuf soil, soils similar to the Wolverine series (Xeric Torripasamment soils) occupy more than 5 million ha from the western United States to the Great Plains (NRCS, 2009a).

Initial Soil Analyses

After collection, the soils were air-dried and passed through a 5-mm sieve before analysis. The soil samples were analyzed for pH (Kalra, 1995), electrical conductivity (EC) (Rhoades, 1996), bicarbonate extractable P (Olsen et al., 1954), NO_3-N and NH_4-N (Mulvaney, 1996), total C and N using a FlashEA1112 CN analyzer (CE, Elantech, Lakewood, NJ), and total elements (Mg, P and K) with ICP-OES detection (U.S. Environmental Protection Agency, 1996) (Table 2.1).

Lime Samples

The PCC used in this study was collected from a lime pile near Sugar City, ID and analyzed for pH (Kalra, 1995), electrical conductivity (EC) (Rhoades, 1996), bicarbonate extractable P (Olsen et al., 1954), NO_3-N and NH_4-N (Mulvaney, 1996), and total elements

(Mg, P, K, Cu, Fe, Mn, Zn, and Al) with ICP-OES detection (U.S. Environmental Protection Agency, 1996) (Table 2.5). Lime rates were based on a dry basis.

Greenhouse Study

For each soil, treatments consisted of PCC applied at rates of 0, 6.7, 22.4, 67.3 Mg ha^{-1} (0, 3, 10, 30 tons ac^{-1}) (dry matter basis). Each pot contained 400 g soil. The amount of PCC added to each pot for the 0, 6.7, 22.4, 67.3 Mg ha^{-1} treatments was 0, 1.2, 4, and 12 g, respectively. Because PCC contains N, P and K, urea, superphosphate and KCl fertilizers were added to balance out the PCC N, P and K inputs across all treatments (Table 2.3). For each pot, PCC and fertilizers were homogenized then placed in 400 cm^3 plastic pots. Each treatment was replicated four times in a complete randomized design. On November 19, 2014, for each pot, 0.5 cups of soil were removed, and 10 barley seeds were placed evenly on the soil surface and the removed soil was placed back in the pots on top of the seeds. The study was conducted in a greenhouse. Once per week, water was added to all pots to bring all the soils back to a uniform weight (approximately 70% of soil water content at field capacity). On December 8, 2014, the emerged barley plants were thinned to 8 plants per pot. On December 23, 2014 (tillering growth stage), barley shoots and roots were harvested, cleaned with water, dried at 140° F, and weighed. After barley harvest, the soils in each pot were air dried, ground, and analyzed for pH (Kalra, 1995), and EC (Rhoades, 1996).

Statistical Analysis

Analysis of variance was determined for PCC treatment main effects for barley top and root weight, and soil pH and EC using a randomized design model in Statistix 8.2 (Analytical Software, Tallahassee, FL). For significant (0.05 probability level) main effects, linear or quadratic regression were fitted to the data.

Results and Discussion

Initial Soil and PCC Properties

Pre-treatment PCC and soil PCC analysis are in Table 2.0 and Table 2.1. The calcium carbonate equivalency (CCE) is the acid neutralizing value of PCC compared to 100% calcium carbonate. The average CCE of PCC used in this study was 75%. This PCC is a good lime source compared to other by-product related lime sources. For example, Class C fly ash (by-product of subbituminous coal combustion) utilized in Nebraska as an agricultural lime source, has an average CCE of 40-45% (Tarkalson et al., 2005; Yunusa et al., 2012).

The PCC contains 4.3 kg P_2O_5 Mg^{-1} (8.6 lbs P_2O_5 ton^{-1}) and 0.012 kg K_2O Mg^{-1} (0.024 lbs K_2O ton^{-1}) (Table 2.3). These concentrations are lower than other reported values from other PCC samples in Idaho and across the country. Tarkalson et al. (2023) reported P_2O_5 contents ranging from 11 to 15 kg Mg^{-1} (21 to 30 lbs ton^{-1}) and K_2O contents ranging from 1.2 to 2.3 kg Mg^{-1} (2.4 to 4.6 lbs ton^{-1}). The PCC piles at Sugar City, ID are much older than the piles referred to in Tarkalson et al. (2003). The pH of the Robana-Rin soil is in the acidic range (4.1) compared to the Wolverine and Portneuf soils, 7.9 and 7.3, respectively. The field the Robana-Rin soil was collected was under no-till barley production and the soil surface had acidified over time due to NH_4-N based fertilizer use.

PCC Lime Effects on Early Barley Growth

Generally, the PCC application did not affect barley shoot or root masses across all soils except for barley shoot mass grown in the Wolverine soil. There was no statistically significant effect of PCC on the barley shoot mass planted in Robana-Rin and Portneuf soils. When PCC was added to the Wolverine soil the shoot mass increased by an average of 0.316 g across all PCC treatments compared to the control (Table 2.4, Figure 2.1). There were no significant effects of PCC on barley root masses across all soil types (Table 2.4, Figure 2.1).

PCC Effects on Soil Properties

The PCC rates significantly increased soil pH for all soil types (Table 2.4, Figure 2.2). The increase in pH was expected due to PCC having a high concentration of $CaCO_3$ (Table 2.2). The Robana-Rin soil had the lowest initial pH of 4.1 and the greatest increase in pH when PCC was added, a 2.9 pH unit increase from the 0 to 67 Mg ha^{-1} application rate (Figure 2.2). The Portneuf and Wolverine soils had higher initial pH values and the pH increases from PCC additions were less than in the Robana-Rin soil (Figure 2.2). There were no effects of PCC applications on soil EC for the Portneuf and Wolverine soils (Table 2.4, Figure 2.2). However, soil EC increased with PCC applications in the Robana-Rin soil (Table 2.4 and Figure 2.2). The Robana-Rin soil EC increased by 0.72 dS m^{-1} from the control to the highest PCC treatment. Divalent cations (Mg) are likely a contributing factor in increasing soil EC (Paz et al., 2009).

Conclusion

There were no negative effects of PCC used in this study on early barley growth or soil pH or EC. The results of the study indicate that PCC can safely be added to improve soil pH on acidic soils. This is very important for soil reclamation with the decreasing soil pH worldwide. Further research can evaluate long term effects of PCC application on soil properties and crop production.

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Table 2.1. Selected chemical characteristics of the Robana-Rin silt loam (RRSL), Wolverine sand (WS) and Portneuf silt loam (PSL) soils.

Measurement/Analyte	Robana-Rin silt loam	Wolverine sand	Portneuf silt loam
EC (dS m^{-1})	0.375	0.214	0.629
pH	4.1	7.9	7.3
NO_3-N (mg kg^{-1})	40.2	7.5	47.6
NH_4-N (mg kg^{-1})	23.7	5.8	9.6
Bicarbonate P (mg kg^{-1})	62.4	6.0	33.0
N (%)	0.18	0.03	0.11
C (%)	1.8	0.97	1.23
Calcium (mg kg^{-1})	2818.8	22777.9	9794.54
Magnesium (mg kg^{-1})	3636.5	2410.7	6248.8
Phosphorus (mg kg^{-1})	931.9	581.9	752.6
Potassium (mg kg^{-1})	2358.7	854.9	3425.2

Table 2.2. Selected lime quality and total constituent content in beet lime.

Constituent (units)[1]	Content
Calcium Carbonate Equivalent (%)	75
Effective Calcium Carbonate Equivalent (%)	60
Magnesium (mg kg^{-1})	69.4
Phosphorus (mg kg^{-1})	1878.0
Potassium (mg kg^{-1})	9.9
Copper (mg kg^{-1})	0.27
Iron (mg kg^{-1})	65.1
Manganese (mg kg^{-1})	52.9
Zinc (mg kg^{-1})	0.28
Aluminum (mg kg^{-1})	33.9

1. Dry weight basis

Table 2.3. Precipitated calcium carbonate (PCC) treatment rates and N, P, and K application rates.

		Nutrients Applied in Lime			Nutrients Applied in Fertilizer[2]			Total Nutrients from Lime and Fertilizer[3]		
Lime Rate[1]	Lime Rate	N	P	K	N	P	K	N	P	K
tons ac^{-1}	g pot^{-1}	-------------------------------------mg pot^{-1}--								
0	0	0	0	0	40	42	9.8	40	41.9	9.8
3	1.2	0.3	4.2	1.0	40	37.7	8.8	40.3	41.9	9.8
10	4.0	1	14.0	3.3	40	27.9	6.5	41	41.9	9.8
30	12.0	3	41.9	9.8	40	0	0	43	41.9	9.8

1. Rate based on a Mg of lime applied to a hectare-furrow slice (2,425 tons soil)
2. Fertilizers used: N, Urea (46% N); P, superphosphate (21% P_2O_5); K, muriate of potash (52% K_20).
3. N applied to pots was equivalent to 195 to 210 lbs N ac^{-1} across all lime rates. P and K applied to pots were equivalent to 205 and 48 lbs P and K ac^{-1}, respectively, based on application to a hectare-furrow slice (2,425 tons soil).

Table 2.4. ANOVA for top and root mass, and end of study soil pH and soil electrical conductivity (EC).

	Robana-Rin silt loam	Wolverine Sand	Portneuf Silt Loam
Top Mass	0.448	**<0.001**	0.078
Root Mass	0.859	0.759	0.520
Soil pH	**<0.001**	**0.014**	**<0.001**
Soil EC	**0.015**	0.284	0.270

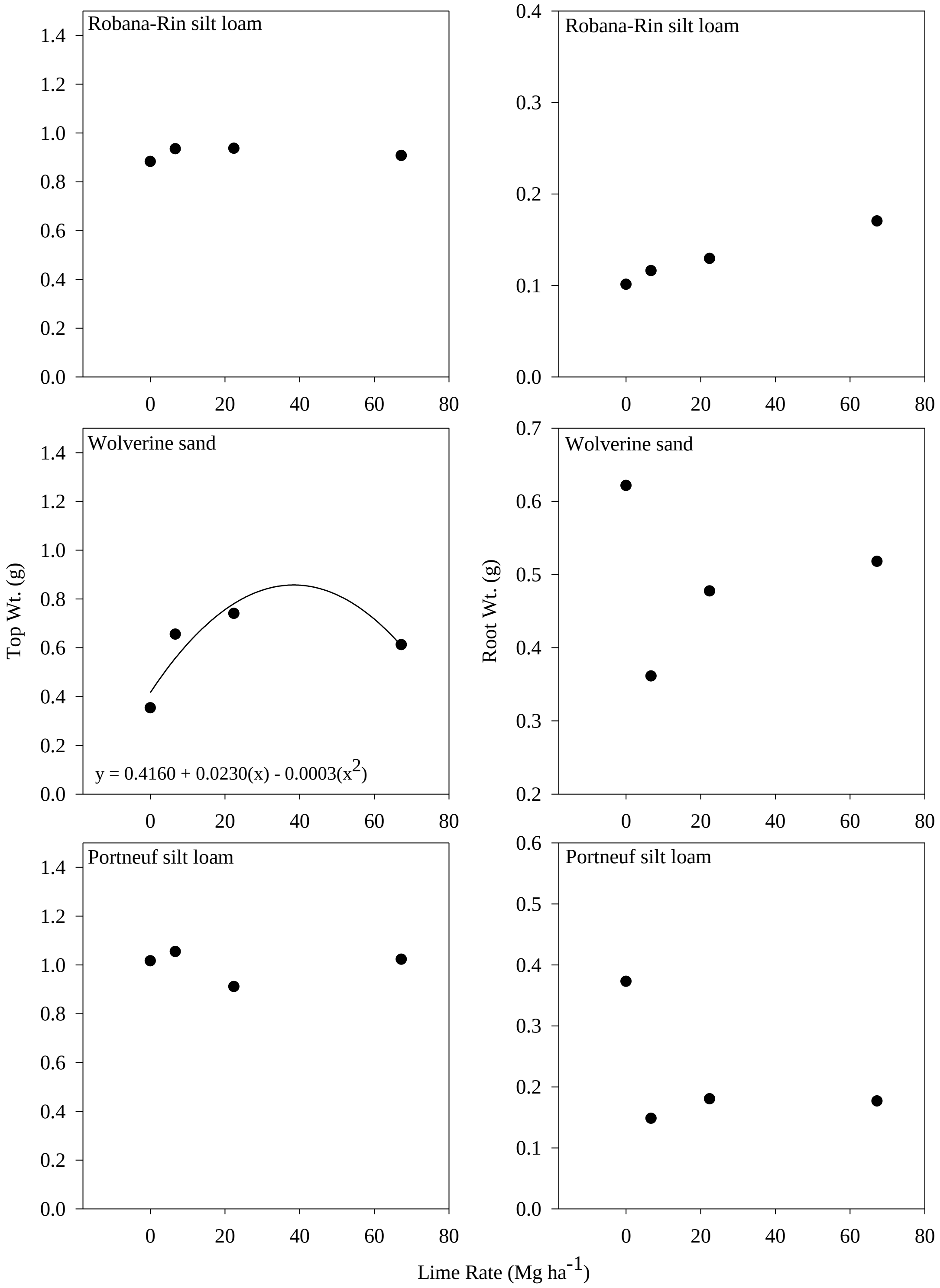

Figure 2.1. Relationship between lime rate and wheat top weight and wheat root weight in the Robana-Rim silt loam, Wolverine sand, and Portneuf silt loam soils.

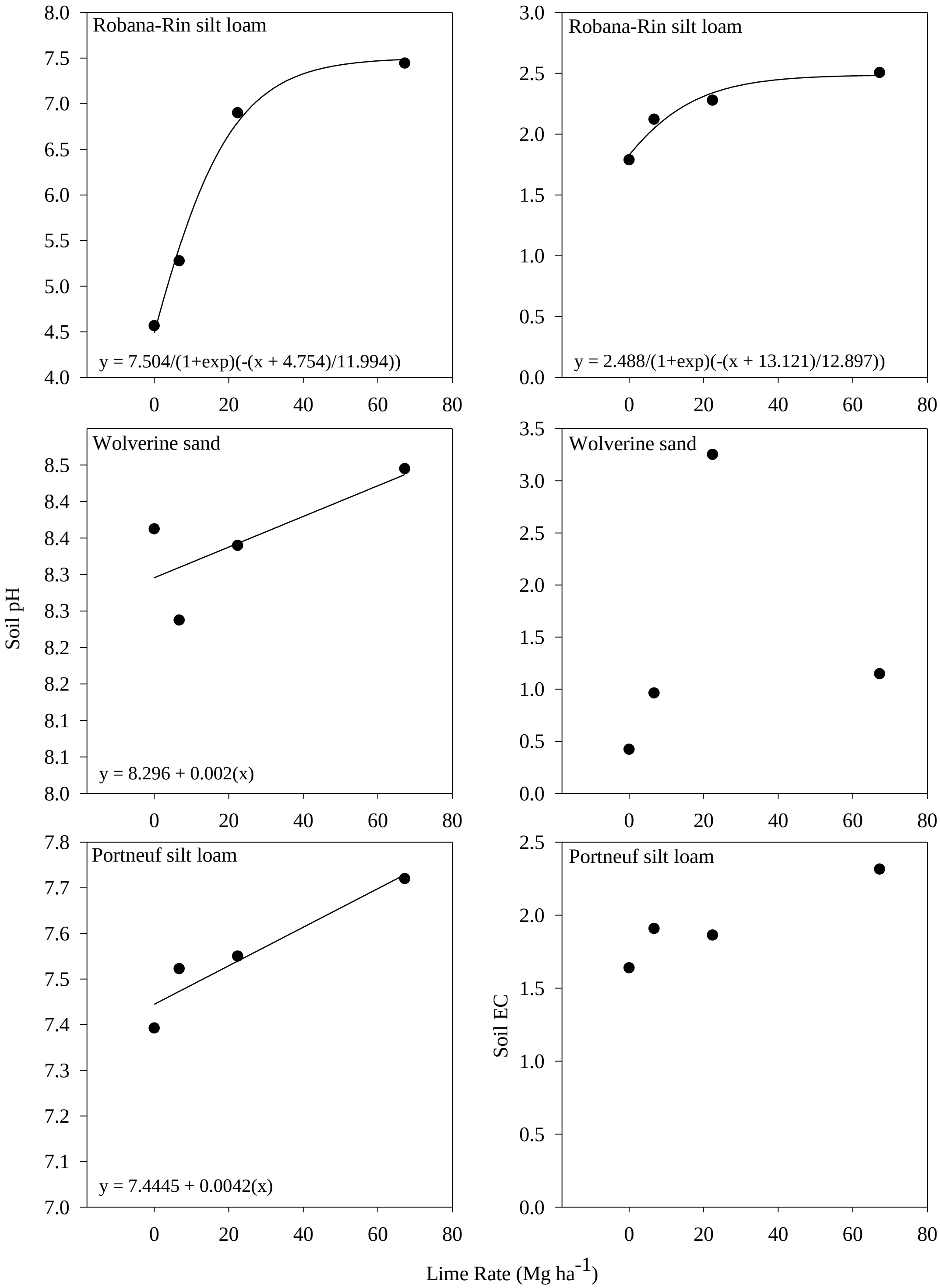

Figure 2.2. Relationship between lime rate and soil pH and soil electrical conductivity (EC) in the Robana-Rim silt loam, Wolverine sand, and Portneuf silt loam soils.

Chapter 3: Determining the Lime Requirements for Idaho Soils

Abstract

Lime requirement analyses can be performed by reacting varying concentrations of lime with soil to provide calibrated equations for estimating how much lime is required to increase the pH of that soil to the desired level. Unfortunately, no known calibration testing has been conducted using soils from Idaho. The objectives of this study were to develop new LR specific to southern Idaho soils and to compare the LR of southern and northern Idaho soils. Soil buffer tests (the Sikora, Adams-Evans buffer, modified Mehlich buffer, and single addition of $Ca(OH)_2$) were also examined as a tool for estimating the LR of northern and southern Idaho soils. Sixteen Idaho soil ($pH \leq 6.1$) were collected from the 0-15 cm depth and incubated for 90d at 21-24°C with increasing $CaCO_3$ rates. Increasing linear soil pH responses to $CaCO_3$ rates ($R^2 = 0.61$ to 0.98) were observed and used to develop incubation lime requirements (target pH; 5.6, 6.0, 6.5 and 7.0). Buffer tests were also used to develop lime requirements (target pH; 5.6, and 6.5). Sikora ($R^2=0.99$) and the Adams-Evans buffer ($R^2=0.92$ to 0.97) methods were best suited for predicting the LR for Idaho soils. However, the calcium hydroxide buffer method had weaker regression ($R^2=0.02$ to 0.11), indicating that this method is poorly suited for predicting the LR for Idaho soils.

Introduction

When amending acidic soils, lime requirement (LR) analysis can help establish the baseline lime rate to avoid under-liming or over-liming soils (Nguyen et al., 2022). The LR of the soil calculates the amount of pure calcium carbonate that must be added to the soil to displace acid-forming cations (H^+, Al^{3+} and Mn^{2+}) and raise the soil pH to a certain threshold level (Thompson, 2015). Predicting LR is dependent on the initial and target pH, bulk density, soil base saturation, cation exchange capacity, exchangeable acidity, and the buffering capacity of the soil (Havlin et al. 2016; Thompson, 2015).

LR calibrations have been done to provide more accurate estimates which relate to the climate, chemical, and physical properties of acidic soils from different geographical areas (Makepeace, 2021). There are several methods for determining soil LR estimates and these include buffer tests (Godsey et al., 2007), fields experiments (McLean, 1983), and incubation titration studies (Makepeace, 2021; McFarland et al, 2020; Godsey et al., 2007). For each method, the typical response of a particular soil type can be evaluated to the increasing lime application rates (Aitken et al., 1995; Peech, 1965).

Soil buffer tests are mixtures of reagents that respond in a predictable way to soil acidity (McFarland et al., 2020). The change in buffer solution pH following the addition of acidic soil is plugged into a prior calibration study equation to determine the LR of a soil. Soil buffer tests are often correlated with soil properties such as organic matter (OM), cation exchange capacity (CEC), and soil texture (Godsey et al., 2007). Common examples of buffer test methods include the Adams-Evans buffer (Adams and Evans, 1962), Sikora buffer (Sikora, 2006), single addition of calcium hydroxide ($Ca\ (OH)_2$) (Kissel et al., 2007), and the modified Mehlich buffer (Hoskins et al, 2008).

Field experimentation is another method to determine the LR of soil (Patel et. al, 1952). A liming material, usually $CaCO_3$, is applied at incrementally greater rates, and the resulting change in soil pH is measured after a period of time (Liebig et al., 1996; Patel et. al, 1952). This approach is known to provide the most accurate LR since experimental and environmental conditions (e.g., weather conditions, soil properties, and biological factors) are accounted for. However, replicated field investigations are typically too expensive to conduct under many different growing environments and soil conditions (Thompson, 2015). Rather, lab-based lime incubation studies allow for many different soils to be tested simultaneously to develop buffer test calibrations (Aitken et al. 1995). Incubation studies enable thorough assessments of LR at various time durations, although they are typically done in 90 days (Makepeace, 2021; McFarland et al, 2020). After adding increasing $CaCO_3$ amounts to fixed quantities of the soil, soils are homogenized, and deionized water is regularly added throughout the soil incubation study to maintain 90% field capacity (Nguyen et al., 2022; Makepeace, 2021; McFarland et al, 2020). Post incubation, the applied rate of $CaCO_3$ is plotted against soil pH, to determine LR graphically (Makepeace, 2021; McFarland et al, 2020; Godsey et al., 2007).

While the majority of southern Idaho soils are alkaline, there are regions where soils are trending acidic or have acidified sufficiently to be crop-limiting. To our knowledge, no known LR calibrations have been done for these southern Idaho soils, but LR research has been done in Montana, northern Idaho, Washington, and Oregon. The objectives of this study was to develop new LR specific to southern Idaho soils and to compare the LR of southern and northern Idaho soils. Soil buffer tests (the Sikora, Adams-Evans buffer, modified Mehlich buffer, and single addition of $Ca(OH)_2$) were also examined as a tool for estimating the LR of northern and southern Idaho soils.

Materials and methods

Soil sampling and site description

Soil samples were collected in the early spring and summer of 2022 from dryland and irrigated agricultural fields throughout Idaho. Soil samples were primarily from Fremont, Bonneville, and Caribou Counties in southern Idaho and Benewah and Latah Counties in northern Idaho. The majority of the soils were classified as silt loam (Table 3.1). Soil samples were collected from the 0-15 cm depth targeting soils with a pH < 6.0. Approximately 22 kg of soil was collected from each site and dried in a forced air oven at 37 ^{0}C until dry. The soil was then ground to pass through a 2 mm sieve and homogenized using a concrete mixer.

Pre-incubation analysis

All initial soil chemical properties were assessed by Stukenholtz Laboratories Inc, Twin Falls, ID, USA. Soil analyses were conducted based on methods described in Gavlak et al. (2003) except the soil series classification which was done using the Web Soil Survey Database (2022) (Table 3.1). Each soil was analyzed for particle size analysis (S-14.20; Table 3.1), soil pH $1_{soil}:1_{water}$ (S-2.20), Ca and Mg (S-5.10), cation exchange capacity (CEC) (S-10.10), K (S-5.10 and S-4.10), ammonium-N (S-3.10), Fe (S-6.10) and organic matter (OM; S-9.20) (Table 3.2).

Soil water holding capacity and field capacity

Soil water holding capacity (WHC) was determined for each soil by weighing 50 g of dry, sieving soil into a perforated plastic cup and tapping the cup gently to allow the soil to settle. The soil volume was determined by placing an identical, unperforated plastic cup next to the first and filling the cup with deionized water to be level with the soil surface in the perforated cup. The mass of the water was weighed on a tared scale and, under the assumption that 1 g of water is equivalent to 1 cm^3, the volume was determined.

The bulk density of the soil was determined as the quotient of the mass of the soil and the volume of water measured. Subsequently, the soil-filled perforated cup was submerged in a basin of deionized water and left for 24 hours to ensure complete soil wetting. The cup was removed from the basin and gravitational water was allowed to drain for 1 minute. The perforated cup was then reweighed and the soil water holding capacity was assumed to be the difference between the wet mass and dry mass of the soil per volume of the soil. The perforated cup was then allowed to continue draining for 24 hours while minimizing evaporation from the soil surface by covering the cups with plastic wrap. The soil field capacity was assumed to be the difference between the wet mass and dry mass of the soil.

Lime incubation

A lime incubation study was conducted similar to McFarland et al. (2020) and Makepeace (2021) at the University of Idaho Kimberly Research and Extension Center (42.54987 N, 114.34962 W). Each of the 16 soils was subdivided into plastic deli dishes containing 800 g of oven-dried soil. Treatments were applied as eight rates (0, 1.1, 2.2, 4.5, 9.0, 13.5, 17.9, and 22.4 Mg ha^{-1}) of dry, powdered, reagent grade $CaCO_3$ (ACROS Organics, 98%). Treatments were replicated four times in a completely randomized design on a greenhouse lab bench. The soil and $CaCO_3$ were mixed by shaking the plastic container for at least 3 min until the white $CaCO_3$was not visible in the soil. Then the soils were tamped to a bulk density of 1.3 g cm^{-3}. All samples were incubated for 90 days at a fluctuating greenhouse temperature of 21-24^0C. During the incubation study, each soil was weighed, and sufficient deionized water was added to return the soil moisture content to 90% of field capacity every 8 to 10 days.

Post incubation

After 90 days, the incubation study was terminated. Each soil was dried in a forced-air oven at 35 ℃ and ground to pass through a 2 mm sieve. Each soil was analyzed for soil pH using the $1{:}1_{water}$ method (Gavlak et al., 2003), and $1{:}1_{0.01\ M\ CaCl2}$ method (Gavlak et al., 2003). Soil pH was measured using an Orion ROSS Sure-Flow pH electrode Orion Star A215 pH/conductivity benchtop meter (Thermo Scientific Inc., Waltham, MA, US).

Estimating the Lime requirements

Four buffer solution tests were performed on the non-incubated soils and included the single addition of $Ca(OH)_2$ (Sikora Moore 2014 and Kissel et al., 2007), Modified Mehlich buffer (Sikora & Moore, 2014), Adams-Evans buffer (Gavlak et al., 2003; Adams and Evans, 1962; Shoemaker, McLean & Pratt, 1961), and Sikora buffer (Sikora Moore, 2014; Sikora, 2006).

Single addition of Ca $(OH)_2$ buffer test

Western semi-arid and arid United States soils have a higher buffering capacity than Georgia soils, for which this buffer method was developed. Therefore, 10 ml of 0.220 M Ca $(OH)_2$ was used (Makepeace, 2021) instead of the 2.7 mL in the original method (Sikora Moore, 2014; Kissel et al., 2007; Kissel et al., 2005). Even with the 10 mL of 0.220 M Ca $(OH)_2$ used in our study, there was a minimum of 0.31 pH increase between the initial pH from the 0.01 M $CaCl_2$ and the pH taken after the addition of 0.220 M Ca $(OH)_2$ as per Sikora Moore (2014) and Kissel et al. (2007) protocols.

This method relies on the soil-buffering capacity (which is expressed in units of cmol H^+ kg^{-1} pH^{-1} (Kissel et al., 2005). Soil buffering capacity is described as lime buffer capacity (LBC; ppm $CaCO_3$ per pH^{-1}) and is calculated as:

$$\boldsymbol{LBC = \frac{ml * N * EW\mathrm{CaCO_3}}{Soil\ weight/(\frac{pH_{CaCl2}}{pH_{CaOH2}})}}$$

Where;

- LBC is lime buffer capacity expressed in ppm $CaCO_3$ per pH^{-1}.
- N is the normality of saturated Ca $(OH)_2$ (0.046N) added.
- $EWCaCO_3$ is the equivalent weight of $CaCO_3$ (50 mg meq^{-1}),
- Soil weight (used in $pH1{:}1_{0.01\ M\ CaCl2}$) in kilograms for LBC to be directly expressed as mg $CaCO_3$/ kg /pH
- pH_{CaCl2} and pH_{CaOH2} measured values of soil pH, which are also plugged to the equation (Kissel et al., 2005).

The LR estimate (in lbs ac^{-1}) is calculated as:

$$\boldsymbol{LR\ (lb\ ac^{-1} = LBC * (target\ pH_W - pH_{CaCl2}) * 2 * 1.5 * (soil\ depth/6)}$$

Where;

- Target pH_w is the desired pH of the soil in water, Target pH_w should be at least 0.6 units greater than pH_{CaCl2}.
- $CaOH_2$ is pH measured in 0.01M $CaCl_2$ before the addition of $CaOH_2$.
- The factor of 2 converts LBC units of ppm pure $CaCO_3$ to lbs of pure $CaCO_3$ per acre for 6-inch depth of soil (assuming bulk density = 1.5 g cm^3) (Kissel et al, 2005). To

account for $CaCO_3$ equivalents of less than 100%, Kissel et al. (2005) suggest an additional factor of 1.5. Finally, LR was converted from lb ac^{-1} to Mg ha^{-1}.

Modified Mehlich buffer test

The LR estimate using the modified Mehlich buffer (Sikora and Moore, 2014) was determined by mixing 10 g of air-dried soil with 10 mL deionized water to record pH 1:1$_{water}$. To this mixture, 10 mL of the Mehlich buffer solution was added, stirred, and left to soak for 30 minutes. After 30 minutes, the soil-buffer pH reading was taken, and the following formula was used to calculate LR.

$$\boldsymbol{Buffer\ pH\ acidity = (6.6 - soil\ buffer\ pH) * 4 = meq\ H^{+}\left(100\ cm^{3}\right)}$$

where 6.6 is the pH of the Mehlich buffer. Then LR can be calculated as:

$$\boldsymbol{LR\left(\frac{ton}{ac}\right) = Buffer\ pH\ acidity * \left(\frac{Target\ pH - Soil\ pH}{6.6 - soil\ pH}\right)}$$

The final LR estimate was then converted from tons $CaCO_3$ ac^{-1} to Mg $CaCO_3$ ha^{-1}.

Adams-Evans buffer test

The Adams and Evans method was determined with Method S-2.70 (Gavlack et al., 2003), by mixing 20 g of air-dried and sieved soil to pass <2.0 mm sieve with 20 mL deionized water and 20 ml of Adams-Evans buffer. This solution was stirred for 1 minute and again every 5 minutes until pH was measured after 20 minutes. Adams-Evans (1962) quadratic equations were used to calculate LR. This equation depends on the acid saturation H-sat$_1$ (our value; 0.42) and acid saturation at the desired pH is measured by H-sat$_2$ (our value; 0.26). Our H-sat$_1$ values were calculated with (Dlamini, 2009; Adams, 1962):

$$\boldsymbol{Soil\ pH = 7.79 - 5.55 * (H - sat_{1}) + 2.27(H - sat_{1})^{2}}$$

This equation can also be used to calculate the H-sat$_2$. Then exchangeable acidity (Soil H (meq/100cm^3) can be calculated with:

$$\boldsymbol{Soil\ H\ (meq/100cm^{3}) = 8 * (8 - buffer\ pH)}$$

Then LR (ton ac^{-1}) can be calculated as:

$$\boldsymbol{LBC\left(\frac{ton}{ac}\right) = \frac{4(8 - buffer\ pH)}{H - sat_{1}} * (H - sat_{1}) - (H - sat_{2})}$$

The final LR in lbs $CaCO_3$ ac^{-1} was converted to Mg $CaCO_3$ ha^{-1}.

Sikora buffer test

Ten grams of soil was mixed with 10 ml deionized water and 10 mL Sikora buffer. This solution was homogenized in an end-to-end oscillating shaker, at a low speed for 10 minutes, followed by buffer pH measurement. Our Sikora buffer calculations were based on Best-Test Analytical Services, LLC (Moses Lake, WA, U.S.) generalized LR equation, which was derived from linear regression equations by Makepeace (2021). This generalized equation was derived to accommodate for target pH ranging from 5.4-6.6.

$$\boldsymbol{Ag\ lime\ in\ lbs\ per\ acre = (24.26 * pH_{Target}) + (16.59 * pH_{Sikora}) - (3.624 * (pH_{Target} * pH_{Sikora})) - 111.92}$$

Then final LR in lbs $CaCO_3$ ac^{-1} was converted to Mg $CaCO_3$ ha^{-1}.

Data analysis

All data analyses were performed in R statistical language version 4.0.2 (R Core Team, 2023). Linear models were fitted using the lm function in R (Faraway, 2014; Sheather, 2009). Estimated marginal means were calculated, and *post-hoc* Tukey-adjusted pairwise treatment comparisons were performed at an alpha level of 0.05 using the emmeans and multcomp packages (Hothorn et al., 2008; Lenth, 2022).

Results and discussion

Initial Soil Physical and Chemical Conditions

The soils used in this study had a silt loam texture (except Site A which was a loam) with clay content ranging from 6 to 13% (Table 3.2). Initial soil pH values ranged from 4.4 to 6.1, but all northern Idaho soils (Site A to E) had an initial soil pH ≤5.0 (Table 3.3). Soil organic matter ranged from 2.3 to 6.7% (Table 3.3). Typically, Idaho soil reflects a long history of volcanic activity (Hughes 1999). Even though volcanic ash is alkaline (8.5-8.9 pH), environmental and physical factors likely contributed to the current acidic and trending acidic soils. For example, some northern Idaho soil was historically forested (Daubenmire, 1952), which released tannins and other acids to the soil. Compared to short vegetation (grasslands) in southern Idaho, forests can significantly modify precipitation and the physical, chemical and biological features of the soil (Cannell, 1999). Since precipitation increases with higher altitudes, forested areas are prone to have acidifying soils due to stronger base cations leaching through higher precipitation (Ulrich, 1983).

In the 16 soils tested in this study, we observed that there was a strong ($r>0.5$), positive correlation between soil pH and calcium ($r=0.60$), magnesium ($r=0.67$), cation exchange capacity ($r=0.63$), chloride ($r=0.54$), boron ($r=0.81$) and base saturation ($r=0.72$)

and a strong, negative correlation with aluminum (r=-0.71), iron (r=-0.51), and sulfate-S (r=-0.62). Several authors have observed that Al toxicity can negatively affect crops, especially when the soil pH drops below 4.5 and the Al concentration is>5 mg kg^{-1} (Azam et al., 2020). Further, it is not uncommon for small grains to develop iron and manganese toxicity symptoms as soils acidify. In this study, KCl extractable Al was <5 mg kg^{-1} at all sites but Mn (10.6 – 58.9 mg kg^{-1}) and Fe (49 – 468 mg kg^{-1}) concentrations were high (Table 3.3).

Soil pH response

For all 16 incubated soils, significant linear responses to increasing rates of $CaCO_3$ were established with R^2 values that ranged from 0.61 to 0.98 depending on the sample site, and regression slopes that ranged from 0.04 to 0.13 pH units per Mg of $CaCO_3$ ha^{-1} (Figure 3.1 to 3.3; Table 3.5 and 3.6). The greatest change in soil pH was observed at 1.2, 2.2, 4.5, 9.0 and 13.5 Mg of $CaCO_3$ ha^{-1}, but pH values plateau at 17.9 and 22.4 Mg of $CaCO_3$ ha^{-1} (Figure 3.1 to 3.3). However, even at the highest rates (17.9 and 22.4 Mg of $CaCO_3$ ha^{-1}), linear response was still observed at other sites (Site N, O, K, L, G, A) without any plateau (Figure 3.1 to 3.3). Our results are similar to Makepeace (2021), McFarland et al. (2020), and Jones et al. (2018) who all reported that soil pH significantly increased with $CaCO_3$ lime rates during the 90-d incubation period. The alkalinity of the $CaCO_3$ liming material is due to the dissolution from $CaCO_3$ that reacts with active H^+ (Fidel et al., 2017), which increases the carbonate (CO_3) concentration in the soil and detaches acidic cations (Al^{3+}) out of the soil colloids (Liang et al., 2017; Demeyer et al., 2001).

The LR estimates that raising the soil to a target pH of 6.5 ranged from 0 to 26 Mg $CaCO_3$ ha^{-1} for pH 1:1$_{\text{water}}$ or 8 to 28 Mg $CaCO_3$ for the pH 1:1$_{\text{0.01 M CaCl2}}$ method (Table 3.5 and 3.6). Similar to McFarland et al. (2020), the more acidic the soil was at the time of lime application the more $CaCO_3$ was required to achieve a target pH. The LR for southern Idaho soils (Sites G, H, M, N, O) had smaller slopes relative to northern Idaho soils, possibly due to the differences in OM that buffers the soil pH (Tables 3.5 and 3.6). These differences influence the variations in the $CaCO_3$ dissolution and neutralization reaction times for each incubated soil (Jones et al., 2018).

While most sites soil pH increased, 1.12 Mg ha^{-1} $CaCO_3$ lime rate did not increase pH at site A. For example, with 1.12 Mg ha^{-1} $CaCO_3$ lime rate, our average incubated soil pH was 3.93 (data not shown) which was lower than the initial non-incubated soil pH of 4.4. It is interesting to note that dynamics in soil incubation pH are common. Soil pH for this site likely increased within the first periods of soil incubation (e.g., 15 d, 30 d, or 60 d), but later declined due to OM mineralization. Ding et al. (2023) reported that within 20 d of the incubation period, soil pH increased with liming rates. However, the pH of the soil started to decline after 40 d and the soil pH was significantly lower after 80 d with all lime rates, as compared to the treatment rates at 5 d incubation. This suggests that lime amendment effects on soil pH are dependent on time.

Buffer responses

For this study, the target pH values used to determine buffer LR were 6.5 and 5.6 (Table 3.7 and 3.8; Figures 3.4 and 3.5). The linear regression relationships to raise soil pH to 6.5 and 5.6 by all buffer solutions were significant except the $Ca(OH)_2$ buffer method. Regression intercepts for target pH 6.5 were numerically higher (-15.6 to 104.8) compared to lower target pH 5.6 intercepts (-1.3 to 96.4) (Table 3.8), indicating that slightly less lime is recommended to adjust soil pH to 5.6 than 6.5. However, these differences may not be practical in real life when LR recommendations are made in Mg ha^{-1} or ton ac^{-1} (Huluka et al., 2005).

Linear regression models fitted for each buffer method showed that Sikora had higher R^2 values (0.99 at target pH= 6.5; 0.99 at target pH=5.6) >Adams-Evans method (0.97 at target pH= 6.5; 0.92 at target pH=5.6) > Modified Mehlich (0.92 at target pH= 6.5; 0.81 at target pH=5.6) > $Ca(OH)_2$ (0.11 at target pH= 6.5; 0.02 at target pH=5.6) (Table 3.8). Our results are consistent with the results reported by Makepeace (2021) for Oregon soils and McFarland et al. (2020) for Palouse soil, which covers northern Idaho. This suggests that the Sikora and the Adams-Evans buffer methods are best suited for predicting the LR for Idaho soils. However, the calcium hydroxide buffer method had weaker regression and lower R^2 values at both target pH, indicating that this method is poorly suited for predicting the LR for Idaho soils (Table 3.8).

Adams-Evans was originally developed for Alabama Red Yellow Podsol soils with lower CEC (0.8 to 13.0 meq per 100g) and few 2:1 clays (smectite, vermiculite), to detect small differences in LR (McFarland et al., 2020; Sims 1996; Adams & Evans, 1962) and avoid the damage effects from over liming soils. Our soils had similar CEC values (8.8-10.8 meq per 100g for northern Idaho soils; 5.4-13.2 meq per 100g for southern Idaho soils; Table

3.3) to the CEC values of Alabama soils. This is likely why there was a strong regression relationship for our Idaho soil.

Single Addition of Ca $(OH)_2$ method was originally developed for Georgia soils as a direct titration method that incorporated acid soils with 0.220 M of Ca $(OH)_2$ through 4 d incubation trial (Liu et al., 2004). However, this method has a short period of equilibration that is not enough to allow Ca $(OH)_2$ to fully react (Makepeace, 2021). Additionally, this method heavily relies on the relationship between soil pH and added base, which means that it uses only a few data points to determine a soil's buffering capacity that could then be used for calculation of the lime requirement (Liu et al., 2004). Therefore, Ca $(OH)_2$ method remains a mystery for soils outside of Georgia as it is unclear if it correlates well with other soils. This is likely why it was a poor fit for our soil and Oregon soils (Makepeace, 2021). Several authors such as Liu et al., (2004) recommend that the single addition of Ca $(OH)_2$ method should be done for longer time such as 4d incubation, to allow Ca $(OH)_2$ to fully react and accurately predict lime requirement.

Conclusion

Overall, significant linear responses to increasing rates of $CaCO_3$ were established. Our results have shown LR for southern Idaho soils had the lowest slopes as compared to northern Idaho soils. Therefore, the response to lime varied across incubated soils due to the variations in initial soil pH and textural classification. To adjust soil pH at higher pH targets, more lime is required. Sikora (R^2=0.99) and the Adams-Evans buffer (R^2=0.92 to 0.97) methods were best suited for predicting the LR for Idaho soils compared to the calcium hydroxide buffer method (R^2=0.02 to 0.11).

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Table 3.1. Site description of soils used in the incubation study from agricultural fields in Idaho.

Site	County	Coordinates	Soil series
A	Latah	46.729455 ˚, -116.949319˚	Westlake (Fine-silty, mixed, superactive, frigid Cumulic Ultic Haploxerolls) – Latahco (Fine-silty, mixed, superactive, frigid Argiaquic Xeric Argialbolls) complex, 0 to 3 percent slopes
B	Latah	46.945934 ˚, -116.874327˚	Joel silt loam, 7 to 25 percent slopes
C	Latah	46.961094 ˚, -116.868081˚	Taney ashy silt loam, 2 to 8 percent slopes
D	Benewah	47.165820 ˚, -116.868081˚	Taney ashy silt loam, 8 to 20 percent slopes
E	Benewah	47.193046 ˚, -116.907704˚	Larkin-Southwick complex, 3 to 12 percent slopes
F	Fremont	44.07132778 ˚, -111.39533333˚	Marystown-Robinlee-Rexburg, hardpan substratum silt loams, 1 to 4 percent slopes
G	Fremont	44.03803 ˚, -112.34512˚	Malm-Rock outcrop complex
H	Bonneville	44.49540833 ˚ -111.35486389˚	Rin silt loam, 4 to 12 percent slopes
I	Caribou	42.5641 ˚, -111.3912˚	Cavemountain-Crossley-Zeale family, complex, 30 to 70 percent slopes
J	Fremont	44.09688 ˚, -111.34914˚	Lostine (Coarse-silty, mixed, superactive, frigid Pachic Haploxerolls) silt loam, 1 to 4 percent slopes
K	Caribou	42.76031 ˚, -111.64237 ˚	Foundem-Rexburg, very deep, complex, 1 to 4 percent slopes
L	Fremont	44.08833333 ˚, -111.48666667˚	Kucera-Sarilda silt loams, 2 to 6 percent slopes
M	Fremont	44.0421611 ˚, -111.3975833˚	Marystown-Robinlee-Rexburg, hardpan substratum silt loams, 1 to 4 percent slopes
N	Caribou	42.8364975 ˚, -111.5036388˚	Lostine-Foundem complex, 1 to 4 percent slopes
O	Caribou	42.81294444 ˚, -111.62476944˚	Ririe (Coarse-silty, mixed, superactive, frigid Calcic Haploxerolls), very deep-Lostine (Coarse-silty, mixed, superactive, frigid Pachic Haploxerolls) complex, 1 to 8 percent slopes
P	Caribou	42.8610073 ˚, -111.6497263˚	Ririe, very deep-Lostine complex, 1 to 8 percent slopes

Table 3.2. Soil textural analysis in the top 30 cm of agricultural fields in eastern Idaho, USA.

Site	Sand	Clay	Silt
	———————————	%	———————————
A	43	13	45
B	25	11	65
C	25	11	65
D	27	12	45
E	13	13	73
F	19	10	71
G	27	12	60
H	17	6	77
I	20	8	72
J	24	10	66
K	24	8	68
L	26	9	65
M	19	11	70
N	22	10	68
O	36	10	54
P	12	9	78

Table 3.3. Site characterization for soils used in the incubation study from agricultural fields in Idaho from a 0-15 cm soil depth.

Site [a]	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
pH	4.4	5	4.7	4.8	4.8	4.9	5.5	5.5	4.5	4.5	4.4	5.3	5.8	6	6.1	5.4
Salts, mmhos cm^{-1}	1.1	0.3	0.7	0.5	0.5	0.9	2.3	1.8	0.5	0.7	0.8	0.5	1.2	0.7	0.9	1.1
Ca, cmolc kg^{-1}	7	3.2	4.1	5.1	4	5.5	8.8	7.7	2.4	3.7	5.3	5.1	7.6	6.2	6.9	6.2
Mg, cmolc kg^{-1}	1.6	0.7	1.3	1.3	1.2	1.1	1.2	1.3	0.4	0.6	0.6	1	1.4	1.9	1.9	1.3
K, cmolc kg^{-1}	0.51	0.6	0.6	0.6	0.5	0.4	1.5	1.3	0.8	1	0.6	0.4	0.5	1	1	1.3
Na, cmolc kg^{-1}	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.1	0.1	0.1
CEC, cmolc kg^{-1}	10.8	6.2	7.7	8.8	7.4	8.8	13.2	12	5.4	7.2	8.3	8.3	11.1	10.2	11	10.7
Al, mg kg^{-1}	2.44	0.36	0.47	0.31	0.46	0.35	0.27	0.18	0.98	1.48	1.39	0.33	0.23	0.23	0.1	0.32
Fe, mg kg^{-1}	468	111	130	79	146	132	161	117	112	133	162	111	92	65	49	79
Mn, mg kg^{-1}	10.6	58.9	40.9	21.4	41.4	26.1	18.6	20.5	36.8	28.5	11.3	15.6	35.5	NA	NA	NA
Cu, mg kg^{-1}	0.9	1.1	1.3	1.2	1.4	0.8	0.7	0.6	0.4	0.4	1.1	0.6	0.9	NA	NA	NA
Zn, mg kg^{-1}	1.6	2.2	40.9	1.1	1.3	2.7	4.5	4.1	1.9	1.9	3.6	2.3	1.9	4.4	2.7	2.8
NH_4–N, mg kg^{-1}	108	12.9	14	10.8	15.6	12.4	11.8	12.2	20.4	32.1	15.3	8.5	11	5.3	5.6	5.9
NO_3-N, mg kg^{-1}	43	5	29	18	21	38	137	62	19	24	24	19	15	22	17	52
SO4-S, mg kg^{-1}	31	11	14	11	13	14	12	10	10	28	25	8	18	9	6	9
Cl, mg kg^{-1}	4	7	6	5	7	13	15	7	5	4	6	7	37	9	10	18
B, mg kg^{-1}	0.26	0.23	0.21	0.24	0.2	0.38	0.51	0.43	0.2	0.27	0.25	0.28	0.52	NA	NA	NA
OM, %	6.7	2.9	3.5	3.7	3.5	2.3	4.7	4.6	2.5	2.9	2.4	2.5	2.6	3.2	2.6	3
BS, %	84	72	77	80	77	80	87	86	67	74	79	78	86	89	89	82

[a] CEC, cation exchange capacity; OM, organic matter; BS, base saturation

Table 3.4. Soil water holding capacity (WHC) and Field Capacity (FC) of incubated soils from agricultural fields in Idaho.

Site	Water Holding capacity	Volume of Water for approximately 90% FC	Volume of Water to maintain 90% FC
	— ml water/g soil—	ml water/800g soil	
Site A	24.5	244	20
Site B	20.3	167	14
Site C	21.5	177	15
Site D	23.6	185	15
Site E	22.5	186	13
Site F	17.3	149	12
Site G	23.9	216	18
Site H	23.9	205	17
Site I	17.7	125	10
Site J	17.2	147	12
Site K	18.6	158	13
Site L	19.2	170	14
Site M	19.2	172	14
Site N	21.7	149	12
Site O	27.2	172	14
Site P	24.8	164	14

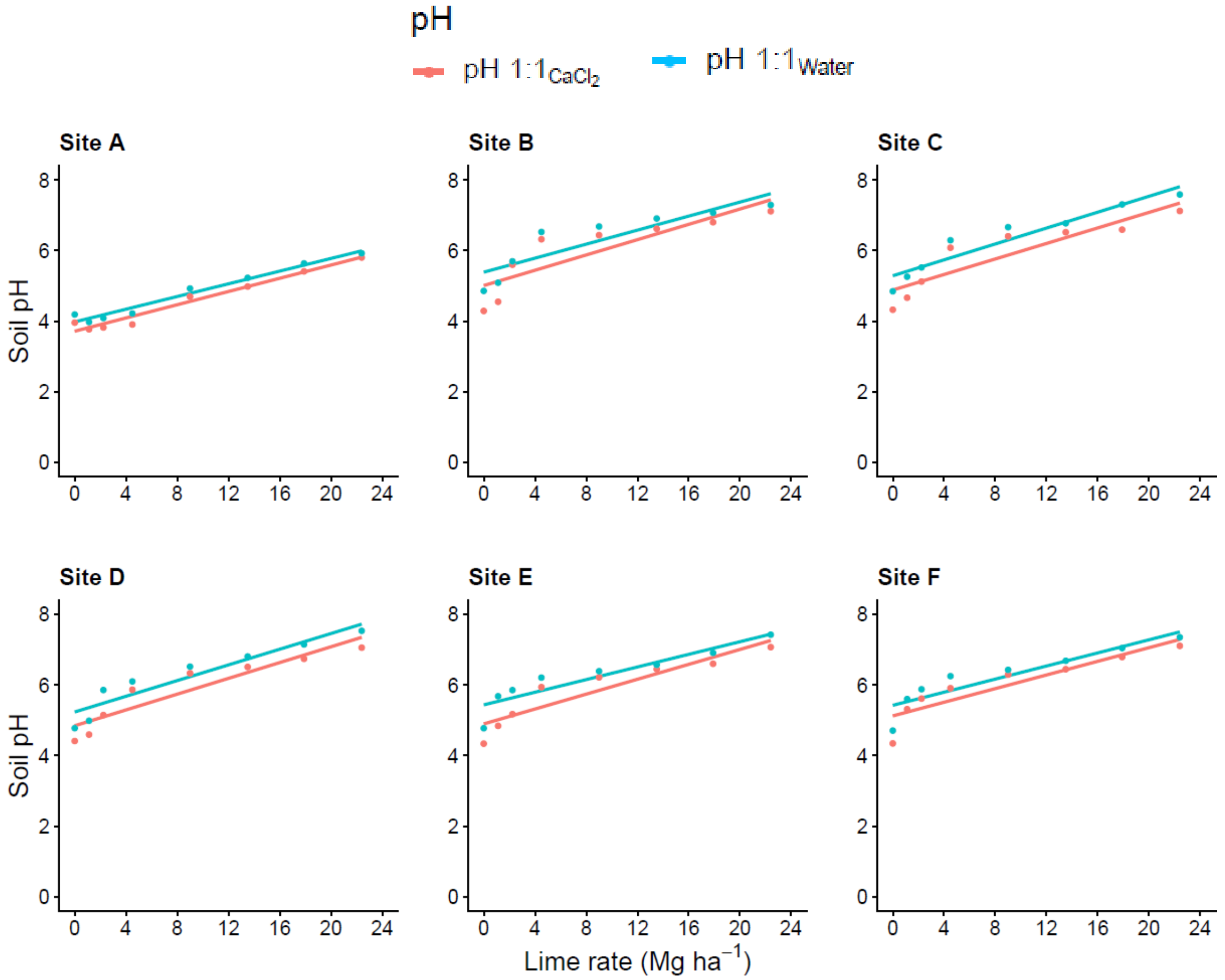

Figure 3.1. Soil pH 1:1 $_{water}$, and soil pH 1:1 $_{0.01M\ CaCl2}$ responses to increasing CaCO$_3$ application rate for Idaho soils following a 90-d lime incubation.

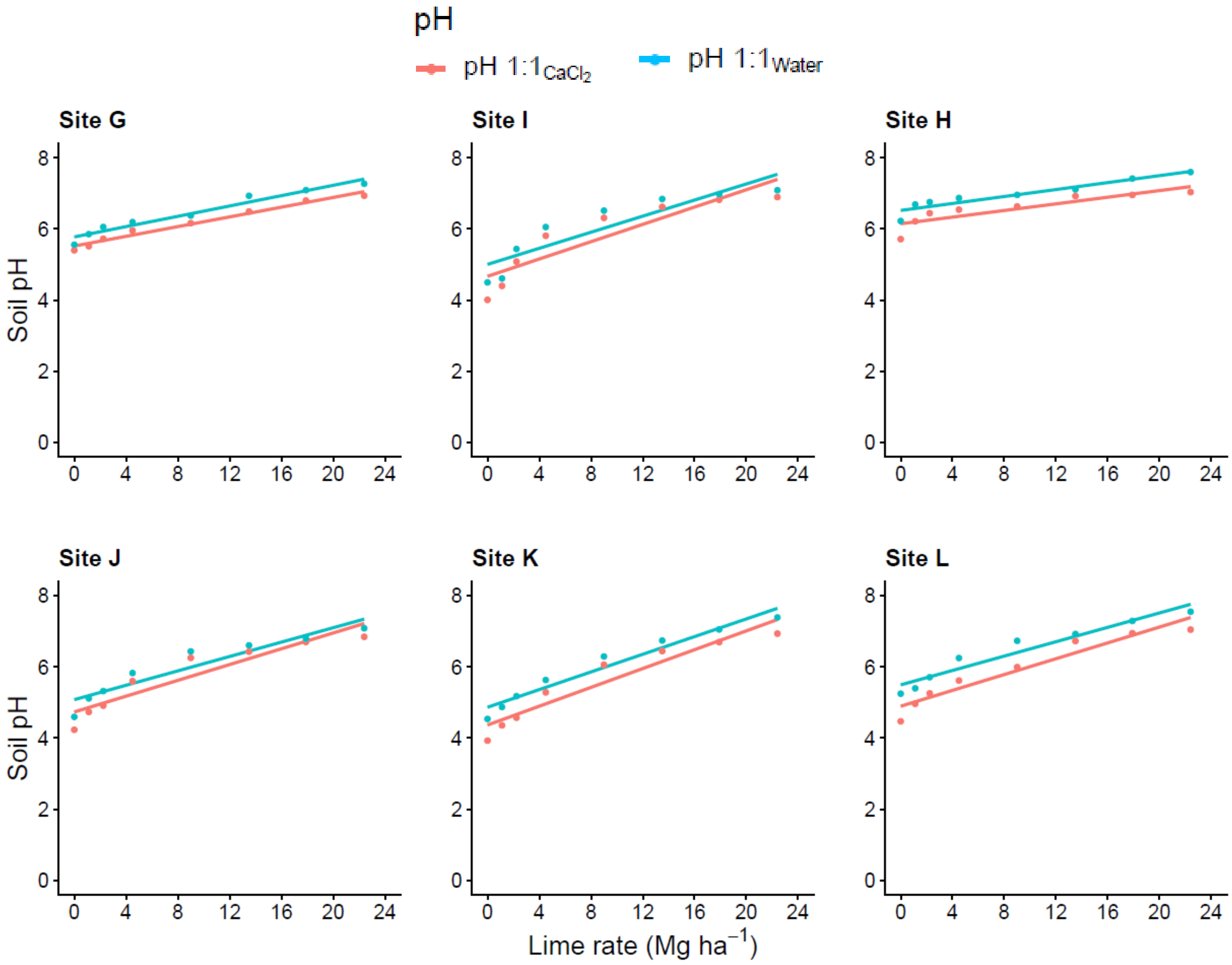

Figure 3.2. Soil pH 1:1 $_{\text{water}}$, and soil pH 1:1 $_{\text{0.01M CaCl2}}$ responses to increasing $CaCO_3$ application rate for Idaho soils following a 90-d lime incubation.

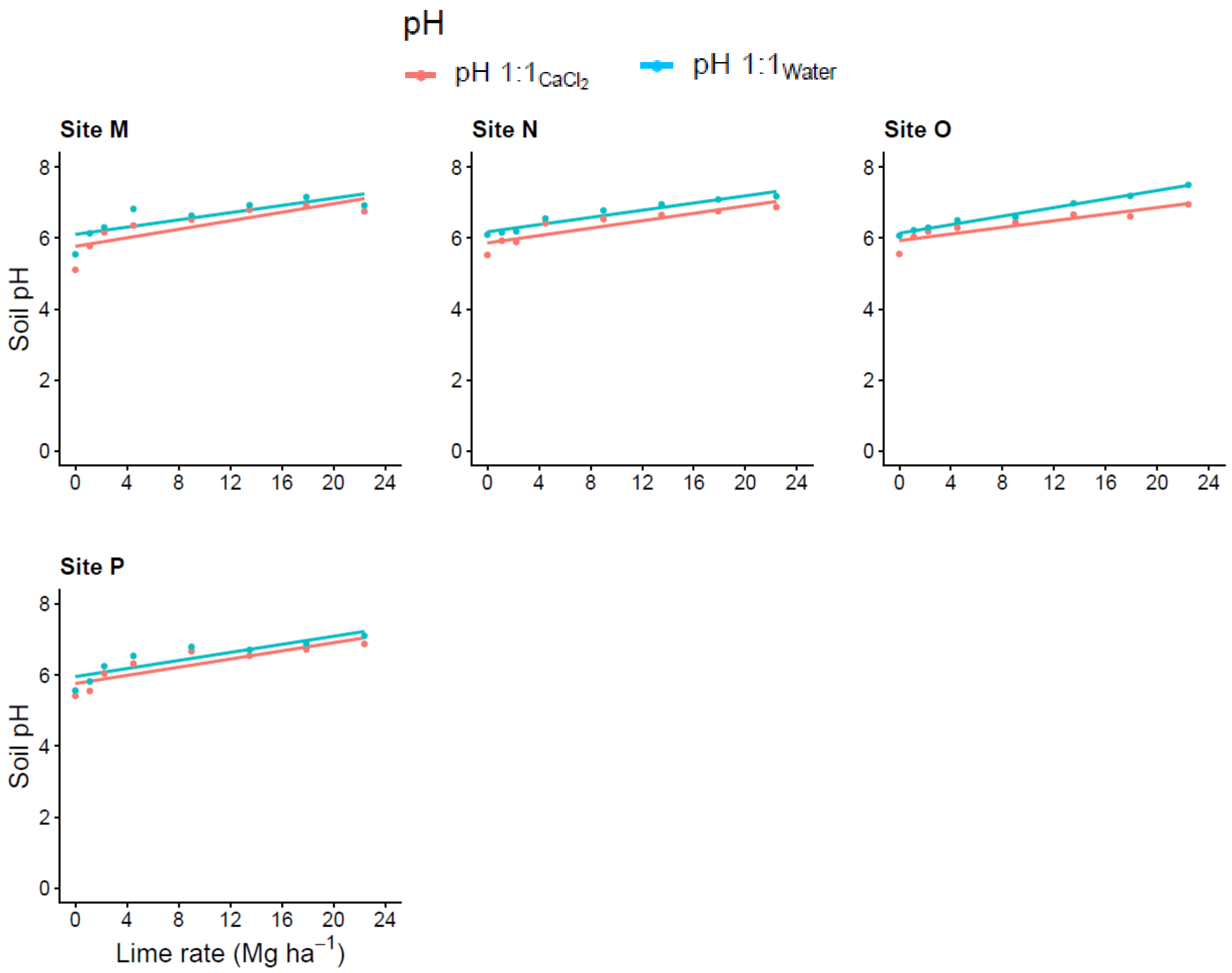

Figure 3.3. Soil pH 1:1 $_{water}$, and soil pH 1:1 $_{0.01M\ CaCl2}$ responses to increasing $CaCO_3$ application rate for Idaho soils following a 90-d lime incubation.

Table 3.5. Lime requirement for Idaho soils at two target pH values attained through lime incubation study.

Site	pH method	Equation	R^2	p-value	Incubation lime requirement (0-15 cm) Target pH 5.6	Target pH 6.0	Target pH 6.5	Target pH 7.0
					Mg ha^{-1}			
A	$1:1_{\text{Water}}$	$y=3.9 + 0.10x$	0.96	<0.001	17	21	26	31
	$1:1_{0.01\mathit{M}\ \text{CaCl2}}$	$y=3.7 + 0\ .11x$	0.96	<0.001	19	23	28	33
B	$1:1_{\text{Water}}$	$y=5.4 + 0.12x$	0.79	<0.001	2	6	11	16
	$1:1_{0.01\mathit{M}\ \text{CaCl2}}$	$y=5.1 + 0.11x$	0.74	<0.001	4.64	8.18	12.73	17.27
C	$1:1_{\text{Water}}$	$y=5.4 + 0.13x$	0.79	<0.001	2	6	11	16
	$1:1_{0.01\mathit{M}\ \text{CaCl2}}$	$y=4.9 + 0.09x$	0.81	<0.001	7	11	16	21
D	$1:1_{\text{Water}}$	$y=5.2 + 0.11x$	0.88	<0.001	4	8	13	18
	$1:1_{0.01\mathit{M}\ \text{CaCl2}}$	$y=4.8 + 0.12x$	0.85	<0.001	8	12	17	22
E	$1:1_{\text{Water}}$	$y=5.4 + 0.08x$	0.84	<0.001	2.25	7.5	13.75	20
	$1:1_{0.01\mathit{M}\ \text{CaCl2}}$	$y=4.9 + 0.11x$	0.85	<0.001	6.45	10	14.55	19.09
F	$1:1_{\text{Water}}$	$y=5.4 + 0.09x$	0.84	<0.001	2.11	6.67	12.22	17.78
	$1:1_{0.01\mathit{M}\ \text{CaCl2}}$	$y=5.1 + 0.06x$	0.80	<0.001	2.11	5	9	17
G	$1:1_{\text{Water}}$	$y=5.8 + 0.07x$	0.95	<0.001	0	2.86	10	17.14
	$1:1_{0.01\mathit{M}\ \text{CaCl2}}$	$y=5.5 + 0.07x$	0.94	<0.001	0	7.14	14.29	21.43
H	$1:1_{\text{Water}}$	$y=6.5 + 0.05x$	0.88	<0.001	0	0	0	10
	$1:1_{0.01\mathit{M}\ \text{CaCl2}}$	$y=6.1 + 0.05x$	0.76	<0.001	0	0	8	18

[a] Incubation lime requirement equation, where x= $CaCO_3$(Mg ha^{-1}) and y=pH response.

Table 3.6. Lime requirement for Idaho soils at four target pH values attained through lime incubation study.

					Incubation lime requirement (0-15 cm)			
Site	pH method	Equation	R^2	p-value	Target pH 5.6	Target pH 6.0	Target pH 6.5	Target pH 7.0
					Mg ha^{-1}			
I	$1{:}1_{\text{Water}}$	y=5.0 + 0.11x	0.81	<0.001	5.55	9.09	13.64	18.18
	$1{:}1_{0.01M\ \text{CaCl2}}$	y=4.7 + 0.12x	0.81	<0.001	7.67	10.83	15	19.17
J	$1{:}1_{\text{Water}}$	y=4.9 + 0.12x	0.95	<0.001	6	9.17	13.33	17.5
	$1{:}1_{0.01M\ \text{CaCl2}}$	y=4.4 + 0.13x	0.9	<0.001	9.46	12.31	16.15	20
K	$1{:}1_{\text{Water}}$	y=4.9 + 0.12x	0.95	<0.001	6	9.17	13.33	17.5
	$1{:}1_{0.01M\ \text{CaCl2}}$	y=4.4 + 0.13x	0.9	<0.001	9.46	12.31	16.15	20
L	$1{:}1_{\text{Water}}$	y=5.5 + 0.11x	0.92	<0.001	0	4.55	9.09	13.64
	$1{:}1_{0.01M\ \text{CaCl2}}$	y=4.9 + 0.11x	0.92	<0.001	6.45	10	14.55	19.09
M	$1{:}1_{\text{Water}}$	y=6.1 + 0.06x	0.61	<0.001	0	0	13.33	21.67
	$1{:}1_{0.01M\ \text{CaCl2}}$	y=5.7 + 0.07x	0.69	<0.001	0	4.29	11.43	18.57
N	$1{:}1_{\text{Water}}$	y=6.2 + 0.05x	0.91	<0.001	0	0	6	16
	$1{:}1_{0.01M\ \text{CaCl2}}$	y=5.9 + 0.05x	0.75	<0.001	0	2	12	22
O	$1{:}1_{\text{Water}}$	y=6.1 + 0.06x	0.98	<0.001	0	0	6.67	15
	$1{:}1_{0.01M\ \text{CaCl2}}$	y=5.9 + 0.04x	0.79	<0.001	0	2.5	15	27.5
P	$1{:}1_{\text{Water}}$	y=6.0 + 0.05x	0.75	<0.001	0	0	10	20
	$1{:}1_{0.01M\ \text{CaCl2}}$	y=5.8 + 0.06x	0.74	<0.001	0	3.33	11.67	20

Table 3.7. Lime requirement estimates for Idaho soils at two target pH values by standard buffer methods calibration.

	Target pH 6.5				Target pH 5.6			
Site	Adams-Evans	Calcium Hydroxide	Sikora	Modified Mehlich	Adams-Evans	Calcium Hydroxide	Sikora	Modified Mehlich
	———Mg ha^{-1}———				———Mg ha^{-1}———			
A	25	24	28	25	5.9	6	4.8	4.1
B	8	18	6	18	7.3	6.7	6.2	5.1
C	9	10	8	18	7.2	5.8	6.1	4.8
D	9	8	9	18	7.1	5.7	6.1	5.1
E	9	15	9	18	7.1	6.3	6.1	4.9
F	8	15	8	18	7.3	6.6	6.2	4.7
G	5	7	2	13	7.3	6.7	6.5	5.5
H	12	8	14	20	6.9	7.1	5.7	4.7
I	8	31	6	18	7.3	7.4	6.2	4.8
J	7	13	6	17	7.3	6	6.3	5.1
K	3	19	0	11	7.4	7.2	6.6	5.9
L	6	19	8	19	7.3	6.7	6.1	4.6
M	6	15	3	15	7.3	7.4	6.4	5.4
N	5	8	2	13	7.4	6.6	6.5	5.7
O	5	9	2	13	7.4	6.7	6.5	5.7
P	6	4	3	15	7.3	6.4	6.4	5.3

Table 3.8. Lime requirement equations for Idaho soils at two target pH values by standard buffer methods calibration.

Site	Linear regression equations	R^2	p>F
Target pH 6.5			
Adams-Evans	$y= 104.8 - 13.5x$	0.96	<0.001
Calcium Hydroxide	$y= -15.6 + 4.49x$	0.11	0.204
Sikora	$y= 51.6 - 6.88x$	0.99	<0.001
Modified Mehlich	$y= 102.2 - 15.4x$	0.92	<0.001
Target pH 5.6			
Adams-Evans	$y= 96.4 - 12.8x$	0.97	<0.001
Calcium Hydroxide	$y= -1.3 + 41.2x$	0.02	0.623
Sikora	$y= 55.8 - 8.51x$	0.99	<0.001
Modified Mehlich	$y= 3.16 +1.54x$	0.81	<0.001

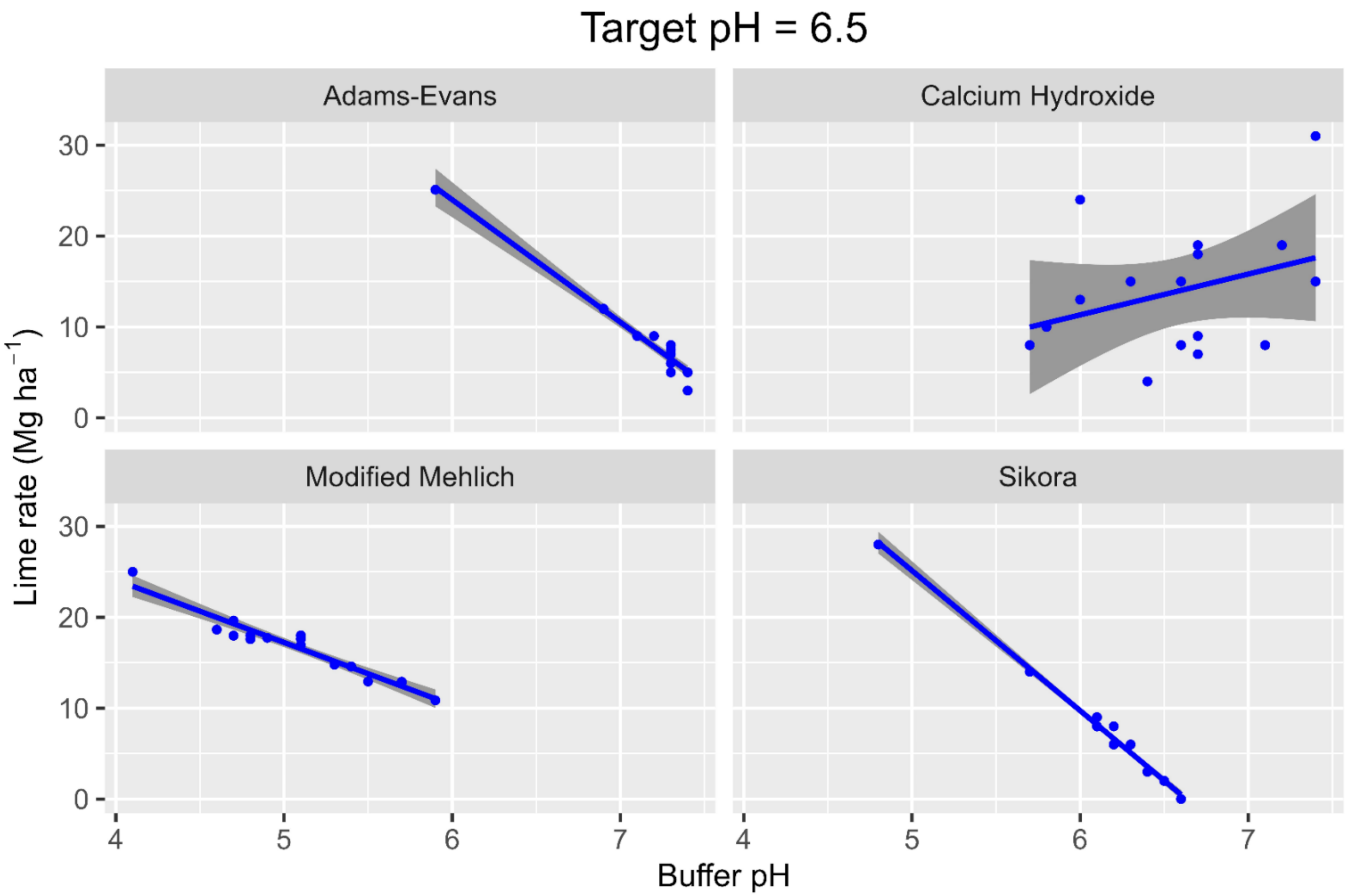

Figure 3.4. Linear regressions between buffer pH methods and lime requirement for 16 Idaho soils at target pH = 6.5.

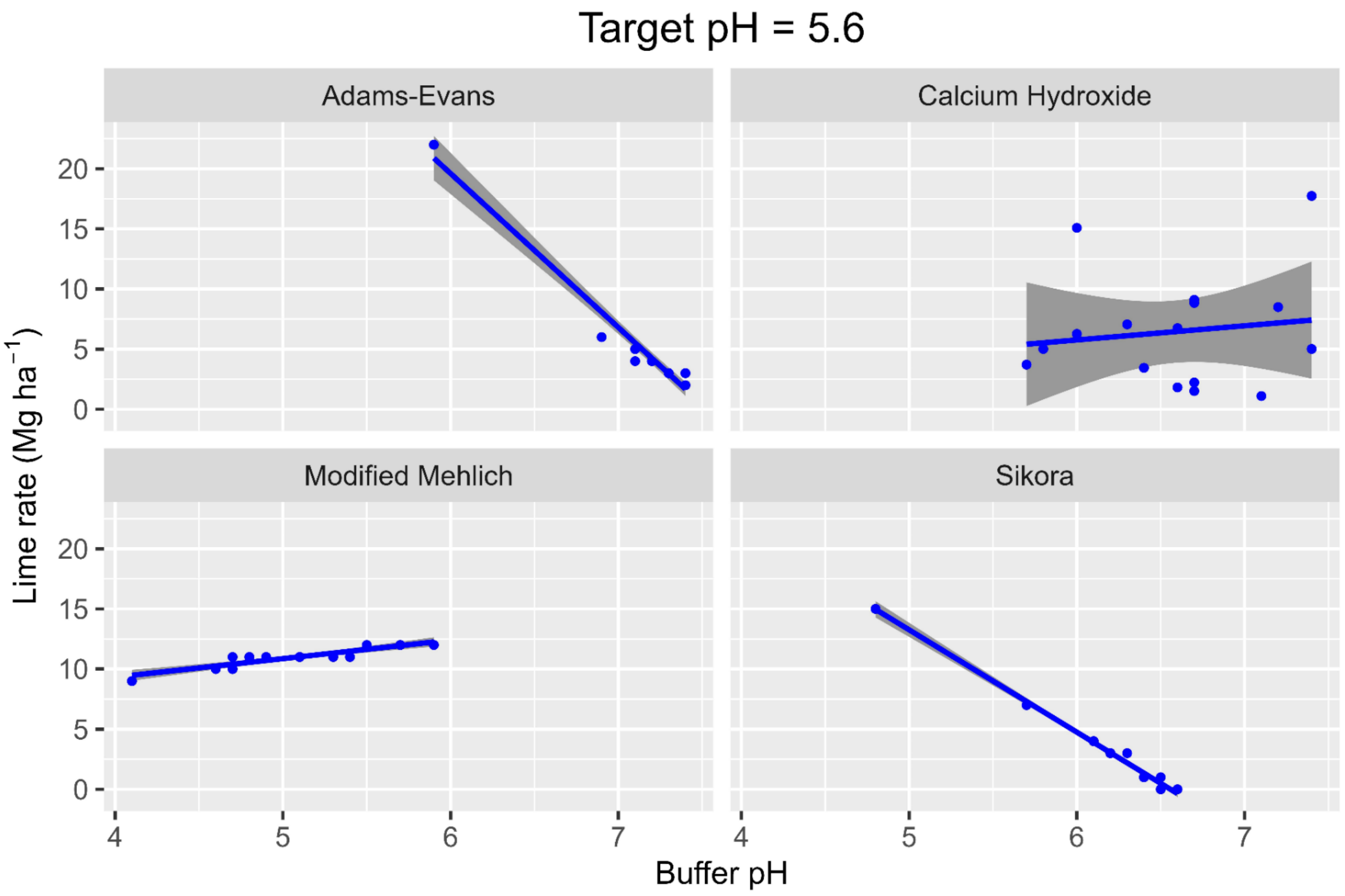

Figure 3.5. Linear regressions between buffer pH methods and lime requirement for 16 Idaho soils at target pH = 5.6.

Chapter 4: Liming for improved weed management

Abstract

Small grains production is severely and frequently affected by the increasing trends of soil acidification and invasive weed species population. Amendment with agricultural lime can help increase soil pH and reduce weed seed bank density by improving the crop vigor to effectively compete against weeds for nutrients and water. However, there is limited information about the specific effect of lime amelioration on certain weed species. Greenhouse trials were conducted in the spring of 2023 at the University of Idaho Kimberly Research and Extension Center, to evaluate the effect of lime amended soils (0, 1.1, 2.2, 4.5, 9.0, 13.5, 17.9, and 22.4 Mg $CaCO_3$ ha^{-1}) on different weed species. There were four weed species (kochia, common lambsquarters, Italian ryegrass, and wild oat) that were grown on lime amended soils. The average post-incubation soil pH recorded ranged from 5.8 to 6.4 pH. However, no statistical differences were observed except for common lambsquarters' height (average= 8.3 cm; site D) and Italian ryegrass top weight at site B (average= 0.14 g $plant^{-1}$). Wild oat top weight (range= 8.3 to 30.4 cm across all sites) and biomass (range= 0.05 to 0.30 g $plant^{-1}$ across all sites) showed no significant response to lime rates. Our results suggest no clear response of lime incorporation on different weed species nor do the weed species have different sensitivity and preferences to soil pH. The effect of soil pH on weed growth and crop competition may be more influenced by crop-weed interaction under different levels of soil pH than just the direct effect of pH on weeds.

Introduction

In the Pacific Northwest, small grain growers experience serious economic losses as a result of weed interference (Ball et.al, 2007). In fact, economic yield losses attributable to weeds have been estimated to be around 7.9% to 47.0%, with a weighted average (by production) of 33.2% for the United States between 2007 and 2017 (Flessner et al., 2021). Weeds have a significant negative impact on crop growth, including reduced tiller number, reduced crop density and stunted growth on small grain crops (Kruidhof et al., 2008). Therefore, small grain yields are greatly reduced under high weed densities, due to the crop-weed competition for available growth resources (Amare et al., 2014; Radosevich et al., 1997; Pandit, 2006).

When weeds invade crops, crop-weed interference associations such as neutralism, protocooperation, commensalism, amensalism and competition may occur (Amare 2014; Hauggaard-Nielsen, 2001). Grassy weeds tend to be more competitive with wheat (*Triticum aestivum*) compared to broadleaf weeds. For example, just nine Italian ryegrass (*Lolium multiflorum*) in 100 winter wheat plants m^{-2} reduced wheat yield by 33% (Hashem et al. 1998). Similarly, just 40 Italian ryegrass per square meter reduced wheat yield by 50% (Stone et al. 1998). In addition, interference of grassy weeds such as jointed goatgrass (*Aegilops cylindrica*) has proven to be a major problem for wheat farmers in the Western U.S, with severely reduced grain yields and dockage losses (Ball et al., 1999). Healthy crops are able to effectively compete with weeds for growth resources, thereby reducing the impact of weeds on crop growth and yield. However, soil properties such as pH can greatly affect the ability of crops to effectively compete with weeds.

Soil acidity remains one of the leading yield setbacks in small grain crop production (Godsey 2007; McFarland, 2020; Fageria, 2014). The core effects of soil acidity on crop health are associated with the acidic toxicity effects on restricted nutrient availability, restricted root growth, restricted clay minerals, and restricted soil organic matter (Havlin et al., 2016). Exchangeable hydrogen (H^+) in the soil increases the relative exchangeable aluminum (Al^{3+}) ions in the soil (at $pH<5$), which inhibits cell differentiation in the root apex root vascular bundles (Havlin et al., 2016; Kochian, 1995; Silva, 2012). This significantly deteriorates root growth which also limits the root membrane permeability to nutrients and water.

Understanding soil acidity relationship with weed growth and competitive ability can provide an insight of how to simultaneously reduce the effect of both problems on small grain production. Several literatures have reported the effects of soil pH on crop nutrient availability or uptake, but there is a dearth of information on the specific effects of soil pH on weeds (Weaver, 1985). Buchanan et al. (1957) reported that weed species have different sensitivity and preferences to soil pH, which also determines weed's competitive ability. For some weeds such as downy brome (*Bromus tectorum*), acidic soils are not a limiting factor for weed growth, since downy brome can take advantage of the reduced competitive resources (Ball et.al, 2007). Downy brome thrives in all soils, has a rapid growth and development, which makes it very competitive with the small grain crops, including winter wheat (Lyon et.al, 2020).

Even though modern agriculture relies heavily on synthetic herbicides, public concerns over the impact of herbicides on human health such the potential leaching of herbicides and contamination of groundwater (Ndou et al., 2022; Poudyal et al., 2022), have raised the need for more ecofriendly tools in weed control. Amendment with agricultural lime can help increase soil pH and reduce weeds seed bank density by improving the crop vigor to effectively compete against weeds for nutrients and water (Koskinen et al., 1986; Skuodienė, 2020).

For some weeds such as rigid ryegrass (*Lolium rigidum*), previous studies have shown that application of agricultural lime can reduce the weed seed germination and vigor (Borger et al. 2020). Borger et al. (2020) reported that application of lime significantly reduced rigid ryegrass population, density, biomass, and seed production from 9,390 to 2,820 seeds m^{-2}, but increased wheat tiller number and yield with a liming application of up to 6,000 kg ha^{-1}.

We conducted a greenhouse experiment to evaluate the effect of lime amended soils on the vigor of different weed species (common lambsquarters, Italian ryegrass, wild oat and kochia).

Materials and methods

Incubation trials summary

A lime incubation study was conducted similar to McFarland et al. (2020) and (Makepeace, 2021) as described in chapter 3.

Greenhouse trials

A greenhouse study was conducted in the spring of 2023 (early March to late April) at the University of Idaho Kimberly Research and Extension Center (42.549877, -114.349615), to evaluate the effect of lime amended soils on different weed species vigor. There were four weed species (kochia, *Bassia scoparia*; common lambsquarters, *Chenopodium album*; Italian ryegrass, *Lolium multiflorum*; and wild oat, *Avena fatua*), each considered a separate experiment. Plastic pots used in this experiment were 5.8 cm in diameter and 5.8 cm deep filled with about 150 g of incubated lime and non-lime amended soils (0, 1.1, 2.2, 4.5, 9.0, 13.5, 17.9, and 22.4 Mg $CaCO_3$ ha^{-1}). Weed seeds were sown at 0.5

cm depth on March 2, 2023. This was followed by immediate irrigation that was set for three minutes, twice a day. Temperature in the greenhouse fluctuated between 23-26 ℃, with high intensity lamps providing supplemental lighting. Weed height was taken weekly following emergence, for a period of five weeks from March 16 to April 20, 2023. After five weeks, weeds were harvested to evaluate the impact of lime amendments on aboveground weed biomass. Above ground growth was oven-dried at 60 ℃ for a period of three days and weighed.

Data Analysis

All data analyses were performed in R statistical language version 4.0.2 (R Core Team, 2023). Analysis of variance (ANOVA) was conducted using the *aov* function in R. For $CaCO_3$ main effects on weeds height and top weight, estimated marginal means were calculated, and *post-hoc* Tukey-adjusted pairwise treatment comparisons were performed at alpha level of 0.05 using the *emmeans* and *multcomp* packages (Hothorn et al., 2008; Lenth, 2022).

Results and discussion

Weeds vigor response

The average post-incubation soil pH recorded in northern Idaho (Benewah and Latah Counties) was lower (5.8 pH) than the southern Idaho (Fremont, Bonneville & Caribou counties) soil pH (6.4 pH; data not shown). Previous studies have reported that soil amelioration with lime not only can cause subsequent increase in soil pH but can also significantly reduce the weed seed germination and vigor (Gazey et al., 2010). However, this was not consistent with our weed study findings. Plant height and shoot weight for each the four weed species grown in soils from each of the 16 sites is outlined in Tables 4.1 to 4.4. Out of all the weed species that were assessed, only common lambsquarters' height (average= 8.3 cm; site D) and top weight biomass were significantly influenced by the $CaCO_3$ lime rates except at site A, I & E (Table 4.2). Similarly, treatment with lime was significant in reducing Italian ryegrass top weight only at site B (average= 0.14 g plant^{-1}; Table 4.4). Wild oat top weight (range= 8.3 to 30.4 cm across all sites; Table 4.5) and biomass showed no significant response to lime rates (range= 0.05 to 0.30 g plant^{-1} across all sites; Table 4.3). In addition, kochia top weight (range= 7.1 to 11.9 cm across all sites; Table 4.1) and biomass showed no significant response to lime rates (range= 0.05 to 0.09 g plant^{-1}

across all sites; Table 4.1). Even though most responses were not significant, it appears that there is a clear trend to lime application in the common lambsquarters plant height, wild oat height and shoot weight, and Italian ryegrass height and shoot weight (Tables 4.1 to 4.4).

Preliminary research has shown that it is often difficult to determine the critical soil pH for weeds and even agronomic crops (Adams et al, 1967; Buchanan et al., 1957), especially since there is a wide variation in solubility and availability of essential nutrients and activity of suitable microorganism in soils. This suggests that weed species have different sensitivity and preferences to soil pH, which also determines weed's competitive ability. However, some studies have shown the pH requirements of some of the weeds included in this study. For example, kochia seed can germinate under either extreme acid or alkaline conditions. Everitt et al. (1983) reported that kochia thrives well on soils with pH of 5 to 9.5, with optimum pH of 6.5.

It appears the effect of soil pH on weed growth and crop-weed interaction is influenced by both the direct effect of pH on weed growth and as well as the effect of pH on crop competitiveness. Most weeds thrive well on poor soil conditions compared to agronomic crops. Thus, soil acidity tends to favor weed growth. Liming makes more nutrients available to increase crop competitiveness against weeds. It appears the absence of crops in the greenhouse may in part have accounted for the reduced weed response to liming. In addition, greenhouse liming studies have rarely shown plant response (Buchanan et al., 1957). Studies that have shown negative effect of liming on weeds were often conducted under field conditions (Borger et al., 2020; Skuodienė et al., 2020; Légère et al., 1994). This study was conducted for only five weeks, which may be too short to observe any drastic changes in weed vigor or growth. Under field conditions, the combined effect of weather and other soil factors as well as intra and interspecific competition may also play a role in weed response to liming.

Conclusion

Incorporation with lime reduced common lambsquarters growth. However, liming had minimal impact on kochia, wild oats and Italian ryegrass growth. These results indicate the effect of soil pH on weed growth and crop competition may be more influenced by crop-weed interaction under different levels of soil pH than just the direct effect of pH on weeds.

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Table 4.1 Average weed height and topweight biomass for kochia (Bassia scoparia) weed grown on Idaho $CaCO_3$ lime amended soils, Kimberly, ID USA.

Lime rate (Mg ha^{-1})	Site A	Site B	Site C	Site D	Site E	Site F	Site G	Site H	Site I	Site J	Site K	Site L	Site M	Site N	Site O	Site P
kochia height (cm)																
0	11.9[1]a	8.6a	8.3a	8.9a	9.8a	9.2a	10.4a	8.7a	7.9a	9.1a	9.2a	8.8a	10.2a	9.4a	8.7a	9.1a
1.1	10.4a	8.6a	8.4a	7.2a	8.7a	8.2a	7.4a	8.6a	8.1a	8.9a	8.3a	8.4a	8.5a	9.1a	8.8a	8.3a
2.2	10.4a	8.4a	8.9a	8.8a	8.2a	8.4a	9.4a	7.1a	8.6a	8.7a	8.4a	7.2a	8.8a	8.7a	9.2a	8.6a
4.5	10.7a	7.9a	8.4a	9.4a	8.7a	7.6a	8.1a	8.1a	8.9a	9.9a	8.3a	8.3a	8.3a	8.3a	7.2a	9.2a
9.0	9.9a	9.4a	8.7a	9.6a	9.1a	10.2a	10.3a	9.8a	8.1a	10.3a	9.5a	9.5a	9.5a	8.2a	9.8a	9.3a
13.5	11.2a	8.6a	8.9a	8.2a	8.3a	10.1a	9.3a	9.1a	9.3a	9.4a	9.5a	9.1a	9.4a	8.1a	9.5a	10.3a
17.9	11.4a	7.8a	7.8a	8.5a	8.9a	9.1a	8.2a	9.1a	8.3a	10.3a	8.6a	8.4a	8.5a	8.0a	9.6a	8.7a
22.4	11.4a	8.6a	8.1a	7.8a	8.6a	7.9a	9.3a	8.7a	9.6a	8.1a	10.1a	9.3a	9.3a	6.8a	8.4a	8.7a
P-value	0.91	0.85	0.96	0.39	0.95	0.33	0.27	0.51	0.61	0.75	0.81	0.51	0.86	0.39	0.69	0.86
kochia weight (g/plant)																
0	0.15a	0.06a	0.06a	0.06a	0.06a	0.06a	0.08a	0.07a	0.06a	0.07a	0.06a	0.08a	0.07a	0.06a	0.06a	0.07a
1.1	0.11a	0.07a	0.08a	0.07a	0.07a	0.08a	0.07a	0.07a	0.07a	0.08a	0.07a	0.08a	0.07a	0.07a	0.08a	0.09a
2.2	0.08a	0.06a	0.07a	0.06a	0.06a	0.07a	0.07a	0.06a	0.05a	0.07a	0.06a	0.06a	0.06a	0.06a	0.06a	0.07a
4.5	0.09a	0.06a	0.06a	0.07a	0.06a	0.06a	0.06a	0.06a	0.05a	0.08a	0.06a	0.06a	0.07a	0.06a	0.06a	0.07a
9.0	0.08a	0.08a	0.07a	0.07a	0.07a	0.11a	0.07a	0.07a	0.07a	0.08a	0.07a	0.07a	0.07a	0.07a	0.08a	0.08a
13.5	0.09a	0.06a	0.06a	0.06a	0.06a	0.09a	0.07a	0.07a	0.06a	0.07a	0.07a	0.07a	0.06a	0.06a	0.07a	0.07a
17.9	0.1a	0.05a	0.06a	0.06a	0.06a	0.06a	0.06a	0.06a	0.06a	0.07a	0.06a	0.06a	0.06a	0.06a	0.03a	0.07a
22.4	0.09a	0.06a	0.06a	0.06a	0.06a	0.06a	0.06a	0.06a	0.06a	0.05a	0.07a	0.06a	0.07a	0.06a	0.06a	0.06a
P-value	0.91	0.34	0.36	0.66	0.57	0.07	0.54	0.43	0.74	0.45	0.66	0.28	0.82	0.28	0.51	0.51

[1] Within the same column, means followed by the same letter are not statistically different with Tukey, at alpha=0.05.

Table 4.2. Average weed height and topweight biomass for common lambsquarters (Chenopodium album) weed grown on Idaho $CaCO_3$ lime amended soils, Kimberly, ID USA.

---common lambsquarters height (cm) ---																
Lime rate (Mg ha^{-1})	**Site A**	**Site B**	**Site C**	**Site D**	**Site E**	**Site F**	**Site G**	**Site H**	**Site I**	**Site J**	**Site K**	**Site L**	**Site M**	**Site N**	**Site O**	**Site P**
0	12.6[1]a	8.7a	8.1a	8.8a	10.3a	9.2a	11.1a	8.9a	7.9a	9.1a	9.3a	8.8a	10.5a	8.2a	8.8a	9.2a
1.1	10.8a	8.6a	8.2a	6.7a	8.7a	8.2a	7.1a	8.8a	8.1a	8.8a	8.2a	8.3a	8.4a	8.2a	8.7a	8.1a
2.2	1.9a	8.3a	9.1a	8.9a	8.3a	8.5a	9.4a	6.9a	8.7a	8.8a	8.1a	7.1a	9.1a	7.9a	9.2a	8.8a
4.5	9.6a	6.8a	7.4a	8.1a	7.5a	6.8a	7.2a	7.2a	7.9a	8.9a	7.2a	7.4a	7.4a	7.7a	6.1a	8.5a
9.0	8.6a	7.4a	6.2a	7.7a	7.1a	8.9a	8.9a	7.9a	5.6a	8.5a	7.7a	7.5a	7.8a	7.1a	8.2a	7.6a
13.5	8.9a	6.3a	6.9a	5.5a	5.9a	7.9a	6.9a	6.8a	7.1a	7.4a	7.3a	6.6a	7.3a	6.7a	7.3a	8.5a
17.9	10.8a	6.7a	6.5a	7.5a	7.5a	8.1a	6.8a	7.9a	7.1a	9.4a	7.5a	7.5a	7.3a	6.7a	8.8a	7.5a
22.4	9.9a	6.3a	5.9a	5.7a	6.4a	5.6a	6.9a	6.5a	7.4a	5.8a	7.9a	7.4a	7.1a	6.0a	6.2a	6.7a
P-value	0.79	0.12	0.11	**0.06**	0.07	0.19	0.06	0.4	0.35	0.41	0.91	0.74	0.34	0.43	0.28	0.79
---common lambsquarters weight (g/plant) --- -----																
0	0.13a	0.07ab	0.08a	0.07a	0.08a	0.07a	0.09a	0.08a	0.07a	0.08a	0.08a	0.09a	0.08a	0.08a	0.08a	0.09a
1.1	0.13a	0.08a	0.08a	0.08a	0.08a	0.08ab	0.08a	0.08a	0.08a	0.09a	0.08a	0.09a	0.08a	0.08a	0.09ab	0.10a
2.2	0.10a	0.07ab	0.08a	0.08a	0.07a	0.08ab	0.08a	0.07ab	0.09a	0.08ab	0.07a	0.07ab	0.08a	0.07a	0.08ab	0.07ab
4.5	0.10a	0.06ab	0.07ab	0.07ab	0.07ab	0.07ab	0.06ab	0.07ab	0.07a	0.08ab	0.07a	0.07ab	0.07a	0.06a	0.06ab	0.07ab
9.0	0.08a	0.07ab	0.06ab	0.06ab	0.06ab	0.11ab	0.06ab	0.07ab	0.06a	0.08ab	0.07a	0.06ab	0.06a	0.05a	0.07ab	0.07ab
13.5	0.08a	0.05ab	0.05ab	0.05ab	0.05ab	0.08ab	0.06ab	0.05ab	0.07a	0.06ab	0.05a	0.06ab	0.05a	0.06a	0.06ab	0.06ab
17.9	0.09a	0.06ab	0.06ab	0.06ab	0.06ab	0.07ab	0.05ab	0.06ab	0.06a	0.07ab	0.06a	0.06ab	0.06a	0.06a	0.07ab	0.07ab
22.4	0.08a	0.03b	0.03b	0.03b	0.03b	0.03b	0.004b	0.03b	0.05a	0.04b	0.05a	0.04	0.05a	0.04a	0.04b	0.04b
P-value	0.24	**0.01**	**<0.001**	**<0.001**	**<0.001**	**0.04**	**<0.001**	**<0.001**	0.29	**<0.001**	0.27	**<0.001**	0.06	**<0.001**	**<0.001**	**<0.001**

[1] Within the same column, means followed by the same letter are not statistically different with Tukey, at alpha=0.05.

Table 4.3. Average weed height and topweight biomass for wild oat (Avena fatua) weed grown on Idaho $CaCO_3$ lime amended soils, Kimberly, ID USA.

Lime rate ($Mg\ ha^{-1}$)	Site A	Site B	Site C	Site D	Site E	Site F	Site G	Site H	Site I	Site J	Site K	Site L	Site M	Site N	Site O	Site P
wild oat height (cm)																
0	30.4[1]a	27.8a	29.1a	28.2a	29.1a	29.5a	29.4a	28.2a	28.6a	28.9a	28.3a	28.7a	28.7a	15.7a	29.6a	29.2a
1.1	27.6a	25.1a	25.3a	25.4a	25.6a	24.9a	26.9a	24.9a	26.6a	26.3a	25.4a	24.9a	25.5a	15.6a	26.5a	26.1a
2.2	26.6a	27.8a	25.4a	25.9a	25.6a	27.1a	25.8a	27.8a	26.0a	26.3a	26.7a	26.1a	26.5a	14.4a	26.7a	27.1a
4.5	25.9a	25.2a	26.5a	27.1a	26.7a	25.2a	26.2a	24.7a	25.8a	26.1a	27.4a	25.3a	25.2a	14.1a	25.3a	25.3a
9.0	26.9a	26.9a	27.4a	25.6a	27.4a	26.1a	26.5a	26.4a	26.7a	27.9a	25.7a	27.6a	27.6a	14.0a	26.2a	26.7a
13.5	24.9a	24.9a	23.1a	23.4a	23.7a	24.4a	24.1a	23.2a	24a	23.1a	23.3a	23.7a	23.9a	12.4a	24.0a	23.3a
17.9	24.9a	23.1a	23.9a	23.7a	25a	24.8a	25.6a	25.5a	24.6a	24.9a	23.8a	24.9a	23.7a	9.5a	23.9a	24.7a
22.4	24.1a	22.9a	23.2a	22.6a	22.8a	23.3a	24.4a	23.1a	23.5a	22.8a	25.5a	23.5a	24.8a	8.9a	22.7a	23.0a
P-value	0.1	0.18	0.11	0.22	0.14	0.14	0.29	0.18	0.33	0.1	0.32	0.24	0.26	0.83	0.07	0.09
wild oat weight (g/plant)																
0	0.30a	0.06a	0.09a	0.04a	0.09a	0.07a	0.17a	0.11a	0.06a	0.10a	0.08a	0.16a	0.11a	0.13a	0.11a	0.17a
1.1	0.30a	0.07a	0.10a	0.05a	0.08a	0.13a	0.14a	0.08a	0.08a	0.13a	0.07a	0.13a	0.10a	0.11a	0.11a	0.19a
2.2	0.29a	0.08a	0.09a	0.09a	0.06a	0.12a	0.13a	0.09a	0.15a	0.11a	0.09a	0.09a	0.10a	0.10a	0.10a	0.12a
4.5	0.23a	0.06a	0.08a	0.11a	0.09a	0.07a	0.07a	0.07a	0.11a	0.14a	0.11a	0.09a	0.09a	0.10a	0.08a	0.12a
9.0	0.18a	0.11a	0.09a	0.08a	0.06a	0.24a	0.08a	0.08a	0.05a	0.14a	0.09a	0.09a	0.07a	0.09a	0.11a	0.12a
13.5	0.21a	0.04a	0.07ab	0.05a	0.05a	0.21a	0.09a	0.07a	0.18a	0.09a	0.07a	0.09a	0.05a	0.07a	0.11a	0.09a
17.9	0.25a	0.04a	0.04a	0.06a	0.08a	0.09a	0.07a	0.09a	0.09a	0.12a	0.05a	0.06a	0.06a	0.06a	0.09a	0.11a
22.4	0.25a	0.05a	0.04a	0.05a	0.03a	0.04a	0.07a	0.04a	0.09a	0.06a	0.16a	0.08a	0.13a	0.05a	0.07a	0.06b
P-value	0.43	0.57	0.33	0.45	0.47	0.61	0.26	0.43	0.66	0.28	0.47	0.58	0.3	0.47	0.24	0.26

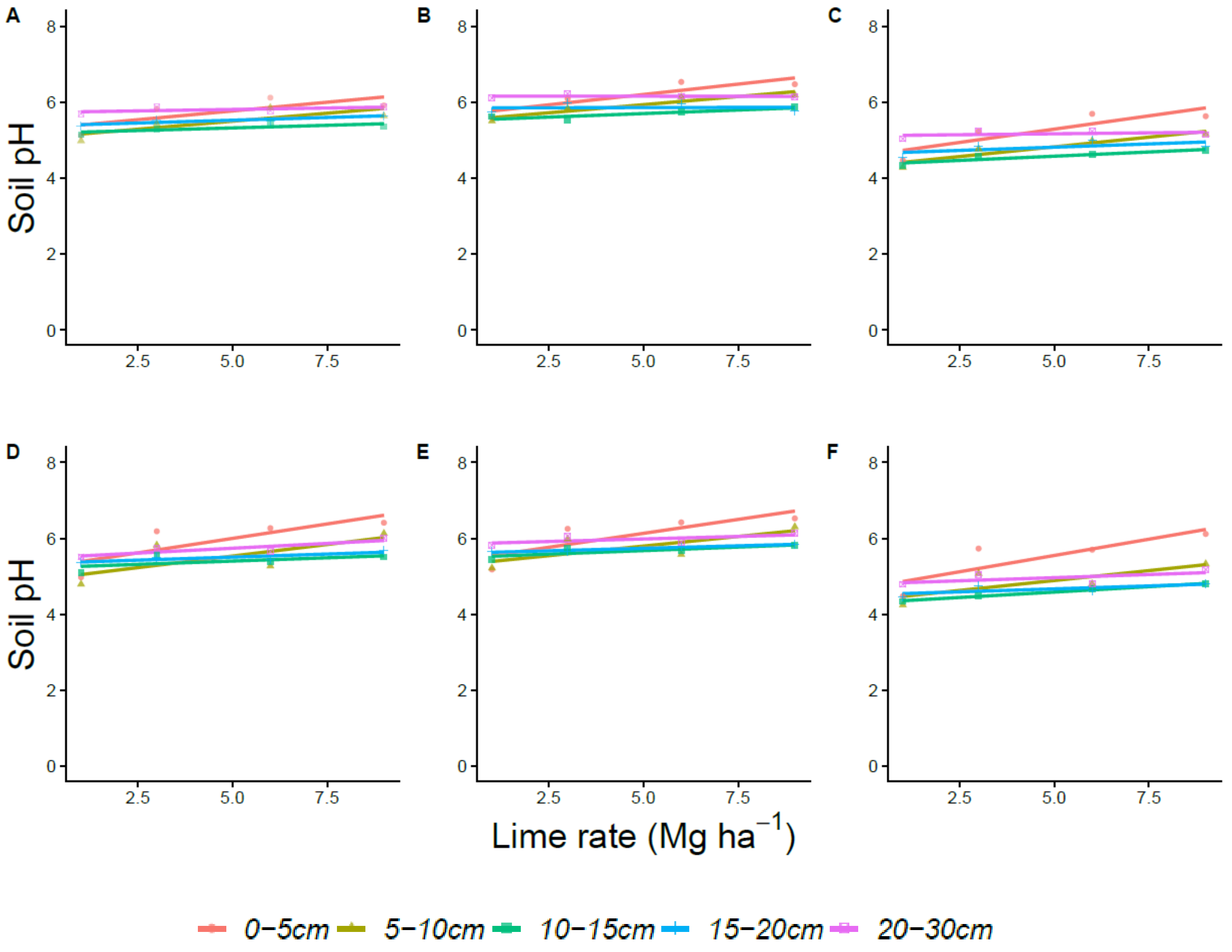
[1] Within the same column, means followed by the same letter are not statistically different with Tukey, at alpha=0.05.

Table 4.4. Average weed height and topweight biomass for Italian ryegrass (Lolium multiforum Lam) weed grown on Idaho $CaCO_3$ lime amended soils, Kimberly, ID USA.

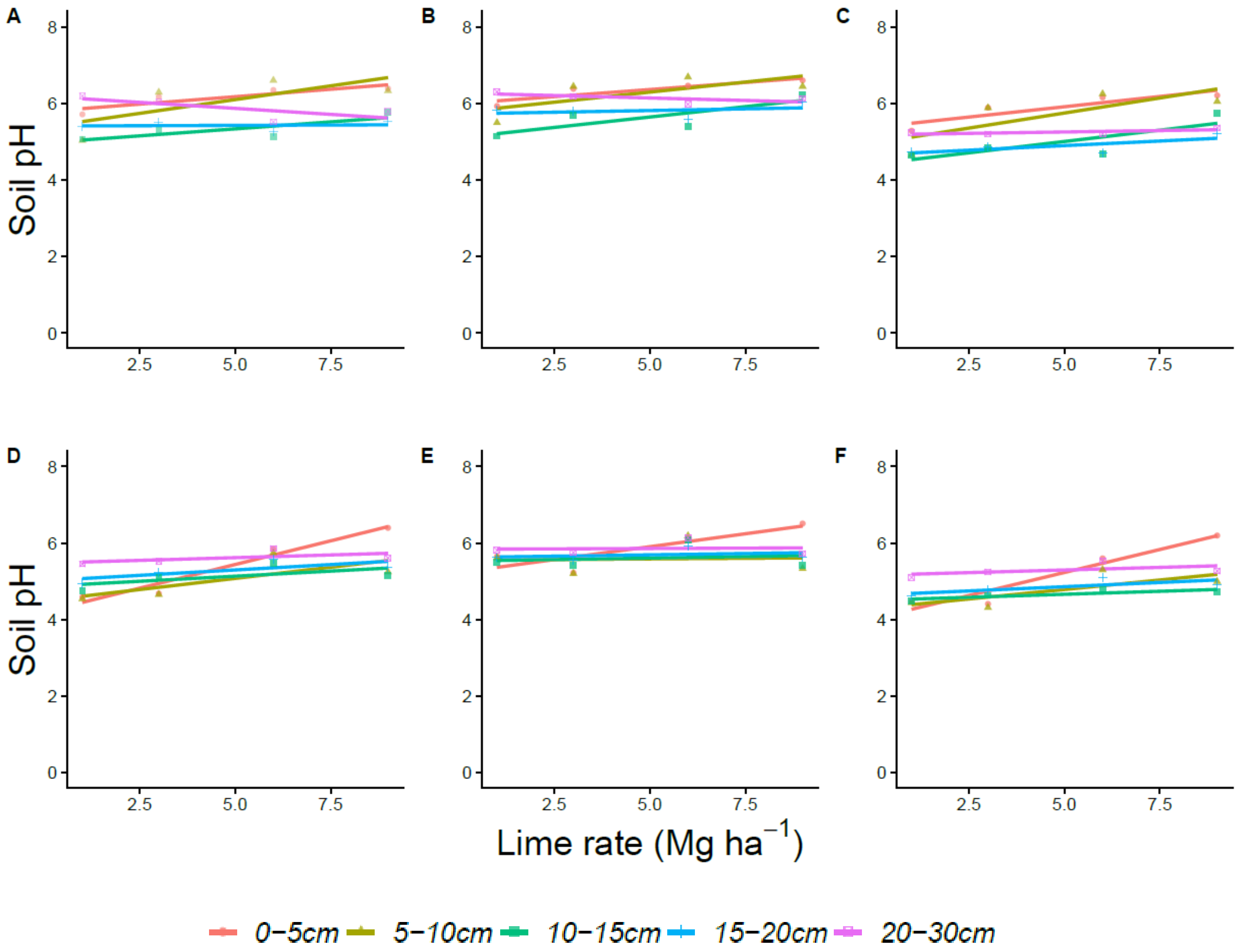
Lime rate ($Mg\ ha^{-1}$)	Site A	Site B	Site C	Site D	Site E	Site F	Site G	Site H	Site I	Site J	Site K	Site L	Site M	Site N	Site O	Site P
ryegrass height (cm)																
0	26.8[1]a	22.8a	23.6a	23.7a	23.7a	24.4a	25.7a	23.1a	22.3a	23.1a	23.0a	23.5a	24.0a	24.3a	23.7a	24.4a
1.1	23.0a	21.1a	21.6a	20.7a	21.4a	20.9a	22.2a	21.5a	21.6a	21.7a	21.5a	21.2a	21.2a	22.0a	20.9a	21.5a
2.2	21.0a	21.6a	20.8a	21.0a	20.0a	21.9a	20.6a	21.3a	20.4a	19.7a	20.7a	20.3a	21.0a	21.0a	20.7a	21.0a
4.5	21.6a	19.6a	21.2a	21.8a	21.4a	20.1a	21.2a	19.9a	20.6a	20.9a	22.1a	20.7a	20.1a	20.6a	19.7a	20.8a
9	21.6a	21.8a	21.7a	21.3a	22.3a	21.8a	22.1a	20.9a	21.0a	23.2a	21.2a	21.9a	22.1a	20.5a	21.3a	21.7a
13.5	22.4a	22.0a	20.8a	20.9a	21.2a	22.2a	21.0a	20.5a	21.8a	21.0a	20.8a	20.8a	20.9a	20.1a	22.2a	21.6a
17.9	21.3a	18.4a	18.4a	19.2a	20.3a	19.3a	19.7a	20.1a	19.5a	21.0a	19.2a	19.3a	18.3a	19.1a	19.7a	19.6a
22.4	21.6a	19.8a	19.3a	19.3a	19.4a	19.3a	20.1a	19.4a	20.3a	19.3a	21.4a	19.1a	21.0a	18.5a	19.2a	19.8a
P-value	0.17	0.27	0.28	0.41	0.43	0.16	0.08	0.65	0.82	0.36	0.75	0.43	0.22	0.11	0.37	0.34
ryegrass weight (g/plant)																
0	0.18a	0.12ab	0.14a	0.13a	0.13a	0.14a	0.15a	0.14a	0.12a	0.13a	0.12a	0.15a	0.13a	0.15a	0.14a	0.15a
1.1	0.17a	0.13ab	0.14a	0.13a	0.13a	0.15a	0.15a	0.14a	0.14a	0.14a	0.13a	0.14a	0.13a	0.15a	0.13a	0.16a
2.2	0.14a	0.13ab	0.13a	0.13a	0.12a	0.14a	0.14a	0.13a	0.14a	0.12a	0.13a	0.13a	0.13a	0.13a	0.13a	0.14a
4.5	0.15a	0.11a	0.11a	0.12a	0.11a	0.11a	0.11a	0.11a	0.12a	0.12a	0.12a	0.12a	0.11a	0.13a	0.11a	0.12a
9	0.16a	0.17ab	0.16a	0.15a	0.15a	0.15a	0.15a	0.15a	0.15a	0.17a	0.15a	0.16a	0.15a	0.13a	0.16a	0.16a
13.5	0.15a	0.16ab	0.15a	0.15a	0.15a	0.16a	0.16a	0.15a	0.16a	0.15a	0.15a	0.16a	0.15a	0.11a	0.16a	0.15a
17.9	0.14a	0.09b	0.09a	0.09a	0.09a	0.09a	0.09a	0.10a	0.10a	0.10a	0.09a	0.09a	0.09a	0.11a	0.10a	0.10a
22.4	0.14a	0.10ab	0.11a	0.09a	0.07a	0.10a	0.1a	0.10a	0.11a	0.10a	0.11a	0.10a	0.11a	0.09a	0.10a	0.10a
P-value	0.66	**0.03**	0.08	0.16	0.1	0.06	0.06	0.2	0.18	0.11	0.31	0.4	0.23	0.27	0.05	0.09

[1] Within the same column, means followed by the same letter are not statistically different with Tukey, at alpha=0.05.

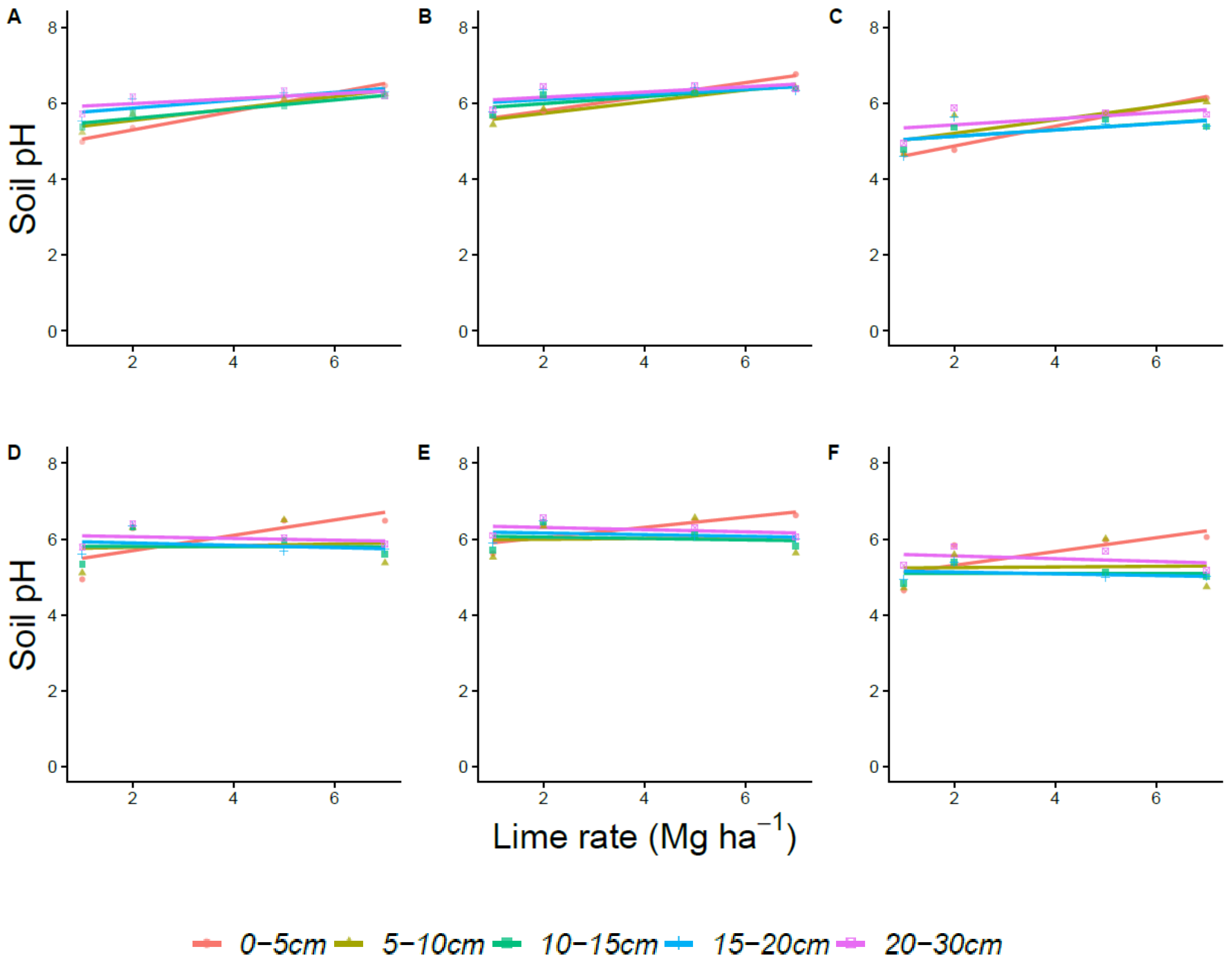
Appendices



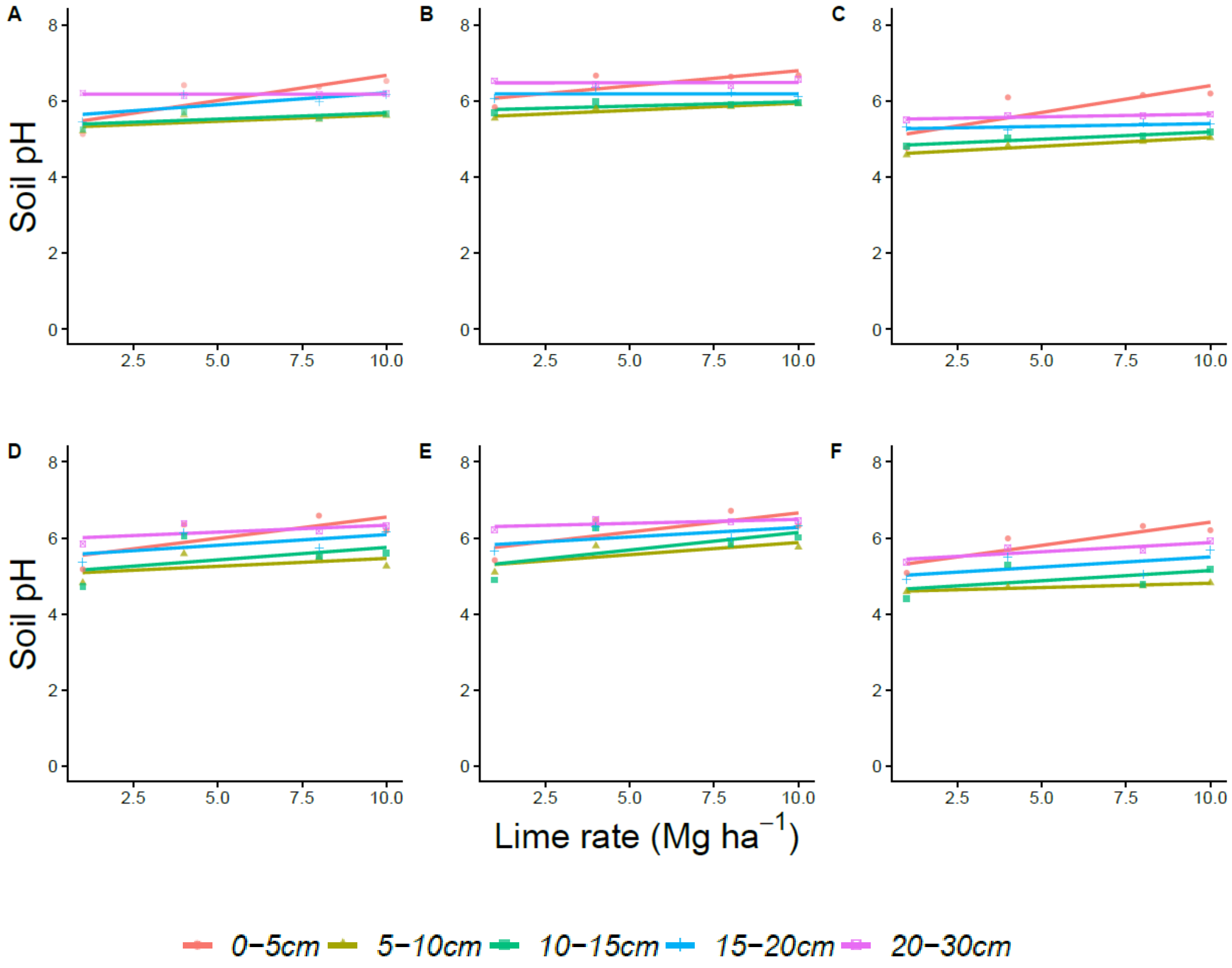
Appendix 1.1. Soil pH 1:1 $_{water,}$ (A & D), soil pH 1:2$_{water,}$ (B & E) and soil pH1:1 $_{0.01M\ CaCl2}$ (C & F) responses after one year of PCC lime application at Site A during Summer 2022 (A, B, C) and Fall 2022 (D, E, F).



Appendix 1.2. Soil pH 1:1 $_{\text{water,}}$ (A & D), soil pH 1:2$_{\text{water,}}$ (B & E) and soil pH1:1 $_{\text{0.01M CaCl2}}$ (C & F) responses after one year of PCC lime application at Site B during Summer 2022 (A, B, C) and Fall 2022 (D, E, F).



Appendix 1.3. Soil pH 1:1 $_{\text{water}}$, (A & D), soil pH 1:2$_{\text{water}}$, (B & E) and soil pH1:1 $_{\text{0.01M CaCl2}}$ (C & F) responses after one year of PCC lime application at Site C during Summer 2022 (A, B, C) and Fall 2022 (D, E, F).



Appendix 1.4. Soil pH 1:1 $_{\text{water}}$, (A & D), soil pH 1:2$_{\text{water}}$, (B & E) and soil pH1:1 $_{\text{0.01M CaCl2}}$ (C & F) responses after one year of PCC lime application at Site D during Summer 2022 (A, B, C) and Fall 2022 (D, E, F).

Appendix 1.5. Treatment means for soil pH 1:1 $_{water}$ in response to one year of PCC liming at site A in eastern Idaho, USA.

Site A

	0 - 5 cm	5 - 10 cm	10 - 15 cm	15 - 20 cm	20 - 30 cm
Lime rate	------------------------------------- pH 1:1$_{water}$-------------------------------- ---				
0.0	5.0c[1]	4.8d	5.1c	5.4b	5.5c
2.8	6.2b	5.3c	5.6a	5.5ab	5.7b
5.5	6.3ab	5.8	5.4b	5.5b	5.7bc
8.3	6.4a	6.1a	5.5ab	5.4b	6.0a
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 1.6. Treatment means for soil pH 1:1 $_{water}$ in response to one year of PCC liming at site B in eastern Idaho, USA.

Site B

	0 - 5 cm	**5 - 10 cm**	**10 - 15 cm**	**15 - 20 cm**	**20 - 30 cm**
Lime rate	--------------------------------- pH 1:1 $_{water}$ ---------------------------------- ---				
0.0	4.6c[1]	4.5c	4.8c	5.0c	5.5c
2.8	4.7c	4.7c	5.1b	5.2b	4.7c
5.5	5.8b	5.2b	5.2b	5.4ab	5.2b
8.3	6.4a	5.7a	5.5a	5.6a	5.7a
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 1.7. Treatment means for soil pH 1:1 $_{water}$ in response to one year of PCC liming at site C in eastern Idaho, USA.

	Site C				
	0 - 5 cm	5 - 10 cm	10 - 15 cm	15 - 20 cm	20 - 30 cm
Lime rate	-------------------------------- pH 1:1$_{water}$---------------------------------------				
0.0	4.9b[1]	5.1b	5.3b	5.8b	5.1b
2.6	6.3a	6.3a	6.3a	6.4a	6.3a
5.2	6.4a	6.5a	5.9a	6.0b	6.5a
7.8	6.5a	5.1b	5.6b	5.9b	5.4b
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 1.8. Treatment means for soil pH 1:1 $_{water}$ in response to one year of PCC liming at site D in eastern Idaho, USA.

	Site D				
	0 - 5 cm	**5 - 10 cm**	**10 - 15 cm**	**15 - 20 cm**	**20 - 30 cm**
Lime rate	---------------------------------- pH 1:1 $_{water}$ -----------------------------------				
0.0	5.2c[1]	4.5c	4.7c	5.4c	5.9b
4.1	6.1b	4.7c	6.1a	6.1a	6.4a
8.2	6.6a	5.2b	5.5b	5.7b	6.2a
12.3	6.1b	5.7a	5.6b	6.2a	6.3a
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 1.9. Treatment means for soil pH 1:2$_{\text{water}}$ in response to one year of PCC liming at site A in eastern Idaho, USA.

Site A

	0 - 5 cm	5 - 10 cm	10 - 15 cm	15 - 20 cm	20 - 30 cm
Lime rate	------------------------------------- pH 1:2$_{\text{water}}$-----------------------------------				
0.0	5.2c[1]	5.2d	5.5b	5.6a	5.8b
2.8	6.3b	6.0b	5.7a	5.7a	6.1ab
5.5	6.4ab	5.9c	5.7ab	5.8a	5.9ab
8.3	6.5a	6.3a	5.8a	5.8a	6.1a
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 2.0. Treatment means for soil pH 1:2$_{\text{water}}$ in response to one year of PCC liming at site B in eastern Idaho, USA.

Site B

	0 - 5 cm	**5 - 10 cm**	**10 - 15 cm**	**15 - 20 cm**	**20 - 30 cm**
Lime rate	------------------------------------- pH 1:2$_{\text{water}}$ ----------------------------------				
0.0	5.7c[1]	5.6b	5.5b	5.6b	5.8b
2.8	5.2d	5.2c	5.4b	5.6b	5.8b
5.5	6.1b	6.2a	6.1a	5.9a	6.1a
8.3	6.5a	5.3c	5.5b	5.6b	5.7b
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 2.1. Treatment means for soil pH 1:2$_{water}$ in response to one year of PCC liming at site C in eastern Idaho, USA.

Site C

	0 - 5 cm	5 - 10 cm	10 - 15 cm	15 - 20 cm	20 - 30 cm
Lime rate	---------------------------------- pH 1:2$_{water}$---------------------------------- ---				
0.0	5.6b[1]	5.5b	5.7c	5.9b	6.1b
2.6	6.4a	6.3a	6.4a	6.5a	6.6a
5.2	6.5a	6.6a	6.1b	6.1b	6.3ab
7.8	6.6a	5.6b	5.8c	6.0b	6.1b
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 2.2. Treatment means for soil pH 1:2 $_{water}$ in response to one year of PCC liming at site D in eastern Idaho, USA.

Site D

	0 - 5 cm	**5 - 10 cm**	**10 - 15 cm**	**15 - 20 cm**	**20 - 30 cm**
Lime rate	------------------------------ pH 1:2 $_{water}$ ------------------------------------ ---				
0.0	5.4c[1]	5.1b	4.9c	5.7b	6.2a
4.1	6.5ab	5.8a	6.3a	6.3a	6.5a
8.2	6.7a	5.8a	5.9b	6.0ab	6.4a
12.3	6.3b	5.8a	6.0ab	6.3a	6.5a
	5.4c	5.1b	4.9c	5.7b	6.2a
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 2.3. Treatment means for soil pH 1:1$_{CaCl2}$ in response to one year of PCC liming at site A in eastern Idaho, USA.

Site A

Lime rate	0 - 5 cm	5 - 10 cm	10 - 15 cm	15 - 20 cm	20 - 30 cm
	------------------	------------------	pH 1:1$_{CaCl2}$	------------------	------------------
0.0	4.5b[1]	4.3b	4.3a	4.6a	5.0a
2.8	52a	4.8ab	4.6a	4.8a	5.2a
5.5	5.7b	5.0a	4.6a	5.0a	4.2a
8.3	5.6b	5.2a	4.7a	4.8a	5.1a
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	0.158				

[1]Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 2.4. Treatment means for soil pH 1:1$_{CaCl2}$ in response to one year of PCC liming at site B in eastern Idaho, USA.

Site B

Lime rate	**0 - 5 cm**	**5 - 10 cm**	**10 - 15 cm**	**15 - 20 cm**	**20 - 30 cm**
	------------------	------------------	pH 1:1$_{CaCl2}$	------------------	------------------
0.0	5.3c[1]	4.7c	4.6b	4.7b	5.2a
2.8	5.9b	5.9b	4.8b	4.8b	5.2a
5.5	6.2b	6.3a	4.8b	4.7b	5.2a
8.3	6.2a	6.1ab	5.7a	5.1a	5.4a
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1]Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 2.5. Treatment means for soil pH 1:1$_{CaCl2}$ in response to one year of PCC liming at site C in eastern Idaho, USA.

Site C

	0 - 5 cm	5 - 10 cm	10 - 15 cm	15 - 20 cm	20 - 30 cm
Lime rate	-------------------------------- pH 1:1$_{CaCl2}$ ---------------------------------------				
0.0	4.7c	4.6c	4.8c	4.6c	4.9c
2.6	4.8c	5.7b	5.4b	5.6a	5.9a
5.2	5.7b	5.7b	5.6a	5.4b	5.7ab
7.8	6.1a	6.0a	5.4b	5.4b	5.7b
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05

Appendix 2.6. Treatment means for soil pH 1:1$_{CaCl2}$ in response to one year of PCC liming at site D in eastern Idaho, USA.

Site D

	0 - 5 cm	**5 - 10 cm**	**10 - 15 cm**	**15 - 20 cm**	**20 - 30 cm**
Lime rate	-------------------------------------- pH 1:1$_{CaCl2}$ ----------------------------------				
0.0	4.8b	4.6b	4.8a	5.3a	5.5a
4.1	6.1a	4.8ab	5.0a	5.2a	5.6a
8.2	6.2a	4.9ab	5.1a	5.4a	5.6a
12.3	6.2a	5.0a	5.2a	5.4a	5.6a
Depth	**<0.001**				
Lime rate	**<0.001**				
Depth * Lime rate	**<0.001**				

[1] Within the same column, means followed by the same letter are not statistically different with Tukey HSD at alpha= 0.05