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Sugarbeet Processing Precipitated Calcium Carbonate Lime Effects on a Crop Rotation and Soil Properties

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Abstract

Each year in Idaho and Oregon, 351,000 Mg of precipitated calcium carbonate (PCC) (a byproduct of sucrose extraction from sugarbeet) is produced and stockpiled at sugarbeet processing factories. Currently there are limited disposal strategies for the PCC and these stockpiles continue to grow over time. The simplest solution would be to apply the PCC directly to agricultural fields each year, however the effects of PCC on high pH soils and crop rotations in the growing area are not well understood and growers are understandably hesitant. Two studies were conducted at the USDA-ARS laboratory in Kimberly, ID to determine the effects of PCC application to a high pH silt loam soil on a sugarbeet, dry bean and barley rotation and soil properties. For each study, three PCC treatments (rate and timing) and an untreated control were evaluated. The PCC had no effects on crop yields and most soil properties. The only common effect of PCC treatments was an increase in soil phosphorus (P) concentrations compared to the control, indicating the PCC can serve as a P fertilizer. For all three crops in this study, PCC was applied at rates that resulted in applied P rates that were 1.6 to 5.3 times greater than even the highest published recommended agronomic P rates. Compared to the control, bicarbonate soil P concentrations increased by 139% and 84% when PCC was applied at a rate of 87.9 Mg ha^{-1} in Study1 and Study 2, respectively. The PCC used in this study can safely be applied at rates up to 87.9 Mg ha^{-1} to heavier textured alkaline soils in the local growing area. Disposing of PCC in this way represents a viable strategy for reducing PCC stockpiles.

Additional Key Words: precipitated calcium carbonate, spent lime, lime, sugarbeet, sugar beet, *Beta vulgaris*, pH, phosphorus

Abbreviations: PCC = precipitated calcium carbonate

Introduction

Precipitated calcium carbonate (PCC) is produced as a waste material from the sugarbeet (*Beta vulgaris* L.) sucrose extraction process (Tarkalson et al., 2024). Lime materials (PCC, calcium oxide, calcium hydroxide, calcium and magnesium carbonates, marl, blast-furnace slag, fly ash, and wastewater treatment sludge) are often used in agriculture to raise soil pH in acid soils and prevent loss of production (Havlin et. al, 1999). Negative issues associated with acid soils include Al and/or Mn toxicity, H ion toxicity, decreased bioavailability of some plant nutrients (Mg, Ca, K, P, and Mo), and inhibition of root growth (Marschner, 1995). An estimated 25 to 30% of world soils are acidic (Havlin et. al, 1999). Soil acidification is common in areas with excess water leaching through soils due to higher rainfall amounts (typically >500 mm/yr) and lower soil base content (Miller and Gardiner, 2001). Periodic application of liming materials is often used on these soils to increase or maintain their productivity.

Although other sugarbeet producing areas in the U.S. produce similar, and even more, amounts of PCC, they do not have the stockpiling issues experienced in the Pacific Northwest. In the North Central U.S. some soils can be acidic and PCC is used to raise soil pH (Barber, 1984) as well as to suppress *Aphanomyces* *cochliodes,* an oomycete pathogen that causes sugarbeet root damage (dampening off and rot) (Olsson et al., 2019; Lien et al., 2016; Brantner et al., 2015; Windels et al., 2008). In Michigan, sugar beet growers apply approximately 220,000 tons of PCC annually (Clark et. al, 2015). In one study in Michigan, PCC applied at rates ranging from 0 to 27 Mg ha^{-1} increased soil pH from 7.1 to 7.8 and sugar beet sucrose yield from 7,846 to 8,540 kg ha^{-1}, respectively (Clark et. al, 2015). This increase in yield was attributed to ameliorating negative effects associated with low soil pH. The application of PCC to agricultural soils in these regions prevents the kind of accumulation of PCC at North Central U.S. sugarbeet factories that is so common, and problematic, in the Pacific Northwest growing area (Clark et. al, 2015).

In the Amalgamated Sugar Company growing area in Idaho, Oregon and Washington calcareous soils prevail. High in base cations, these soils typically have pH's in the range 7.5-8.5. These soils do not cause the same negative effects on crop production as those associated with acidic soils and therefore do not require lime applications to adjust soil pH. The soil pathogen *Aphanomyces cochliodes* is present in some areas and PCC is often applied to reduce its damaging effects, however this accounts for a very small proportion of overall PCC production each year. The limited uses for PCC in this growing area has resulted in growing PCC stockpiles at the factories. Finding additional uses for PCC would be helpful to reduce stockpile sizes and associated negative effects. Some potential negative effects include cost of land, and air and water quality issues.

The simplest way to dispose of the PCC is to apply it to more agricultural production areas. This could only be considered if there was confidence that the PCC did not negatively affect crop production and soil chemical /physical properties. Prior to soil amendment applications to agricultural soils, questions are often raised about suitability for land application due to amendment properties such as salts and toxic metals. High soluble salts concentrations lower the osmotic water potential in soil resulting in plants being unable to draw water into the roots, resulting in water deficiencies in plants. Additionally, high soluble salts in the root zone can compromise sugarbeet seed germination and emergence resulting in poor stand counts (Walter et al., 1951). Preliminary research on the effects of PCC applied to arid alkaline soils (Scottsbluff, NE; Ft. Morgan, CO; and Torrington, WY) showed no negative effects on the emergence of sugarbeet (Hergert et al., 2017). Hergert et al. (2017) stated that additional research was needed to evaluate the effects of PCC on soil characteristics and plant growth under field conditions. In addition, when land applying amendments, concentrations of potentially toxic metals need to be considered. Some common metals that can be toxic to plants if soluble concentrations in soils are high enough are Al, Cu, Zn, Cd, and Pb (Angulo-Bejarano et al., 2021).

The Amalgamated Sugar Company LLC's major sugarbeet processing factories (Paul, ID; Twin Falls, ID; and Nampa, ID) produce approximately 351,000 Mg of PCC annually (Amalgamated Sugar Company LLC, personal conversation). In 2018, PCC stockpiles at these factories totaled approximately 11.4 million Mg. Without an offsite beneficial use or disposal method, these stockpiles will continue to grow. The difficulty in finding more land to stockpile PCC due to availability issues and high land prices, and potential environmental issues have resulted in the need for Amalgamated Sugar Company LLC to find more offsite beneficial use or disposal methods.

The objective of the study was to assess the effects of added PCC to a common alkaline soil on a sugarbeet-dry bean-barley rotation yields and soil chemical properties. The data will guide PCC application to agricultural soils with natively high pH.

Materials and Methods

Two studies were conducted from 2015 to 2022 at the USDA-ARS Northwest Irrigation & Soils Research Lab in Kimberly, ID on a Portneuf silt loam (coarse-silty mixed superactive, mesic Durixerollic Xeric Haplocalcids). The treatments for each study consisted of four PCC application rate/timings in a sugarbeet, dry bean, and barley crop rotation. PCC for both studies was sourced from the Twin Falls Idaho factory. Both studies had the same treatments with Study 1 starting in 2015 and Study 2 starting in 2016. Both studies were adjacent to each other in the same field. Table 1 outlines the treatments application details for both studies. In summary the treatments included:

1. Control, No PCC applied.
2. 6.7A, 6.7 Mg PCC ha^{-1} applied over 4 consecutive years in the fall. Total PCC applied = 26.9 Mg PCC ha^{-1}.
3. 22.4A, 22.4 Mg PCC ha^{-1} applied over 4 consecutive years in the fall. Total PCC applied = 89.7 Mg PCC ha^{-1}.
4. 89.7T, 89.7 Mg PCC ha^{-1} applied at one time in the fall.

Treatments 3 and 4 contained the same cumulative rate of 89.7 Mg ha^{-1} (Table 1). The study designs were a randomized block design with four treatment replicates. Each plot was 6.7 m wide and 18.3 m long.

From each study, soils were sampled from each plot in the fall of each year prior to PCC application. Samples were collected from the 0 to 0.3 m soil depth (Table 1). From each plot, 10 subsamples were collected and combined into one bulk sample. 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), and total elements (P, K, Ca, Na, Al, Cu, Zn, Cd, Pb) with ICP-OES detection (U.S. Environmental Protection Agency, 1996). There were significant concentrations of P in the PCC (Tables 2 and 3) leading to different rates of P application across treatments. To ensure there was no P deficiency across the study areas, in spring 2015, 450 kg P_2O_5 ha^{-1} (mono ammonium phosphate fertilizer) was applied over both study areas. Additionally, the average bicarbonate extractable P concentration for both study sites prior to PCC application at the beginning of the study was 29.5 mg kg^{-1} which was considered adequate for sugarbeet, barley, and dry bean based on University of Idaho nutrient recommendations (Walsh et al., 2019; Moore et al., 2012; Robertson and Stark, 2003). Additional soil fertilizer recommendations were determined each year based on University of Idaho recommendations for each crop.

The PCC was uniformly surface broadcast using a custom experimental plot manure spreader. To ensure the proper PCC application rates and uniform applications, the spreader used a conveyer belt speed control system and a constant tractor ground speed. Following PCC applications each fall the entire study area was disked and roller harrowed. The Study 1 area was planted to sugarbeet (BTS 21RR25) in 2016 and 2019, dry beans (Ruby Small Red) in 2017 and 2020, and barley (Moravian 69) in 2018 and 2021. The Study 2 area was planted to sugarbeet (BTS 21RR25) in 2017 and 2020, dry beans (Ruby Small Red) in 2018 and 2021, and barley (Moravian 69) in 2019 and 2022. The crops were furrow irrigated to meet estimated crop evapotranspiration (ET_c) rates (Wright, 1982). The harvest areas within each plot were 18.7, 25.5, and 25.5 m^2 for sugarbeet, dry bean, and barley, respectively. Sugarbeets were harvested using a custom 2 row (1.1176 m) research harvester. Sugarbeet plot weights were measured on a load cell platform, and two 8 beet subsamples were collected. Subsamples were sent to the Amalgamated Sugar Company Beet Quality Lab for determination of sugar content (%) and sugar quality parameters (conductivity and nitrates). Percent sugar was determined using an Autopol 880 polarimeter (Rudolph Research Analytical, Hackettstown, NJ), a half-normal weight sample dilution, and aluminum sulfate clarification method [ICUMSA Method GS6-3 1994] (Bartens, 2005). Conductivity was measured using a Foxboro conductivity meter Model 871EC (Foxboro, Foxboro, MA) and nitrate was measured using a Denver Instruments Model 250 multimeter (Denver Instruments, Denver, CO) with Orion probes 900200 and 9300 BNWP (Krackler Scientific, Inc., Albany, NY). Recoverable sucrose yield was estimated from root yield, conductivity, and sucrose concentration. Dry bean and barley were harvested with an Almaco (Nevada, Iowa, U.S.) PMC20 Plot Master Combine with a 1.524 m wide cutting head, The harvested grain and beans were collected in sacks, weighed, and yield determined.

Analysis of variance was conducted for each site and year separately for treatment main effects for crop yield and quality factors and soil properties using a randomized block design model in Statistix 8.2 (Analytical Software, Tallahassee, FL). For significant (0.05 probability level) main effects, the LSD mean separation method was used to determine treatment differences.

Results and Discussion

In Study 1 and Study 2 there were no significant impacts of PCC on sugarbeet, dry bean, and barley crop yields across all years (Table 4). Tarkalson et al. (2024a) and Christenson et al. (2000) demonstrated that PCC application rates 5.6 to 90 Mg ha^{-1} did not affect yields of sugarbeet, soybean, dry bean, and barley compared to no PCC. In Study 1 and Study 2 there were some significant effects of PCC on sugarbeet quality (Table 5 and Table 6). In Study 1, the 89.7T treatment had higher root nitrate concentrations compared to the control and 6.7A treatment in 2016 (Table 5). In Study 1, there were no differences in the remaining sugarbeet quality factors in 2016 and 2019 (Table 5). However, all treatments had root nitrate concentrations greater than 200 mg kg^{-1}. Based on ASCO grower production data above average sucrose concentrations resulted when root nitrate concentration was below 200 mg kg^{-1} (ASCO, 2016; Walsh et al., 2019). In Study 2, the root sucrose concentrations in 2017 and root nitrate concentrations in 2020 were greatest in the 89.7T and 6.7A treatments (Table 6). In Study 2, there were no differences in the remaining sugarbeet quality factors in 2017 and 2020 (Table 6). A similar study conducted by Tarkalson et al (2024a) on an adjacent field plot from 2014 to 2020 found that PCC added at rates up to 87 Mg ha^{-1} did not affect sugarbeet quality factors compared to no added PCC. Overall (our study data and Tarkalson et al. (2024a)), the effects of PCC on sugarbeet quality were minimal with no consistent pattern of effect. The lack of consistent effects of PCC on sugarbeet factors is likely due to other factors. For example, past research has shown that other factors such as temporal and spatial variation in climatic factors across the ASCO growing area have a significant effect on sugarbeet quality (King et al., 2017).

Despite PCC's acid neutralizing value and at the high rates applied in this study, the PCC treatments had limited effects on soil pH in any of the years measured (Table 7 and Table 8). The average calcium carbonate equivalency (CCE) of the PCC used in this study was 81%. 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). For Study 1 in 2016 the 89.7T treatment had a slightly higher pH (0.1 to 0.2 pH units) than the Control and 6.7A treatments. In 2020, the 22.4A treatment had a higher pH (0.1 to 0.3 pH units) than all other treatments. For all other years in Study 1 and all years in Study 2 there were no statistically significant PCC treatment differences in soil pH (Table 7 and Table 8). The PCC pH (8.4) was not much higher than many alkaline soils in the arid western U.S. The research area for this study had control treatment (no PCC) pH levels ranging from 7.8 to 8.1 across sampling times (Table 7 and Table 8). Application of PCC up to a total rate of 9.7 Mg ha^{-1} did not increase soluble salts in the soil. The average EC value of the PCC was 2280 µS cm^{-1} (Table 2). Although this was higher than in the control treatment soil (average 706 µS cm^{-1}) it did not result in any significant increase in soil EC even at the highest applied rate (Table 7 and Table 8) in both studies. Additionally, the irrigation water used in the both studies was low in soluble salts (420 µS cm^{-1}) resulting in reduction of any salt accumulation from the PCC (Bjorneberg et al. 2020). This could explain why sugarbeet sugar quality, which is negatively influenced by high salts, had minimal impact from the PCC application. In Study 1, added PCC did not increase soil total Ca and Na concentrations (Table 7). However, in Study 2, the highest rates of PCC (22.4A and 87.9T treatments) increased total Ca concentrations in soil in 2017, 2018, 2019, and 2021 compared to the control. Across these years, the average increase over the control was 6.2%. However, this increase was small compared to the high concentration of Ca in the native soil of over 63,000 mg kg^{-1} (Table 8).

The PCC contained a significant amount of crop nutrients P and K (Table 2 and Table 3). Across all crops and PCC treatments, PCC applied between 1.6 and 5.3 times more P_2O_5 than the highest recommended rates for sugarbeet, barley and dry bean (Walsh et al., 2019; Moore et al., 2012; Robertson and Stark, 2003) (Table 3). In Study 1 and Study 2, the PCC additions increased soil bicarbonate extractable and total P concentrations (Table 7 and Table 8). One year after PCC applications, the 89.7T treatment increased bicarbonate P by 139% and 84% compared to the control treatments in Study 1 and Study 2, respectively (Table 7 and Table 8). This suggests that the P in PCC is quickly available to plants as measured using the bicarbonate extractable P method. In both studies, the 22.4A treatment had similar bicarbonate P concentrations as the 89.7T treatment after two years (44.8 Mg ha^{-1} cumulative PCC applied) (Table 7 and Table 8). Tarkalson et al. (2024a) found that PCC applied at a rate of 90 Mg ha^{-1} increased bicarbonate P concentrations by 73% compared to a control. Due to the high concentrations of P in the PCC (Table 2), there were increases in total P in most years of each study (Table 7 and Table 8). Comparisons between the control treatments and PCC application treatments across years showed that PCC treated soils contained 7% and 8% greater concentrations of Total P in Study 1 and Study 2, respectively. Tarkalson et al. (2024b) estimated to economic value of PCC as a P fertilizer source. They estimated that PCC has a P fertilizer value of between \$13.94 to \$28.15 Mg PCC^{-1} and a K fertilizer value of between \$1.31 to \$3.16 Mg PCC^{-1} depending on commercial fertilizer prices.

In addition to P, the PCC also contained 1008 mg K kg^{-1} (Table 2), however there was little effect on total soil K concentrations for any treatment compared to the control across all years in Study 1 and Study 2. The only significant difference between treatments was in Study 1 where the 22.4A and 89.7T treatment soils had 1.5% higher K concentration than the control treatment (Table 7). Across all crops and PCC treatments, PCC applied between 0.07 and 0.42 times more K_2O than the highest recommended rate (Table 3). The PCC was not a significant source of available N (Table 2 and 3).

The elements Al, Cu, Zn, Cd and Pb when in sufficient plant available concentrations can be toxic to plants (Angulo-Bejarano et al., 2021). However, the PCC did not have significant concentrations of these metals and there were no negative impacts on crop production from these elements. Overall, in both studies, there were minimal changes in measured soil Al, Cu, Zn, Cd, and Pb from PCC applications. This was expected since, the control soil (0-0.3 m) contains 5.0, 1.8, 1.4, and 12.4-times higher concentrations of Al, Zn, Cd, and Pb than the PCC, respectively (Tarkalson et al., 2024).

Conclusion

The results from these studies support findings from a similar study by Tarkalson et al. (2024) located in the same field. The PCC used in these studies can safely be applied (at rates up to 89.7 kg ha^{-1}) to heavier textured alkaline soils in the local growing area. The application of PCC did not negatively affect sugarbeet, dry bean and barley yields in a silt loam soil. The PCC applied at rates up to 89.7 kg ha^{-1} was not a significant source of toxic elements to plants. Although the pH of PCC was higher than the soil, PCC rates application rates up to 89.7 kg ha^{-1} had limited effects on soil pH. There was no accumulation of salts from PCC applications up to 89.7 kg ha^{-1}. The sugarbeet PCC used in this study can be used as a P and K fertilizer. However, the PCC has minimal available N content. In soils that have high soil P, PCC can potentially increase negative surface water impacts. The extent of the environmental impacts will vary based on management practices that affects the amount of runoff that enters off-site water streams. Practices that reduce runoff will reduce risks.

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Literature Cited

Angulo-Bejarano, P.I., J. Puente-Rivera, and R. Cruz-Ortega. 2021. Metal and metalloid toxicity on plants: An overview on molecular aspects. Plants. 10, 635. https://doi.org/10.3390/plants10040635

ASCO. (2016). Sugarbeet Grower's Guide Book. Amalgamated Sugar Company, Boise, ID.

Barber, S.A. 1984. Liming materials and practices, pp. 171-209. In: F. Adams (ed.), Soil Acidity and Liming. 2nd ed. Agron. 12. American Society of Agronomy, Madison,WI.

Bartens, A., 2005. International Commission for Uniform Methods of Sugar Analysis Methods Book 2005. p. 431. Dr. Albert Bartens KG, Berlin, Germany.

Bjorneberg, D.L., Ippolito, J.A., King, B.A., Nouwakpo, S.K., and Koehn, A.C. 2020. Moving toward Sustainable Irrigation in a Southern Idaho Irrigation Project. Transactions of the ASABE. 63:1441-1449.

Brantner, J.R., C.E. Windels, A.L. Sims, and C.A. Bradley. 2015. Ten years after a single field application of spent lime: effects on soil pH, Aphanomyces root rot, and sugarbeet yield and quality. 2014 Sugarbeet Res. Ext. Rept. 45:168-173.

Christenson, D.R., P.B. Brimhall, L. Hubbell, and C.E. Bricker. 2000. Yield of sugar beet, corn, field bean, and wheat as affected by lime application on alkaline soils. Commun. Soil Sci. Plant Anal. 31:1145-1154.

Clark, G.M., L.A. Hubbell, J.F. Stewart, and B.J. Groulx. 2015. *In:* American Society of Sugar Beet Technologists Proceedings from the 40th Biennial Meeting. February 23-27. Clearwater Beach, FL.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 1999. Soil fertility and fertilizers: An introduction to nutrient management. 6th ed. Prentice Hall. Upper Saddle River, N.J.

Hergert, G.W., M.K. Darapuneni, A.M. Aqeel, R.G. Wilson, R.M. Harveson, J.D. Bradshaw, and R.A. Nielsen. 2017. Agronomic potential of using precipitated calcium carbonate on early plant growth and soil quality in the inter-mountain west – greenhouse studies. J. Sugar Beet Res. 54:35-49.

Kalra, Y.P. 1995. Determination of pH of soils by different methods: Collaborative study. J. AOAC Int. 78:310–324.

King, B.A., D.D. Tarkalson. 2017. Irrigated sugarbeet sucrose content in relation to growing season climatic conditions in the Northwest U.S. J. Sugar Beet Res. 54:60-74.

Lien, A.K., J.R. Bratner, A.K. Chanda. 2016. Understanding the effect of spend lime on *Aphanomyces cochliodes*. Sugarbeet Res. Ext. Rep.46:169-173.

Marschner, H. 1995. Mineral nutrition of higher plants. 2nd ed. Academic Press Inc. San Diego, CA.

Miller, R.W. and D.T. Gardiner. 2001. Soils in our environment. 9th ed. Prentice Hall. Upper Saddle River, N.J.

Moore, A., A. Carey, S. Hines, and B. Brown. 2012. Southern Idaho Fertilizer Guide: Dry Beans. CIS 1189. University of Idaho Extension. Moscow, ID.

Mulvaney, R.L. 1996. Nitrogen-inorganic forms. p. 1123-1184. In D.L. Sparks (ed.) Methods of Soil Analysis: Part 3. Chemical Methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Olsen, R.A., M.B. Rhodes, and A.F. Dreier. 1954. Available phosphorus status of Nebraska soils in relation to series classification, time of sampling and method of measurement. Agron. J. 46:175-180.

Olsson, A., L. Perrson, and S. Olsson. 2019. Influence of soil characteristics on yield response to lime in sugar beet. Geoderma. 337:1208-1217.

Rhoades, J.D. 1996. Salinity: Electrical conductivity and total dissolved solids. p. 417–435. D.L. Sparks (ed.) Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Robertson L.D., and J.C. Stark. 2003. Idaho spring barley production guide. Bul 742. University of Idaho Extension. Moscow, ID.

Tarkalson, D.D., G.W. Hergert, W.B. Stevens, D.L McCallister, and S. Kachman. 2005. Fly ash as a liming material for corn production. Soil Sci. 170:386-398.

Tarkalson, D.D., D.L. Bjorneberg, O.T. Neher, D. Olsen, and G. Dean. 2024a. Effects of sugar beet processing precipitated calcium carbonate on crop production and soil properties. Journal of Sugar Beet Research. J. Sugar Beet Res. 61:35-50. DOI: 10.5274/jsbr.61.1.13

Tarkalson, D.D., Olsen, D., Bjorneberg, D.L. 2024b. Fertilizer Value of Sugarbeet Processing Precipitated Calcium Carbonate for Crop. J. Sugar Beet Res. 61:1-22. DOI: 10.5274/jsbr.61.1.27

U.S. Environmental Protection Agency. 1996. Method 3052: Microwave assisted acid digestion of siliceous and organically based matrices. Available at: https://www.epa.gov/sites/default/files/2015-12/documents/3052.pdf. Accessed March 16, 2022.

Walsh, O., D. Tarkalson, A. Moore, G. Dean, D. Ellison, J. Stark, O. Neher, and B. Brown. 2019. Southern Idaho Fertilizer Guide: Sugar Beets. Bul 935. University of Idaho Extension. Moscow, ID.

Walter, R.H., C.D. Moodie, and R.W. Leamer. 1951. The production of sugar beets on a saline soil as affected by type of leaching. Am. Soc. Sugar Beet Tech. 1950:448-452.

Windels, C.E., J.R. Brantner, A.L. Sims, and C.A. Bradley. 2008. Long-term effects of a single application of spent lime on sugarbeet, Aphanomyces root rot, rotation crops, and antagonistic microorganisms. 2007 Sugarbeet Res. Ext. Rept. 38:251-262.

Wright, J.L. 1982. New evapotranspiration crop coefficients. J Irr. Drain. Div., Proc. ASCE 108:57-74.

Yunusa, I.A.M, P. Loganathan, S.P. Nissanka. 2012. Application of coal fly ash in agriculture: A strategic perspective. Crit. Rev. Environ. Sci. Technol. 42:559-600.

Table 1. Site 1 and Site 2 PCC treatment annual rates (Mg ha-1), cumulative PCC amounts applied (Mg ha-1) in parentheses, crop grown, soil sample date, and PCC application date for each year.

STUDY 1							
Year	2015	2016	2017	2018	2019	2020	2021
Crop	--	Sugarbeet	Dry Bean	Barley	Sugarbeet	Dry Bean	Barley
Control	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
6.7A	6.7 (6.7)	6.7 (13.5)	6.7 (20.2)	6.7 (26.9)	0 (26.9)	0 (26.9)	0 (26.9)
22.4A	22.4 (22.4)	22.4 (44.8)	22.4 (67.3)	22.4 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)
89.7T	89.7 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)
Soil Sample Date	Nov. 17	Nov. 15	Oct. 25	Nov. 14	Oct. 31	Oct. 16	Nov. 15
PCC Application Date	Nov. 18	Nov. 30	Oct. 31	Nov. 16	--	--	--

STUDY 2							
Year	2016	2017	2018	2019	2020	2021	2022
Crop	--	Sugarbeet	Dry Bean	Barley	Sugarbeet	Dry Bean	Barley
Control	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
6.7A	6.7 (6.7)	6.7 (13.5)	6.7 (20.2)	6.7 (26.9)	0 (26.9)	0 (26.9)	0 (26.9)
22.4A	22.4 (22.4)	22.4 (44.8)	22.4 (67.3)	22.4 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)
89.7T	89.7 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)	0 (89.7)
Soil Sample Date	Nov. 15	Oct. 25	Nov. 14	Oct. 24	Oct. 16	Nov. 15	Sep. 28
PCC Application Date	Nov. 30	Oct. 31	Nov. 16	Nov. 13	--	--	--

Table 2. Selected average chemical characteristics and constituent contents of the PCC used in this study.

CCE (%)	75
pH	8.4
EC ($^{\gamma}$S cm^{-1})	2280
NO_3-N (mg kg^{-1})	183.8
NH_4-N (mg kg^{-1})	8.5
N (mg kg^{-1})	2986
C (mg kg^{-1})	117109
P (mg kg^{-1})	6559
K (mg kg^{-1})	1008
Ca (mg kg^{-1})	289069
Na (mg kg^{-1})	453.2
Al (mg kg^{-1})	3636
Cu (mg kg^{-1})	16.3
Zn (mg kg^{-1})	36.2
Cd (mg kg^{-1})	0.40
Pb (mg kg^{-1})	0.92

Table 3. Total rates of selected constituents applied from the PCC treatments. Rates are based on total PCC applied for each treatment: 20.2, 89.7, and 89.7 Mg ha-1 for the 6.7A, 22.4A, 89.7T treatments, respectively.

Constituent	6.7A	22.4A	89.7T
	Total kg ha^{-1}		
NO_3-N	4.9	16.5	16.5
NH_4-N	0.23	0.76	0.76
N	60.4	268	268
C	2366	10505	10505
P	176	588	588
P_2O_5	404	1347	1347
K	27.1	90.4	90.4
K_2O	32.5	108	108
Ca	7776	25930	25930
Na	12.2	40.7	40.7
Al	98	326	326
Cu	0.4	1.5	1.5
Zn	1.0	3.2	3.2
Cd	0.011	0.036	0.036
Pb	0.025	0.083	0.083

Table 4. Site 1 and Site 2 analysis of variance for production factors. Bolded p-values were significant at the 0.05 probability level.

Crop	Production Factor	STUDY 1		STUDY 2	
		2016	2019	2017	2020
Sugar Beet	Root Yield	0.669	0.407	0.862	0.373
	ERS Yield	0.62	0.365	0.633	0.481
	Sugar %	0.448	0.651	**0.046**	0.372
	Root Nitrate	**0.006**	0.798	0.716	0.693
	Root Conductivity	0.861	0.993	0.195	**0.023**
		2017	2020	2018	2021
Dry Bean	Bean Yield	0.666	0.508	0.679	0.925
		2018	2021	2019	2022
Barley	Grain Yield	0.389	0.099	0.862	0.115

Table 5. *Study 1 sugarbeet production factors. Within each production measurement and year, values with the same letters are not different at the 0.05 probability level. Sugarbeet root yields are reported at approximately 77% water content. Barley and dry bean yields are reported based on dry matter.*

				Production Measurements				
Year	Crop	Treatment	Cumulative PCC Applied Prior to Listed Year Crop (Mg ha^{-1})	Root Yield Mg ha^{-1}	Sucrose Yield kg ha^{-1}	Sucrose g kg^{-1}	Root Nitrate mg kg^{-1}	Root Conductivity mmhos
2016	**Sugarbeet**	Control	0	60.8	8274	16.3	260 c	0.87
		6.7A	6.7	60.0	7942	15.9	303 bc	0.88
		22.4A	22.4	62.5	7994	15.5	336 ab	0.91
		89.7T	89.7	66.0	8861	16.2	395 a	0.88
		Mean		**62.3**	**8268**	**16.0**	**323**	**0.88**
				Yield Mg ha^{-1}				
2017	**Dry Bean**	Control	0	4313				
		6.7A	13.5	4296				
		22.4A	44.8	3984				
		89.7T	89.7	4299				
		Mean		**4223**				
				Yield Mg ha^{-1}				
2018	**Barley**	Control	0	6146				
		6.7A	20.2	5784				
		22.4A	67.3	6886				
		89.7T	89.7	6377				
		Mean		**6298**				
				Production Measurements				
Year	Crop	Treatment	Cumulative PCC Applied Prior to Listed Year Crop (Mg ha^{-1})	Root Yield Mg ha^{-1}	Sucrose Yield kg ha^{-1}	Sucrose g kg^{-1}	Root Nitrate mg kg^{-1}	Root Conductivity mmhos
2019	**Sugarbeet**	Control	0	64.9	9339	16.8	453	0.69
		6.7A	26.9	72.8	10849	17.4	347	0.70
		22.4A	89.7	74.5	10921	17.0	365	0.68
		89.7T	89.7	70.7	10272	16.9	351	0.69
		Mean		**70.7**	**10345**	**17.0**	**379**	**0.69**
				Yield Mg ha^{-1}				
2020	Dry Bean	Control	0	2847				
		6.7A	26.9	3125				
		22.4A	89.7	2989				
		89.7T	89.7	2937				
		Mean		**2975**				
				Yield Mg ha^{-1}				
2021	Barley	Control	0	4666				
		6.7A	26.9	5077				
		22.4A	89.7	5006				
		89.7T	89.7	4967				
		Mean		**4929**				

Table 6. *Study 2 sugarbeet production factors. Within each production measurement and year, values with the same letters are not different at the 0.05 probability level. Sugarbeet root yields are reported at approximately 77% water content. Barley and dry bean yields are reported based on dry matter.*

				Production Measurements				
Year	Crop	Treatment	Cumulative PCC Applied Prior to Listed Year Crop (Mg ha^{-1})	Root Yield Mg ha^{-1}	Sucrose Yield kg ha^{-1}	Sucrose g kg^{-1}	Root Nitrate mg kg^{-1}	Root Conductivity mmhos
2017	**Sugarbeet**	Control	0	49.9	6239	14.6 b	252	0.70
		6.7A	6.7	53.4	6951	15.6 a	292	0.86
		22.4A	22.4	51.3	6242	14.5 b	288	0.75
		89.7T	89.7	56.0	7208	15.3 ab	309	0.79
		Mean		**52.7**	**6660**	**14.9**	**285**	**0.78**
				Yield Mg ha^{-1}				
2018	**Dry Bean**	Control	0	4247				
		6.7A	13.5	3953				
		22.4A	44.8	4099				
		89.7T	89.7	3889				
		Mean		**4047**				
				Yield Mg ha^{-1}				
2019	**Barley**	Control	0	5725				
		6.7A	20.2	5540				
		22.4A	67.3	5520				
		89.7T	89.7	5503				
		Mean		**5572**				
				Production Measurements				
Year	Crop	Treatment	Cumulative PCC Applied Prior to Listed Year Crop (Mg ha^{-1})	Root Yield Mg ha^{-1}	Sucrose Yield kg ha^{-1}	Sucrose g kg^{-1}	Root Nitrate mg kg^{-1}	Root Conductivity mmhos
2020	**Sugarbeet**	Control	0	75.1	12043	18.4	97	0.62 b
		6.7A	26.9	67.1	10677	18.6	110	0.72 a
		22.4A	89.7	79.8	12545	18.0	130	0.60 b
		89.7T	89.7	75.2	11996	18.5	109	0.67 ab
		Mean		**74.3**	**11815**	**18.4**	**111**	**0.65**
				Yield Mg ha^{-1}				
2021	**Dry Bean**	Control	0	2501				
		6.7A	26.9	2179				
		22.4A	89.7	2317				
		89.7T	89.7	2316				
		Mean		**2328**				
				Yield Mg ha^{-1}				
2022	**Barley**	Control	0	5207				
		6.7A	26.9	5689				
		22.4A	89.7	5681				
		89.7T	89.7	5464				
		Mean		**5510**				

Table 7. *Study 1 fall soil sample analysis and analysis of varia*nce *(significance at p>f = 0.05) for selected variables for treatments across years of the study.*

Treatment	Cumulative PCC Applied Prior to Soil Sample Mg ha^{-1}	pH	EC μS cm^{-1}	Bicarbonate P	Total Inorganic N	Total P	Total K	Total Ca	Total Na	Total Al	Total Cu	Total Zn	Total Cd	Total Pb
				mg kg^{-1}										
2015														
Site Mean	0	7.9	477.1	29.5	16.9	1004	3881	60269	384	18166	12.0	61.5	0.92	7.6
2016														
Control	0	7.7 b	740.3	32.5 c	29.0	979 c	3561 b	62536	292	16608	11.8	59.1	0.91 b	10.4
6.7A	6.7	7.8 b	762.0	32.9 bc	29.7	980 c	3516 b	60383	293	16646	12.1	60.8	0.94 a	10.7
22.4A	22.4	7.8 ab	770.1	44.8 b	29.8	1027 b	3752 a	63579	328	17310	11.9	60.6	0.89 c	9.7
89.7T	89.7	7.9 a	771.6	77.6 a	31.8	1114 a	3476 b	68597	290	16419	11.8	59.0	0.89 c	9.8
p>f		***0.024***	*0.990*	***<0.001***	0.985	***<0.001***	***0.018***	*0.231*	*0.359*	***0.011***	*0.861*	*0.374*	***0.002***	*0.369*
2017														
Control	0	8.0	660.0	30.7 b	40.0 b	999 b	3577	60362	416	16757	12.1	64.0	0.90	10.8
6.7A	20.2	7.9	885.9	33.0 b	64.8 a	1001 b	3498	59476	383	16451	12.5	68.3	0.91	11.7
22.4A	67.3	8.0	785.1	49.9 a	52.4 ab	1094 a	3487	63725	365	16295	12.1	62.7	0.90	9.8
89.7T	89.7	8.0	724.2	58.4 a	42.9 b	1070 a	3537	64467	481	16487	12.4	61.7	0.89	10.7
p>f		*0.142*	*0.110*	***0.002***	***0.042***	***0.014***	*0.766*	*0.306*	*0.095*	*0.600*	*0.698*	*0.696*	*0.906*	*0.193*
2018														
Control	0	8.2	553.8	34.7 b	29.4	993 b	3410	63103	285	16340	11.9	59.6	0.93	10.7
6.7A	26.9	8.2	540.5	37.5 b	23.1	980 b	3385	63537	311	16368	11.8	57.7	0.94	10.3
22.4A	89.7	8.2	599.5	60.9 a	29.5	1114 a	3594	67639	278	16963	12.1	58.6	0.92	10.2
89.7T	89.7	8.3	599.3	68.9 a	29.8	1110 a	3368	68833	291	16032	11.9	61.0	0.90	10.1
p>f		*0.074*	*0.550*	***<0.001***	0.416	***0.004***	*0.398*	*0.071*	*0.933*	*0.524*	*0.854*	*0.738*	*0.748*	*0.238*
2019														
Control	0	7.9	676.3	30.1 b	36.9	1040	3420	64326	207	16447	11.7	65.8	1.03	9.8
6.7A	26.9	8.0	568.9	39.4 b	38.9	1006	3437	62066	162	16438	12.1	59.7	0.97	10.3
22.4A	89.7	8.0	671.3	63.1 a	36.4	1109	3473	66179	155	16472	12.0	58.8	0.97	10.1
89.7T	89.7	7.3	577.3	56.4 a	29.8	1103	3450	67463	146	16538	11.9	59.2	0.96	10.1
p>f		*0.523*	*0.468*	***<0.001***	0.547	*0.091*	*0.943*	*0.259*	*0.116*	*0.980*	*0.599*	*0.456*	*0.760*	*0.823*
2020														
Control	0	7.8 b	973.4	27.1 b	59.0	980 b	3357	63240	173	16008	11.9	55.0	0.90	10.4
6.7A	26.9	7.9 b	799.5	32.4 b	52.2	986 b	3488	60911	266	16697	12.8	58.3	0.91	10.0
22.4A	89.7	8.1 a	743.6	57.4 a	33.5	1121 a	3478	66096	252	16353	12.0	57.6	0.91	9.9
89.7T	89.7	8.0 b	880.1	54.5 a	44.7	1145 a	3389	67651	176	16029	12.0	57.5	0.92	9.7
p>f		***0.008***	*0.188*	***<0.001***	0.173	***0.002***	*0.772*	*0.184*	*0.319*	*0.658*	*0.087*	*0.382*	*0.921*	*0.692*
2021														
Control	0	7.8	822.7	32.7 b	44.0	1020 b	3574	58352	314	16564	12.4	60.0	0.98	11.2
6.7A	26.9	7.8	782.3	36.2 b	39.1	1050 b	3483	58298	317	16284	12.5	60.1	0.99	11.1
22.4A	89.7	7.8	815.6	59.0 a	41.9	1146 a	3572	63557	319	16502	12.4	59.2	0.95	11.0
89.7T	89.7	7.9	735.3	61.4 a	35.5	1134 a	3607	62532	304	16621	12.6	60.0	0.96	11.0
p>f		*0.202*	*0.529*	***<0.001***	0.775	***<0.001***	*0.792*	*0.081*	*0.771*	*0.847*	*0.939*	*0.763*	*0.094*	*0.685*

Table 8. Study 2 fall soil sample analysis and analysis of variance (significance at p>f = 0.05) for selected variables for treatments across years of the study.

Treatment	Cumulative PCC Applied Prior to Soil Sample Mg ha^{-1}	pH	EC µS cm^{-1}	Bicarbonate P	Total Inorganic N	Total P	Total K	Total Ca	Total Na	Total Al	Total Cu	Total Zn	Total Cd	Total Pb
				mg kg^{-1}										
2016														
Site Mean	0	7.8	429.7	29.5	10.4	1019	3253	63369	288	15939	11.1	59.1	0.89	7.5
2017														
Control	0	8.0	745.3	28.6 b	38.4	985 b	3496	63320 c	235	16671	11.5	57.8	0.91	10.1
6.7A	6.7	8.0	715.2	34.8 b	32.3	1000 b	3455	63632 c	208	16355	11.6	57.3	0.91	10.2
22.4A	22.4	8.0	796.0	35.8 b	41.1	1016 b	3539	65435 b	260	16988	11.5	58.2	0.92	9.4
89.7T	89.7	8.0	918.9	52.7 a	45.5	1106 a	3472	69792 a	212	16645	11.8	61.9	0.97	10.7
p>f		*0.211*	*0.071*	**0.005**	0.364	***0.001***	*0.766*	***<0.001***	*0.261*	*0.289*	*0.340*	*0.490*	*0.444*	*0.411*
2018														
Control	0	8.0	942.0	25.5 b	22.8	993 b	3500	64531 bc	276	16547	11.4	60.2	0.87	10.0
6.7A	20.2	8.1	946.0	39.9 a	19.4	1036 ab	3441	63528 c	271	16190	11.6	60.1	0.86	10.1
22.4A	67.3	8.1	996.3	48.7 a	21.9	1050 a	3546	66495 b	262	16723	11.5	59.6	0.87	10.0
89.7T	89.7	8.1	966.8	45.4 a	21.9	1074 a	3384	70289 a	262	16088	11.3	58.8	0.88	9.8
p>f		*0.064*	*0.830*	**0.002**	0.963	***0.022***	*0.288*	***0.001***	*0.630*	*0.067*	*0.389*	*0.752*	*0.559*	*0.263*
2019														
Control	0	8.1	540.6	31.2 b	31.4	984 c	3474	63334 b	253	16542	11.8	61.6	0.83	10.3
6.7A	26.9	8.1	524.1	45.2 a	30.4	1027 bc	3407	62505 b	249	16203	11.9	61.5	0.82	10.2
22.4A	89.7	8.1	590.5	45.7 a	36.2	1116 a	3603	66467 a	270	17009	12.1	62.1	0.84	10.1
89.7T	89.7	8.1	576.4	50.2 a	31.7	1065 ab	3337	68297 a	254	16171	11.9	60.2	0.81	10.4
p>f		*0.140*	*0.127*	**0.038**	0.103	***0.021***	*0.170*	***0.006***	*0.319*	*0.230*	*0.222*	*0.418*	*0.105*	*0.824*
2020														
Control	0	7.9	705.9	23.3 c	22.2	992 b	3284	63686	269	16075	11.4	62.4	0.93	10.0
6.7A	26.9	7.9	653.5	32.6 bc	18.4	1038 ab	3337	64317	270	16079	11.7	62.0	0.95	10.3
22.4A	89.7	8.0	714.4	45.4 a	21.5	1101 a	3554	68543	293	16971	11.8	64.0	0.94	10.4
89.7T	89.7	8.0	652.6	36.3 ab	21.3	1067 a	3380	68986	292	16498	11.7	59.8	0.90	9.4
p>f		*0.134*	*0.880*	**0.006**	0.929	***0.024***	*0.250*	*0.066*	*0.442*	*0.146*	*0.673*	*0.292*	*0.249*	*0.347*
2021														
Control	0	8.2	917.5	22.9 d	43.4	1038 c	3479	61907 b	301	16749	12.0	69.5	0.94	11.4
6.7A	26.9	8.2	947.8	32.9 c	40.2	1113 b	3651	62525 b	303	17120	12.1	68.8	0.95	11.3
22.4A	89.7	8.6	1035.7	47.0 a	50.7	1196 a	3625	66043 a	341	17192	12.5	69.8	0.97	11.1
89.7T	89.7	8.3	1057.6	40.4 b	40.2	1155 ab	3503	65212 a	311	16798	12.3	75.6	0.97	11.9
p>f		*0.342*	*0.624*	**<0.001**	0.649	***0.003***	*0.602*	***0.011***	*0.456*	*0.806*	*0.144*	*0.258*	*0.065*	*0.377*
2022														
Control	0	8.1	693.1	18.5 c	17.8	962 c	3362	63024	326	16238	11.5	61.2	0.89	10.5
6.7A	26.9	8.1	704.7	27.2 b	19.6	1009 b	3473	62892	343	16515	11.7	61.4	0.90	10.4
22.4A	89.7	8.2	714.0	41.2 a	18.5	1089 a	3390	67021	324	16460	11.9	60.6	0.90	10.2
89.7T	89.7	8.2	720.8	33.7 b	20.8	1068 a	3424	66132	322	16659	11.9	61.4	0.91	10.2
p>f		*0.165*	*0.968*	**<0.001**	0.658	***<0.001***	*0.551*	*0.071*	*0.418*	*0.625*	*0.400*	*0.948*	*0.908*	*0.614*