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# Influence of source and particle size of agricultural limestone on efficiency at increasing soil pH

John David Jones  
*Iowa State University*

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**Influence of source and particle size of agricultural limestone on efficiency at increasing soil pH**

by

**John David Jones Jr.**

A thesis submitted to the graduate faculty  
in partial fulfillment of the requirement for the degree of  
**MASTER OF SCIENCE**

Major: Soils (Soil Fertility)

Program of Study Committee:  
Antonio P. Mallarino, Major Professor  
John Sawyer  
Allen Knapp

The student author and the program of study committee are solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2017

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## CHAPTER 1: GENERAL INTRODUCTION

### Introduction

Excessive soil acidity is known to have potential negative impacts on crop production. The chemical and physical characteristics of a liming material determine its capacity to neutralize soil acidity. The calcium carbonate ( $\text{CaCO}_3$ ) equivalent (CCE) value and estimates of particle size impact on the efficiency at increasing soil pH are considered when assessing a material's liming value. Agricultural limestone (aglime) is the most commonly used material used to neutralize soil acidity in production agriculture. Both  $\text{CaCO}_3$  and magnesium carbonate ( $\text{MgCO}_3$ ) in different proportions are the main constituents of aglime. The Soil Science Society of America defines dolomitic limestone as a natural liming material composed mainly of carbonates of Mg and Ca in approximately equal proportions. In production agriculture and limestone trade there is no widely accepted definition, however, an aglime containing more than 70%  $\text{CaCO}_3$  is usually referred to as calcitic and that containing 10% or more  $\text{MgCO}_3$  concentration is considered dolomitic. While  $\text{MgCO}_3$  has a higher acid neutralizing potential than  $\text{CaCO}_3$  (due to its lower molecular weight), the reaction rate of dolomitic limestone is known to be slower. Recent field experiments in Iowa also showed that the time to reach a certain pH value was longer for dolomitic lime and that sometimes the maximum pH reached also was lower.

The degree of reaction of particles within the soil depends largely on the soil pH and the material surface area in contact with the soil. Particle size then influences the speed of reaction, with finer materials allowing for more particles and surface area to react in a given volume of soil, and may also influence the maximum pH reached. The most common method of describing

the fineness of aglime is through the use of mesh sieve sizes that are standardized across many industries. The U.S. Tyler Sieve size nomenclature uses a number to describe a specific mesh size. The mesh-number used corresponds to the number of wires that is found in a square inch (2.54 cm<sup>2</sup>) of the specific sieve. A typical sample of aglime includes multiple particle sizes in varying proportions. An *effective* liming material has the potential to raise the soil pH to a desired level. An *efficient* liming material has the potential to raise the soil pH to a desired value with the smallest amount of material applied possible. Cost and availability must be taken into account when deciding to apply a liming material.

In spite of extensive previous research on soil acidity and aglime use in production agriculture, the literature shows scarce research describing how different particle size fractions of aglime affect soil pH increases over a period of time. This knowledge is needed to develop methods that appropriately evaluate the value at increasing soil pH of aglime being offered to producers. Therefore, the objective of this study was to evaluate the effect of different particle size fractions on the efficiency of commercially available calcitic aglime, dolomitic aglime, and calcitic pelleted lime at increasing soil pH in various Iowa soils under controlled conditions.

### **Thesis organization**

This thesis is presented as one paper suitable for publication in scientific journals of the American Society of Agronomy. The title of the paper is Influence of Source and Particle Size on Agricultural Limestone Efficiency at Increasing Soil pH. The paper includes sections for an abstract, introduction, materials and methods, results and discussion, conclusions, references, and tables or figures. This paper is preceded by a general introduction and is followed by a general conclusion section.

## **CHAPTER 2: INFLUENCE OF SOURCE AND PARTICLE SIZE ON AGRICULTURAL LIMESTONE EFFICIENCY AT INCREASING SOIL pH**

*A paper to be submitted to Soil Science Society of America Journal*

By John D. Jones and Antonio P. Mallarino

### **ABSTRACT**

Excessive soil acidity is known to have potential negative impacts on crop production. The chemical and physical characteristics of a liming material determine its capacity to neutralize soil acidity. The material  $\text{CaCO}_3$  equivalent (CCE) and fineness effectiveness estimates are included in effective CCE (ECCE) assessments of a material's liming value and to decide application rates. The objective of this study was to evaluate the effect of particle size on efficiency at increasing soil pH of commercial calcitic and dolomitic agricultural lime (aglime) compared with pure ground  $\text{CaCO}_3$  and a commercial calcitic pelleted lime. Both aglime sources were fractionated to pass US Standard Tyler Mesh screen sizes 4 but not 8, 8 but not 20, 20 but not 60, and 60 but not 100, and 100. A rate equivalent to  $7.1 \text{ Mg CCE ha}^{-1}$  of the materials was mixed with three Iowa acidic soils having contrasting texture and organic matter, and were incubated for 7, 21, 35, 70, 105, 140, 175, and 210 days at  $25^\circ\text{C}$  and 80% field moisture capacity. Initial soil pH values were 5.20 to 6.01. Materials efficiency at increasing pH relative to pure  $\text{CaCO}_3$  showed large differences among soils, materials, fineness fractions, and incubation times. Increasing fineness increased the efficiency of the aglime fractions following an exponential trend with decreasing increments. On average across soils and the longest incubation period, calcitic aglime fractions efficiency relative to  $\text{CaCO}_3$  were 29, 39, 60, 81, and 97% for mesh sizes 4, 8, 20, 60, and 100, respectively. Efficiencies for the dolomitic aglime were lower (10, 20, 43, 66, and 86%). For the last incubation period, the commercial calcitic,



dolomitic, and pelleted aglime sources had average efficiencies across all soils of 60, 47, and 90%, respectively.

Abbreviations: aglime, agricultural limestone; ANOVA, analysis of variance; CCE, calcium carbonate equivalent; ECCE, effective calcium carbonate equivalent.

## INTRODUCTION

Strong soil acidity limits crop growth and productivity. Therefore, measuring soil pH is critical for a complete assessment of soil productivity and, when needed, lime should be applied to increase pH to an optimum level. The acidity of a soil can be greatly affected by both natural and anthropogenic processes. Natural sources of acidity can be, but are not limited to, precipitation, decomposition of organic matter, and dissociation of carbonic acid in soil with a pH above 5.0 (Thomas and Hargrove, 1984; Brady and Weil, 2008). Anthropogenic sources of acidity most commonly include the application of fertilizers containing  $\text{NH}_4$  or urea, liquid swine manure, removal of crop residue, and removal of base cations by crop nutrient uptake. Soil total acidity is comprised of three types of pools: (1) an active acidity pool,  $\text{H}^+$  ion in the soil solution which is measured as soil pH, (2) a readily exchangeable acidity pool,  $\text{H}^+$  and  $\text{Al}^{+3}$  ions located on cation exchange sites, and (3) a nonexchangeable or residual acidity pool,  $\text{H}^+$  and  $\text{Al}^{+3}$  ions on pH-dependent exchange sites that become exchangeable as solution pH increases (Thomas and Hargrove, 1984). When liming to increase the soil pH, it is important to consider that all three pools of acidity have a dynamic relationship. Soil pH indicates if acidity is limiting crop growth or not, but a measure of the other acidity pools is needed to find the amount of lime to apply. Several analytical methods have been developed to determine lime requirement, but the use of buffer solutions is the most common method in the US. A buffer solution (a mixture of a weak acid and its conjugate base) resists pH change, decreases pH of a slurry with soil when the soil's

potential acidity reacts with the buffer, and this decrease is used to estimate the amount of lime required to raise pH to a desired level (Barber, 1984).

The most commonly used liming material is ground limestone (aglime). The application of aglime to neutralize soil acidity has been a common practice for decades in Iowa and for centuries in many parts of the world (Barber, 1984). Publications reviewed by Adams (1984), some as early as 1919, demonstrate the need for liming acid soils and the agronomic benefits following lime applications. Although aglime is the predominant liming material used, other sources such as hydrated lime, industry by-products, and residuals from water treatment plants sometimes are utilized. Liming materials vary in chemical and physical properties and are utilized in different degrees in different regions due to their capacity to increase pH, availability, or price. Pelleted aglime is a relatively recent liming material designed to facilitate application of ground aglime, and typically is very finely ground aglime that is pelletized and coated with a water-soluble coating (Higgins, 2012).

The composition of aglime is primarily determined by the mineral source that is being quarried. Calcite ( $\text{CaCO}_3$ ) and dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ) are the dominant minerals of which aglime is derived. The Soil Science Society of America defines dolomitic limestone as a natural liming material composed mainly of carbonates of Mg and Ca in approximately equal amounts. In production agriculture and limestone trade there is no widely accepted definition, however, and aglime containing more than 70%  $\text{CaCO}_3$  is usually referred to as calcitic and that containing 10% or more  $\text{MgCO}_3$  concentration is considered dolomitic. While  $\text{MgCO}_3$  has a higher acid neutralizing potential than  $\text{CaCO}_3$  due to the Mg lower molecular weight, the reaction rate of dolomitic aglime is slower (Lindsay, 1979; Barber, 1984; Thomas and Hargrove, 1984; Stevens

and Blanchar, 1992). This was confirmed by recent Iowa field research (Pagani and Mallarino, 2012).

It has been known for a long time that the particle size (fineness) of aglime also has a significant influence on its capacity to neutralize soil acidity and the time needed to achieve a desirable soil pH level (Barber, 1984). The fineness of a specific aglime source is determined during the processing of the raw material. A typical sample of aglime includes various particle sizes, which depends on the degree to which the limestone is ground and sieved. The dissolution of aglime is a surface area driven reaction (Hartwig and Loeppert, 1992). The more potentially reactive surface a particle has, the quicker it can dissolve and neutralize soil acidity. An aglime particle has a porous structure and is not perfectly spherical in shape. Although it is common to assign theoretical surface area values based on the diameter of a mesh screen, it is important to note the potentially internal reactive surface (or porosity) of a limestone particle (Beacher and Merkle, 1949; Motto and White, 1957).

Previous research has suggested that a minimum particle size be defined for efficient aglime use, and that a minimum percentage of the limestone sample must pass this threshold mesh size. Early research by Beacher and Merkle (1949) and others summarized in reviews (Barber, 1984) have concluded, for example, that aglime which is finer than about 100 to 200-mesh (0.15-0.075 mm) is equal to pure ground  $\text{CaCO}_3$  or hydrated lime in promoting crop yield but material coarser than about 8 to 20-mesh (2.36-0.85 mm) has such small surface area that it is very slow to react with the soil and has been found to remain almost unaltered for many months. This early research also showed that dolomitic aglime needs to be finer to effect a pH change similar to that with calcitic aglime. For example, Beacher and Merkle (1949) evaluated the effects of different particle sizes of calcitic and dolomitic aglime at increasing soil pH (mesh

sizes 20-60, 60-100, 100-200, and finer than 200). They assigned a “relative effectiveness” to each fraction when compared to pure hydrated lime by a 10-week incubation with soil and a separate short term (10 and 15 min) reaction with 0.3N CH<sub>3</sub>COOH. Their results showed that calcitic aglime was twice as effective at increasing pH as dolomitic aglime, that both aglime types increase in effectiveness as the particles became finer until a 200-mesh size. With finer particles both aglime types had similar efficiency to hydrated lime.

Meyer and Volk (1952) used two Illinois soils to conduct an incubation study with calcitic and dolomitic aglime sieved to different particle size fractions. They also conducted greenhouse studies with alfalfa (*Medicago sativa* L.) as a first crop, remixing the soil in the pots, and planting soybean [*Glycine max* (L.) Merr.] as a second crop. The fineness fractions were 4-8, 8-20, 20-30, 30-40, 40-50, 50-60, 60-80, 80-100, and < 100 Tyler mesh sieves. Results of the incubations showed that material coarser than 20-mesh had very little or no value in correcting soil acidity. Materials varying in particle size from 20 to 60-mesh initially increased pH very slowly but after 18 months approached the effectiveness of finer particles. Material finer than 100-mesh reacted soon after application and reached a maximum pH at about 6 months after application, but pH began to decrease and by the last sampling date 18 months later the pH was similar to or lower than materials with particle sizes 50 to 100 mesh. Calcitic and dolomitic aglime with particle sizes < 100 mesh were similarly effective at increasing soil pH. For coarser particle sizes, however, the pH increase was faster for the calcitic aglime, the maximum pH reached was similar for both sources when particle sizes were between 40-100 mesh, but the maximum pH was much lower for the dolomitic aglime when the particle sizes were > 40 mesh. In the greenhouse studies, yield of the first crop after application (alfalfa) was higher with the calcitic aglime than with the dolomitic aglime, and the yield response increased with decreasing

particle size. The yield of the second crop after soils were remixed, were higher with the dolomitic aglime, however, and also increased with decreasing particle size.

Motto and White (1957) conducted a study focusing on the relationship between a calcitic aglime specific surface area and the reaction rate. They found an exponential increase in the time required to raise the soil pH from 4.8 to 5.0 as surface area decreased. The reaction rates were 24-35 times faster for particles smaller than 60 mesh when compared to the 8-10 mesh fraction. Motto and Melsted (1960) conducted a 10-wk incubation study to assign efficiency values to differing particle sizes of calcitic aglime and  $\text{CaCO}_3$ . Their results showed that fineness fractions of 10-28 mesh were 14% as effective as those finer than 100 mesh. They suggested that a large portion of commercial aglime should be ground to pass a 40 mesh sieve.

Haby et al. (1979) studied the efficiency of a calcitic aglime and a dolomitic aglime at neutralizing soil acidity and increasing crop yield in two acidic sandy or sandy loam Texas soils through field and incubation experiments. Each aglime source was sieved to obtain fractions they called coarse, medium and fine. For the calcitic aglime coarse fraction, 99% of the particles had a size 2.0-0.82 mm; in the medium fraction 53% were 2.0-0.82 mm, 21% were 0.83-0.45 mm, and 20% were < 0.15 mm; and in the fine fraction 100% were < 0.15 mm. For the dolomitic aglime coarse fraction, 21% of the particles had a size > 2.0 mm and 65% were 2.0-0.82 mm, in the medium fraction 38% were 0.82-0.15 mm and 63% were <0.15 mm; and in the fine fraction 99% were < 0.15 mm. Lime application did not increase crop yield at any site for any of the aglime types and particle size fractions evaluated. The calcitic aglime produced a higher maximum pH than did the dolomitic aglime at both field sites. At one site maximum soil pH was reached 7 months after application with the calcitic aglime and 12 months after applying the dolomitic aglime, but at the other site there were no clear differences. An incubation study using

one soil and all three aglime fractions also showed that calcitic aglime effected a higher maximum pH than the dolomitic aglime, that the maximum pH was reached within 2 months with all calcitic aglime fractions but only with the longest incubation period of 8 months for all fractions of the dolomitic aglime, and that with the fine and medium fractions there were small or no differences between aglime types in the rate of pH increase or the time to reach a maximum but differences with the coarse fraction were much larger for the calcitic lime than for the dolomitic lime.

Scott et al. (1992) conducted a field study with continuous wheat (*Triticum aestivum* L.) in an acidic Australian soil with six particle size fractions and three application rates of a calcitic aglime. The coarser fraction had particles sizes 5-2 mm in size and the finest < 0.075 mm. Soil was sampled 6 months after application and after 1, 2, and 3 years. Their results showed an exponential increase in lime effectiveness as particle size decreased for all application rates (2.5, 5, and 10 Mg ha<sup>-1</sup>) and sampling dates. A very high pH increase was observed by the 6-month sampling date for all fractions and thereafter was little or no increase or decrease for any fraction when the two highest rates were applied, but there were decreases for all fractions when the lowest rate was applied. At the 6-month sampling date, the average efficiency of the different particle size fractions compared with the finest fraction were 17, 43, 52, 58, and 65%. The authors concluded that the finer aglime should be used. However, although wheat grain yield each year was greatly increased by liming, they did not report if or how the particle size fractions affected the yield response.

Stevens and Blanchar (1992) studied the soil pH gradients near calcitic and dolomitic (13% Mg) aglime particles reacting with an acidic silt loam soil in an indoor study using cylinders with dried soil sieved to pass a 2-mm screen. The aglime sources were sieved into five

fractions with sizes 2-1, 1- 0.5, and 0.5- 0.25 mm. Microelectrodes were used to measure soil pH at several distances from the surface of a single particle (0.1 to 3 mm) after several time intervals (15 min to 10 d). Calcitic aglime reacted about twice as fast and produced a larger pH gradient near the particle surface than dolomitic aglime; the greater effectiveness of calcite was attributed to a faster dissolution. There were inconsistent differences between aglime types for pH gradients with increasing distance from particles of different size and different times after application.

Pelleted limestone is a particular liming product because finely ground aglime is granulated with a binding agent to facilitate the handling and application. Little is known about the fineness of the initial material in various commercial pelleted aglime sources and how the material behave after granulation. Since the granules should break apart more readily than aglime, it is generally assumed that the granules disintegrate effectively after application to moist soil or after rainfall. However, scarce published research has investigated the efficiency of pelleted aglime at increasing soil pH. Incubation or field research during the 1980s and 1990s in Michigan (Warncke and Pierce, 1997) and Wisconsin (Kelling and Schulte, 1988a, 1988b) briefly summarized in short extension articles showed that pelleted lime and aglime did not differ at increasing soil pH or crop yield. Ohio field research conducted one year at one site evaluated aglime and pelleted lime (Lentz et al., 2010) by applying three similar rates of effective neutralizing power (ENP) of each material in spring 2004 before planting corn and measuring soil pH in seven sampling dates until November. Application of the low aglime rate ( $2.9 \text{ Mg ha}^{-1}$ ) increased corn yield and a similar pelleted aglime rate did not, but increased yield did not differ between the two sources when the higher rates ( $5.6$  and  $11.2 \text{ Mg ha}^{-1}$ ) were applied. Both sources increased soil pH, but the aglime increased pH more rapidly and to a higher value than

the pelleted aglime. Higgins et al. (2012) applied various annual rates of ground pelleted and ground dolomitic aglime from the same quarry to a perennial grass grown for silage during four years (0, 175, 350 and 525 kg product ha<sup>-1</sup>). They reported that liming maintained or slightly increased soil pH, particularly in the top 2.5 cm of the profile, but there were no differences between the two lime sources for any crop measurement. Lollato et al. (2013) evaluated several liming strategies for three years of continuous wheat in an acidic Oklahoma soil. The lime treatments were broadcast incorporated aglime at 2.25 or 4.50 Mg ha<sup>-1</sup> yr<sup>-1</sup> of effective CaCO<sub>3</sub> and pelletized aglime banded to the seed furrow at 225 or 450 kg ha<sup>-1</sup> yr<sup>-1</sup> effective CaCO<sub>3</sub>. The liming did not affect wheat grain yield. Both rates of broadcast aglime greatly increased soil pH but only the highest rate of pelleted aglime increased it slightly, which was expected given the much lower amounts applied with pelleted aglime. Brown et al (2008) conducted an experiment in eastern Washington that analyzed soil pH two years after application of pelleted aglime (broadcast at 7 Mg ha<sup>-1</sup> and subsurface-banded at 0.224 Mg ha<sup>-1</sup> yr<sup>-1</sup>) on three acidic Mollisols. Urea NH<sub>3</sub>NO<sub>3</sub> solution was banded 7 cm below the soil surface and 1.25 cm to the side of the seed. They found that broadcasted pelleted aglime significantly increased pH to a depth of 15 cm more than the banded annual application and control treatments.

Aglime and pelleted aglime analysis procedures in most states of the US follow similar procedures to determine its neutralizing value compared with pure CaCO<sub>3</sub> independently of the particle size distribution. The method uses 0.50 M HCl, and usually the result is referred to as calcium carbonate equivalent (CCE). However, the procedures to assess aglime fineness or the assumed particle sizes efficiencies at increasing soil pH are developed on a state-by-state basis. The Iowa Department of Agriculture and Land Stewardship (IDALS) requires that all aglime sold in the state be analyzed by a specific procedure called effective calcium carbonate



equivalent (ECCE) (IDALS, 2008). State personnel take the samples from the quarries and the samples must be analyzed at the Iowa State University Soil and Plant Analysis Laboratory. The procedure uses a wet sieving method that measures the percentage of material that passes a Tyler mesh size 4 (4.75 mm opening), a mesh size 8 (2.38 mm), and a mesh size 60 (0.25 mm). The percentage of the material that passes mesh sizes 4, 8, and 60 is multiplied by efficiency factors 0.1, 0.3, and 0.6, respectively. The sum of the resulting numbers are multiplied by the CCE of the material to establish its ECCE. These fineness factor values have been used for many decades and their origins are not known. Most states of the US North Central Region use mesh 8 and 60 sizes, but others also include intermediate or finer mesh sizes, and recommend use of often widely different efficiency for the different particle sizes.

The summarized literature surrounding aglime use in crop production has shown large variability or inconsistent results across studies when attempting to assess the influence of fineness on neutralizing potential and assigning efficiency values that correctly estimate neutralizing potential. This variation may be explained by large dissimilarity in the liming materials and properties of the soils used in studies. Furthermore, current state recommendations or requirements concerning efficiency factors for different aglime fineness fractions in place for several decades often, such as in Iowa, cannot be traced to supporting research. Therefore, the objective of this study was to evaluate the effect of particle size on efficiency of commercially available calcitic aglime, dolomitic aglime, and calcitic pelleted lime at increasing soil pH in Iowa soils under controlled conditions.

## MATERIALS AND METHODS

Three acidic soils were selected to be used in the incubation experiment. Bulk soil was collected from the Ap horizon (0- to 15- cm depth) in the fall 2014 from fields in central, eastern, and southeast Iowa. Soil series were Fruitfield (Sandy, mixed, mesic Entic Hapludolls), Nicollet (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls), and Otley (Fine, smectitic, mesic Oxyaquic Argiudolls). These soils represent areas with corn and soybean production in Iowa where acidic soils are frequently found and differ in topsoil properties such as texture, organic matter, exchangeable cations, or mineralogy. The soils were air-dried and sieved through a 2-mm sieve. Soil test results from the initial bulk soil samples are summarized in Table 1. Soil particle size was determined by the pipette method (Gee and Bauder, 1979). Each soil also was analyzed in duplicate by several routine soil testing procedures. Soil pH by the soil/distilled water 1:1 ratio method (Peters et al., 2012), buffer pH by the Sikora method (Peters et al., 2012), organic matter by combustion (Wang and Anderson, 1998), P by the Mehlich-3 colorimetric method (Frank et al., 1998); and extractable K, Ca, Mg, and Na by the  $\text{NH}_4\text{OAc}$  method (Warncke and Brown, 1998) with measurement by inductively coupled plasma spectrometry. The soil cation exchange capacity (CEC) for each soil was estimated by summing K, Ca, Na, and Mg extracted with  $\text{NH}_4\text{OAc}$  and exchangeable  $\text{H}^+$  estimated from buffer pH as suggested by the NCERA-13 committee (Warncke and Brown, 1998).

The lime sources were pure finely ground reagent-grade calcium carbonate, commercially available pelleted calcitic lime, and calcitic or dolomitic agricultural limestone (aglime). The two aglime sources were sieved to obtain material within five particle-size fractions. These were material passing through mesh 4 but not mesh 8, materials passing through mesh 8 but not mesh 20, material passing through mesh 20 but not mesh 60, material passing

through mesh 60 but not mesh 100, and material passing through mesh 100 (Tyler equivalent mesh sieves). Mesh sieve sizes of 4, 8, 20, 60, and 100 have corresponding opening sizes of 4.35, 2.36, 0.85, 0.25, and 0.15 mm, respectively. Bulk samples of all four lime sources and the five fractions of the two limestone sources were analyzed for CCE, total Ca, Mg, and moisture. The laboratory limestone analysis results are summarized in Table 2. The pelleted calcitic aglime used is commercially available (Calcium Products' 98G Pelletized Limestone). Information provided by the company (personal communication. Andrew Hoiberg, Calcium Products, Ames, Iowa) indicates that the pelleted aglime is made from mined calcitic limestone from quarries near Gilmore City and Fort Dodge in Iowa. The pellets are created by a pelletizing process known as pan agglomeration. Limestone is ground very fine (on average: 100% passing 30-mesh, 99% passing 60-mesh, 75% passing 100-mesh, 60% passing 200-mesh prior to pelletizing). The pellets are held together with a commonly used binding agent, calcium lignosulfonate, the amount and type of which are paramount to make pellets that can withstand the handling in the distribution from the manufacturing plant to the farm fields and to also solubilize in the soil. The final pellets ranged in size from 2.0 to 4.0 mm.

The incubation procedure used was developed for previous soil incubation experiments (Ruiz-Diaz et al., 2008; Dagna and Mallarino, 2014). The air-dried bulk soil was crushed, mixed well in cement mixing machine, and sieved through a 2-mm sieve. This was done to mitigate any variation that would occur in an *in situ* field setting. There were 45 soil-by-lime treatments incubated for eight different periods (7, 21, 35, 70, 105, 140, 175, and 210 d) and three replications. The liming materials were mixed at an equivalent rate of 7.14 Mg CCE ha<sup>-1</sup>. An amount of each dried soil and the appropriate liming material weight more than sufficient for cups needed for all incubation periods was thoroughly mixed for each lime source and

replication combination, and 200 g of the mixture was incubated in 300-mL cups. The moisture field capacity of each soil was estimated gravimetrically in triplicate by carefully adding water until all the soil volume was wet and there was no water leak. Distilled water was added to each cup as needed to achieve 80 to 90% of water holding capacity. The cups were placed in a randomized design in a small dark room of the Agronomy Department building having the same air circulation and control system used for laboratories and kept a constant temperature of 25°C. Each cup was fit with a plastic lid with three 5-mm diameter holes to allow gas exchange. Thirty randomly selected cups for each soil were weighed every 7 d during incubation to monitor the water content, and moisture was added to keep water loss to less than about 70% of the field capacity. After each incubation period, the material in each cup was dried at 40°C in a forced-air oven, crushed to pass through a 2-mm sieve, and analyzed in duplicate for pH in a 1:1 water slurry with an Accumet Model-25 pH meter and dual glass and reference electrode. Soil pH also was measured in a 1:2 soil to 0.01M CaCl<sub>2</sub> solution using the same instrument.

To simulate the effect of a change in soil water content and soil mixing after lime application, an additional procedure was added for 140 and 175 d incubation periods. At the end of the 140-d incubation period the soil was divided into two halves on a mass basis, remixed and weighed. Half of the amount was analyzed for soil pH as described above. The other half was allowed to air-dry in the same room described above until soil water content reached about 30 to 45%. At that time the soil was rewet with distilled water to reach 80-90% of field moisture capacity as for the other samples still being incubated. These cups were incubated to complete the last 35 d of a 175-d incubation period with the two mixing/moisture regimes. A similar procedure was used when other cups that were incubated at constant moisture for 175 days.

The efficiency of the different materials at increasing soil pH compared to pure CaCO<sub>3</sub> was calculated by dividing the net pH change for a material (pH<sub>final</sub> - pH<sub>initial</sub>) by the net pH change of pure CaCO<sub>3</sub> and multiplying by 100 according to Equation 1. Initial pH is the pH before starting the incubation and final is the pH measured at the end of each incubation period.

Equation 1:

$$\text{Efficiency (\%)} = (\text{sample pH}_{\text{final}} - \text{sample pH}_{\text{initial}}) \div (\text{CaCO}_3 \text{ pH}_{\text{final}} - \text{CaCO}_3 \text{ pH}_{\text{initial}}) \times 100$$

There were two analysis of variance (ANOVA) analyses. One type of ANOVA assessed the effects of the three liming sources (including the untreated control) on soil pH for each soil and incubation period and also for means across the three soils for each incubation period.

Similar ANOVA was conducted for lime source efficiencies at increasing pH compared with CaCO<sub>3</sub>. The other ANOVA assessed the effects of particle size fractions (excluding the control) on soil pH and efficiencies for each aglime source, soil, and incubation period; and for means across the three soils for each aglime source and incubation period. Each ANOVA was conducted using the GLIMMIX procedure of SAS (SAS Inc., Raleigh, NC) for a completely randomized design assuming lime source as a fixed effect and replication as a random effect. Differences between the treatment means were assessed by using the LINES option of the LSMEANS statement for comparison of means only when the treatments main effect was significant at  $P \leq 0.05$ .

Regression (REG or NLIN procedures of SAS) was used to study the effect of each lime source or particle size fraction on pH and efficiency compared to CaCO<sub>3</sub> for all incubation periods for each soil and for means across the three soils. The pH or percent efficiency data were regressed on the incubation period (d). Models fit were linear, quadratic, quadratic-plateau, and exponential with decreasing increments rising to a maximum. All models were statistically

significant for all treatments ( $P \leq 0.05$ ). The best fit model was chosen for each instance based on  $R^2$  values adjusted for degrees of freedom, pair-wise  $F$  tests of the models residual sums of squares, and observation of distribution of residuals. The model with the highest  $R^2$  was chosen when its residual sums of squares was significantly smaller ( $P \leq 0.05$ ) than for other models. When the residual sums of squares for two or more models with high  $R^2$  did not differ, we chose the best fitting model according to observation of the distribution of residuals.

## **RESULTS AND DISCUSSION**

### **Soil pH Change over Time**

All liming materials increased pH over time for all soils and all incubation periods but the magnitude of the pH increase for each liming source varied across soils (Table 4). This should not be unexpected due to differing initial soil pH, buffering capacity, organic matter content, and texture (Table 1), which influence liming materials dissolution and acid neutralization properties. The range of maximum pH attained by the different liming materials was 7.1 to 7.8, 6.0 to 7.7, and 6.2 to 7.4 for the Fruitfield, Nicollet, and Otley soils, respectively. Statistically significant differences among the sources occurred less frequently during early incubation periods because of larger variability among the replications and less time for pH correction.

Response models fit to the data for each soil and lime source across incubation periods (not shown) indicated that with  $\text{CaCO}_3$ , a plateau or maximum pH was reached at 35, 15, and 59 days of incubation for the Fruitfield, Nicollet, and Otley soils, respectively. For the longest incubation period (210 days), the  $\text{CaCO}_3$  increased soil pH the most for the Fruitfield and Nicollet soils with pH values of 7.8 and 7.7, respectively, but for the Otley soil the  $\text{CaCO}_3$  and pelleted aglime increased pH the most and did not differ from each other. The pelleted aglime

always effected the greatest maximum pH of the aglime sources for the 70-day incubation period and longer periods for all soils. Models fit to the pelleted calcitic aglime response curves (not shown) indicated that a plateau or maximum pH was reached at 48, 210, and 120 days of incubation for the Fruitfield, Nicollet, and Otley soils, respectively, which were longer than for  $\text{CaCO}_3$  for all soils. The maximum pH and the date it was reached by the calcitic and dolomitic aglime sources varied among the soils. For the Fruitfield soil, the calcitic aglime increased pH more than the dolomitic aglime ( $P \leq 0.05$ ) for about one-half of the early incubation periods (7, 70, 140, and 175 days), and fit models indicated that a plateau or maximum was reached much earlier by the calcitic aglime. For the Nicollet soil, the calcitic aglime increased pH more than the dolomitic aglime ( $P \leq 0.05$ ) for incubation periods of 21 days and longer, and fit models also indicated that a plateau or maximum was reached much earlier by the calcitic aglime. For the Otley soil, however, the calcitic aglime effected higher pH than the dolomitic aglime ( $P \leq 0.05$ ) only for the first two incubation periods and the fit models indicated that a plateau or maximum pH was reached earlier by the dolomitic aglime. The soil properties shown in Table 1 did not provide an obvious explanation for the slightly better performance of the dolomitic aglime in the Otley soil compared with the other soils. However, the calcitic and dolomitic aglime did not statistically differ for the longest incubation period ( $P \leq 0.05$ ).

Figure 1 shows how the finely ground  $\text{CaCO}_3$ , calcitic aglime, dolomitic aglime, and pelleted aglime increased the mean soil pH across the three soils. This average assessment is important because although there were some differences among soils, seldom are liming management practices specific for different soils except by considering buffer pH or soil properties that affect the amount of lime to apply to raise pH to a certain value. Application of all liming sources resulted in curvilinear pH increases over time with decreasing increments to a

maximum. Table 9 shows the models fit, statistics, and the maximum pH as estimated by each model. The pH increases for CaCO<sub>3</sub> and pelleted lime did not reach a maximum before the longest incubation period since the responses were best fit by an exponential model with rise to a maximum compared with quadratic and quadratic-plateau models ( $P \leq 0.05$ ). For both aglime sources, however, a plateau pH was reached before the longest incubation period. Observation of the curves in the figure and model coefficients show that the CaCO<sub>3</sub> increased pH the fastest and reached a greatest maximum value (pH 7.6) than the other three lime sources did. This agrees with what has been found in many field studies. The pelleted aglime and calcitic aglime showed a statistically similar rate of pH increase for the three shortest incubation periods but over time the pelleted aglime continued to increase pH to a much higher maximum than the calcitic aglime. For the longest incubation period, the pelleted lime nearly approached the maximum pH attained by CaCO<sub>3</sub>. Murdock (1997) reported that the coating on pelleted aglime may reduce the reaction rates, so a small effect of pelleted lime with short incubation periods may be reasonable. This figure also demonstrates that the calcitic aglime reacted faster than the dolomitic aglime, it effected much larger pH increases for the shortest incubation periods, and the pH difference tended to decrease for the longer periods. This difference between calcitic and dolomitic aglime was also reported in previous research (Beacher and Merkle, 1948; Lindsay, 1979; Barber, 1984; Thomas and Hargrove, 1984; Stevens and Blanchar, 1992; Rippy et al., 2007; Pagani and Mallarino, 2015). It is important to note that the differences in pH among all sources were statistically different even for the longest incubation periods.

Table 5 shows the effect of different fractions of calcitic and dolomitic aglime on soil pH for all soils and incubation periods. All particle size fractions of both sources increased pH significantly ( $P \leq 0.05$ ) from the initial pH for all soils with all incubation periods. The pH



increase was smallest for the coarser aglime fractions and largest for the finest fractions, but there were some important differences. The maximum pH reached by both the calcitic and dolomitic aglime sources often was from the application of the finest fraction (material passing a 100-mesh size) but there were exceptions when variability was higher in the early incubation periods. Material passing mesh sizes 60 and 100 were not statistically different in the Fruitfield soil for the calcitic aglime for all incubation periods except the 70-day period. The material passing mesh sizes 60 and 100 were statistically significant for incubation periods of 70 days and longer and both sources reached a maximum at the longest incubation periods for two of the three soils. In the Nicollet soil for both aglime sources the 60-100 and 100+ mesh sizes were significant from each other from the 35-day incubation period and longer. In the Otley soil the calcitic aglime difference between the two finest fractions was significant for all incubation periods, and for the dolomitic aglime the two finest fractions differed significantly for the 35-day period and longer.

Models fit to the response curves for each soil and fineness fraction across the incubation periods (not shown) indicated no consistent differences concerning the time at which a maximum pH was reached with the different fractions, and sometimes seemed counter intuitive, because often the rate of pH increase became smaller over time with decreasing increments towards a maximum although the observed or modeled maximum pH often differed greatly. In the Fruitfield soil, for example, the three coarser fractions of calcitic aglime reached a maximum pH earlier than the finest fractions did but with a much lower maximum pH. In the Nicollet soil, most fractions of both aglime sources increased pH without reaching a maximum or did it with the longest incubation period. In the Otley soil, the material fineness did not consistently affect the time to reach a maximum pH for any source.

Figures 2 and 3 show the effect of different calcitic and dolomitic aglime fineness fractions on increasing soil pH for means across the three soils, and Table 9 shows the models fit as well as the maximum pH reached as estimated by each model. As expected, pH increased faster and reached a higher maximum value for the finer materials. The 100+ mesh size fraction of both aglime source showed the fastest rate of pH increase for the three shortest incubation periods and the highest pH throughout all incubation periods. For the calcitic aglime fractions (Fig. 2) the 60-100 and 100+ mesh size fractions rapidly reached a pH of 6.5 21 days after application or earlier (6.5 is the optimum pH for corn and soybean for most Iowa soils), and continued increasing pH until the longest incubation period. The mesh size fraction 20 reached pH 6.5 about 40 days after application, and 52 days after application reached a plateau at pH 6.7. The two coarsest fractions (material passing 4-8 and 8-20 mesh sizes) showed a lower rate of pH increase, and did not increase pH above 6.3 even for the longest incubation period. For the dolomitic aglime fractions (Fig. 3), the rate at increasing pH was slightly lower than for the calcitic aglime and, most importantly, the differences between the fineness fractions was proportionally greater than for the calcitic aglime. The pH increases for the fractions finer than mesh size 20 fit best to exponential models rising to a maximum beyond the longest incubation period (material passing mesh 60 or finer) or to a plateau at an earlier time (material passing mesh size 20 but not 60). However, material larger than that passing mesh size 20 better fit quadratic models with a maximum at a lower pH and at intermediate incubation periods with a slight decrease thereafter.

Therefore, results demonstrated that, within the scope of the methods and treatments for this incubation study, the fineness of the material was very important at determining the maximum pH reached by aglime application but not necessarily the time at which the maximum

pH was reached within a time span of 210 days. Results for either liming source showed that the effect on soil pH increase was significantly larger by decreasing particle size and that often, but not always, grinding aglime to particle sizes that pass a 100-mesh size resulted in larger pH increases. These results agree with results of a laboratory study conducted by reacting aglime with  $\text{NH}_4\text{Cl}$  in the presence of steam by Rippey et al. (2007), who reported that the fineness of calcitic limestone did affect aglime reactivity but decreasing particle size beyond a 50 mesh size had no effect.

### **Drying and Rewetting Effects on pH Increases Due to Liming**

Table 8 shows the effect on pH increase from liming of simulating remixing moist soil, drying, and rewetting of soil for a 35-day final period for each of the two longest incubation periods (175 and 210 days) for means across the three soils. The data for each soil are not shown because the effect of these treatments were proportionally similar. Soil pH for the remixed, dried, and rewetted treatment was numerically higher than the treatments with constant moisture for both incubation periods and all lime sources, and differences reached statistical significance ( $P \leq 0.05$ ) with only a few exceptions. Interestingly, treatment did not affect (for the 175-day incubation period) or slightly decreased soil pH (for the 210-day incubation period). The exceptions were for  $\text{CaCO}_3$  with the 175-day incubation period and for the dolomitic mesh size 60 with both the incubation periods of 175 and 210 days. The coarser fractions of both the calcitic and dolomitic aglime responded to a fluctuation of soil moisture much more than the finer fractions. Topsoil pH at the field has been known to decrease during dry periods, which is usually attributed to accumulation of soluble salts that otherwise would be leached. In this incubation study, care was taken to avoid leaching from the cups. Therefore, any decrease in pH

due to lower water content must have been reversed by the remixing and rewetting of soil by an increase in the dissolution of lime particles. The porous nature of aglime also allows for further physical breakdown of individual particles after time and could explain the pH increases. A similar response of soil pH to drying and rewetting of soil samples was noted by Van Lierop (1990). Remixing and an influx of water would promote continued acid neutralization by the lime particles (Thomas and Hargrove, 1984; Van Lierop, 1990). Therefore, if we had remixed, dried, and rewetted soil for the shorter incubation periods perhaps we could have seen more rapid effects of the lime sources at increasing soil pH, and mainly for those with the coarser particle sizes.

#### **Treatment Effects by Measuring Soil pH with 0.01M CaCl<sub>2</sub>**

All the combinations of soil, lime source, and incubation periods (1,080 constant moisture samples + 270 simulated dry/rewet samples considering three replications) also were analyzed for soil pH with 0.01M CaCl<sub>2</sub> to assess if the accumulation of salts derived from the soil or the dissolving lime particles would affect differently the effect of lime sources, particle size, or incubation periods on soil pH. Data are not shown because the results showed that the measurement of soil pH with 0.01M CaCl<sub>2</sub> decreased measured pH slightly but the effect was proportionally similar across all treatments, including the effect of the incubation period. Therefore, any concentration of salts in any of the soils or the liming materials used did not exist to the degree that it changed the relationships between limes sources, mesh sizes, or incubation time with pH increases for the CaCl<sub>2</sub> pH analysis. Soil pH measured with CaCl<sub>2</sub> was regressed on soil pH measured with distilled water across all soils, limes sources, particle sizes, and incubation periods, and there was a linear relationship with an  $r^2$  of 0.99 (Equation 2).

Equation 2: Soil  $\text{pH}_{\text{CaCl}_2} = -0.79 + 1.03(\text{Soil } \text{pH}_{\text{water}})$ , ( $P \leq 0.01$ )

The slope of the linear relationships did not differ ( $P \leq 0.05$ ) from 1.00, so we conclude that the pH measurement in 0.01M  $\text{CaCl}_2$  were on average 0.58 pH units lower than the measurements made in distilled water. These results agree with other studies that have focused on pH measurement comparisons and summarized by Bloom et al. (2005).

### **Efficiency of Increasing Soil pH**

Efficiency of the commercial liming sources at increasing soil pH for each soil and incubation period is shown in Table 6. Values are expressed in percentages of net pH change relative to the change in pH from application of pure finely ground  $\text{CaCO}_3$ . The efficiencies quantify differences in pH increases shown in the previous section. As for the pH results, the efficiency of each liming material was most variable for the short incubation periods, as is shown by the LSD values. The pelleted aglime was the most efficient of the commercial materials at increasing soil pH and had maximum efficiencies of 85, 84, and 100% for the Fruitfield, Nicollet, and Otley soil, respectively. Neither the calcitic or dolomitic aglime approached efficiencies greater than 71% when compared to  $\text{CaCO}_3$ . The calcitic aglime was numerically more efficient at increasing soil pH for all soils than the dolomitic aglime, but for the Fruitfield and Otley soils the differences did not reach statistical significance ( $P \leq 0.05$ ) for several incubation periods and without clear trends for short or long periods. In the Otley soil the calcitic and dolomitic aglime clearly differed for the shortest incubation period but did not differ for the longest incubation periods. This was also seen in the pH results. The calcitic aglime efficiency reached a maximum earlier than the two other commercial sources for the Fruitfield and Nicollet soils. The pelleted aglime did not reach a maximum even with the longest incubation period for

the Fruitfield and Nicollet soils, but efficiency showed no significant trend over time for the Otley soil. On average across the three soils (Table 6), the efficiency of calcitic aglime, dolomitic aglime and pelleted aglime for the longest incubation period was 60, 47, and 90%, respectively. On average across soils, the dolomitic and pelleted aglime fit exponential models rising to maxima beyond the longest incubation period (fit models are not shown). The calcitic aglime efficiencies varied at a high level across the incubation periods and no model had a significant fit over time ( $P \leq 0.05$ ).

State of Iowa regulations for the sale of aglime require that aglime be analyzed for CCE and its particle size distribution by applying established fineness efficiency factors relative to pure  $\text{CaCO}_3$  to the percent material passing US Tyler sieves with mesh sizes 4, 8, and 60 (IDALS, 2008). There are no records indicating the research used to support use of those sieve sizes and development of those efficiency factors. The CCE, efficiency factors, and ECCE values determined for the commercial liming sources used in the study are shown in Table 2, and ECCE was 59, 65, and 92% for calcitic aglime, dolomitic aglime, and pelleted aglime, respectively. The experimentally determined efficiencies those those particle size ranges across all three soils and for the longest incubation period (Table 6) were 1% greater, 18% smaller, and 2% greater for the calcitic aglime, dolomitic aglime, and pelleted aglime; respectively. Therefore, the current Iowa assumed impact on efficiency of different particle sizes are very close to values determined in this incubation study for calcitic aglime and pelleted lime, but underestimated the overall efficiency of dolomitic aglime.

The efficiency of fractioned calcitic aglime and dolomitic aglime materials at increasing soil pH compared with pure  $\text{CaCO}_3$  for each soil and incubation period is shown in Table 7. Negative values indicate that the specific source-mesh-incubation period combination led to an

increase in pH that was over an equivalent CCE rate of  $\text{CaCO}_3$ , which should be explained by variability and experimental error. As for pH results, all sources and particle sizes showed greater variability for early incubation periods, but much less for longer incubation durations. This can be seen by the decrease in LSD values as the incubation periods increase. For the two longest incubation periods (175 and 210 days) all mesh sizes for both sources and all soils differed from each other, except the calcitic mesh 60 and 100 for the Fruitfield soil which showed no significant difference ( $P \leq 0.05$ ). The means across the three soils (Table 7) show that the efficiency for calcitic aglime fractions compared to  $\text{CaCO}_3$  for the longest incubation period increased from 29% for the coarsest fraction to 97% for the finest fraction. For the dolomitic aglime, however, efficiencies increased from only 10% for the coarsest fraction to 86% for the finest fraction. The time to reach a maximum efficiency was not consistent for the different fineness fractions within or across aglime types as indicated by the time to reach a maximum (fit models are not shown). In general, however, the coarser particle sizes reached a lower maximum earlier than the finer particle sizes. Beacher and Merkle (1948) found that the effectiveness at increasing pH of calcitic aglime mesh size fractions of 20-60, 60-100, 100-200, and 200+ increased as each fraction became finer. In the same study, dolomitic aglime fractions of the same size fractions showed a similar trend but the magnitude of effectiveness was lower than for the calcitic aglime. The findings from our study agree with the results reported from that early study as both aglime sources increased in efficiency as particle size decreased.

Figure 4 shows aglime efficiency at increasing pH as a function of mesh size fractions for calcitic and dolomitic aglime for means across the three soils. The data in the figure show that the efficiency of both aglime sources increased curvilinearly with increasing material fineness and that the efficiency of all calcitic aglime particle size fractions was significantly higher than

for the dolomitic aglime fractions ( $P \leq 0.05$ ). The higher efficiency of the calcitic aglime was compared with the dolomitic aglime was approximately similar for all the fineness fractions, and for observed values was 36% higher on average. Moreover, Fig. 4 shows that the efficiency of calcitic aglime passing a mesh size 8 but not 20 and dolomitic aglime passing a mesh 20 but not 60 did not differ, and similar lack of difference was found for calcitic mesh 20 and dolomitic mesh 60, and calcitic mesh 60 and dolomitic mesh 100 are. Barber (1984) summarized 18 studies that compared reaction rates of calcitic and dolomitic aglime and found that to obtain equal reaction rates the dolomitic aglime must have 18% more particles by weight passing a mesh 60 sieve. Therefore, we arrive at an analogous conclusion to that by Barber (1984) in that dolomitic aglime must be ground more finely to reach equal reaction rates and efficiencies at increasing pH as calcitic aglime. Some state recommendations recognize this difference. For example, North Carolina recommends 35% of dolomitic aglime to pass a 100-mesh sieve but only 25% calcitic aglime to pass the same size (Crozier and Hardy, 2014).

The CCE, efficiency factors to calculate ECCE, and ECCE values as required in Iowa (IDALS, 2008) for the five mesh fractions and two aglime sources are listed in Table 3. When the Iowa fineness factors are applied to a range of a material particle sizes, a proportionality equaling 1.0 (representing 100%) must be distributed among the range of particle sizes that are analyzed. The fineness factors are 0.1 for material passing a sieve size 4, 0.3 for material passing a sieve size 8, and 0.6 for material passing a sieve size 60 (IDALS, 2008). We recalculated materials efficiency relative to pure  $\text{CaCO}_3$  from this study to compare our results with sieve sizes and efficiencies assumed in Iowa. In this analyses, the ECCE calculations consider any particles within ranges of 4-8, 8-60, and 60+ mesh sizes to be similar in effectiveness and, if CCE values are the same, will not differ in ECCE. Calculations based on data in Table 3 and Fig.



4 indicated that for fractions within 8-60 mesh sizes the efficiency for calcitic and dolomitic aglime would be 21 and 22%, respectively. Similar calculations indicate 17 and 21% efficiency for material passing a 60+ mesh size for calcitic and dolomitic aglime, respectively. When the data from Table 3 and Fig. 4 are used to calculate fineness factors according to the method currently used in Iowa for material passing a sieve with mesh size 4, 8, or 60, the values on average across both aglime sources are 0.2, 0.2, and 0.6, respectively, whereas the assumed values in Iowa are 0.1, 0.3, and 0.6. Therefore, these values demonstrate that if the effect of particle size is assessed for material passing sieves with mesh sizes 4, 8, and 60 the efficiencies currently assumed in Iowa are in close agreement accordance with the findings in this study except for dolomitic aglime.

## SUMMARY AND CONCLUSIONS

All commercial liming materials significantly increased soil pH above the control treatment for the 35-day period after the incubation started and longer periods. The pure  $\text{CaCO}_3$  increased soil pH to the highest maximum for the Fruitfield and Nicollet soils and reached a maximum faster than all commercial aglime sources. The pelleted aglime was statistically similar to  $\text{CaCO}_3$  at the longest incubation period for the Otley soil, and was greater than either commercial aglime sources at the longest period for all soils. At the longest incubation periods, the calcitic aglime was only greater than the dolomitic aglime for the Nicollet soil and both were statistically similar for the Fruitfield and Otley soil, although the calcitic was numerically larger. However, the dolomitic aglime often reached lower pH values than the calcitic aglime with shorter incubation periods for all three soils.

Increases of soil pH were influenced by the aglime fineness. For the two longest incubation periods, fineness fractions ranging from material that passed sieve mesh sizes 8 to 100 differed from each other for all individual soils except for the calcitic mesh sizes 60 and 100+ treatments in the Fruitfield soil where particles finer than 60 mesh increased pH further. Fineness fractions that increased soil pH the most not always reached their respective pH maxima the fastest, however. Very few aglime fineness fractions differed from each other for the shortest two incubation periods, due to small pH increases and large variability. On average across all soils, all fineness fractions for both the calcitic and dolomitic aglime statistically differed for the 70-day incubation period and longer. The fineness of calcitic and dolomitic aglime particles influenced the time to approach a maximum or plateau. Soil pH continued to increase until the longest incubation period for the 60-100 and 100+ mesh size fractions, while those of mesh sizes 20-60 and smaller reached a plateau or began decreasing before the longest incubation period. Soil pH for the dolomitic aglime mesh size fractions 4-8 and 8-20, the two coarsest, began to significantly decline at 167 and 162 days, respectively.

Calculations of efficiency at increasing soil pH compared with  $\text{CaCO}_3$  showed that the pelleted aglime increased soil pH more than either aglime source, and was 85 and 90% as efficient as  $\text{CaCO}_3$  for the longest two incubation periods across all soils. The efficiency of the pelleted aglime was well represented by the ECCE analysis used by the State of Iowa, which was 92.3% ECCE. Mean efficiencies across all soils for the longest incubation period for the calcitic, dolomitic, and pelleted aglime were 60, 47, and 90%. For the longest two incubation periods, the efficiency of all fineness fractions differed from each other, except the calcitic 60-100 and 100+ mesh for the Fruitfield soil where the finest material showed greater efficiency. The calcitic aglime had higher efficiency at all finesses fractions than the dolomitic aglime. The neutralizing

potential of dolomitic aglime was overestimated when analyzed for ECCE. The results show that aglime source, fineness, and duration to which it is allowed to react in the soil can significantly influence the potential of the material to efficiently increase soil pH.

In conclusion, the efficiency of a liming material at increasing pH relative to pure, powdered  $\text{CaCO}_3$  showed large differences among soils, materials, fineness fractions, and incubation times. Increasing fineness increased the efficiency of the calcitic and dolomitic aglime fractions following an exponential trend with decreasing increments. On average across soils and the longest incubation period, calcitic aglime fractions efficiency relative to  $\text{CaCO}_3$  were 29, 39, 60, 81, and 97% for mesh sizes 4, 8, 20, 60, and 100, respectively. Efficiencies for the dolomitic aglime were lower (10, 20, 43, 66, and 86%, respectively). For the longest incubation period, the calcitic, dolomitic, and pelleted aglime sources had average efficiencies across all soils of 60, 47, and 90%, respectively. The results from this study give agronomists and farmers additional insight into the aglime properties that can influence successful management of acidic soils used for crop production.

**REFERENCES**

- Adams, F. 1984. Soil acidity and liming (2nd ed.). Agron. Monogr. No. 12. ASA, Madison, WI.
- Barber, S.A. 1984. Liming materials and practices, p. 171–209. *In*: F. Adams (ed.). Soil acidity and liming. 2nd ed. Agron. Monogr. 12. ASA, CSSA, Madison, WI.
- Beacher, R.L. and F.G. Merkle. 1949. The influence of form and fineness of lime compounds upon the correction of acidity and upon the nutrient status of soils. *Soil Sci. Soc. Am. J.* 13: 391.
- Bloom, P. R., Skyllberg, U. L., Sumner, M. E., Tabatabai, M. A., Sparks, D. L., Al-Amoodi, L., & Dick, W. A. (2005). Soil acidity. *Chemical processes in soils*, pp. 411-459.
- Brady, N.C. 2008. *The nature and properties of soils* / Nyle C. Brady, Ray R. Weil. Rev. 14th ed.. ed. Upper Saddle River, N.J. : Pearson Prentice Hall, Upper Saddle River, N.J.
- Crozier, C. and D. Hardy. 2014. Soil Acidity and Liming for Agricultural Soils. *Soil Facts*. NC Cooperative Extension. pp. AG-439-450.
- Dagna, N.E. and A.P. Mallarino. 2014. Beef cattle manure survey and assessment of crop availability of phosphorus by soil testing. *Soil Sci. Soc. Am. J.* 78: 1035.
- Frank, K., D. Beegle, and J. Denning. 1998. Phosphorus. pp. 21-29. *In* J.R. Brown (ed.) *Recommended chemical soil test procedures for the North Central Region* Publ. 221 (rev.). Publ. SB 1001. Missouri Exp. Stn., Columbia.
- Gee, G.W. and J.W. Bauder. 1979. Particle Size Analysis by Hydrometer: A Simplified Method for Routine Textural Analysis and a Sensitivity Test of Measurement Parameters<sup>1</sup>. *Soil Sci. Soc. Am. J.* 43: 1004.
- Hartwig, R.C. and R.H. Loeppert. 1992. A pH-stat procedure for evaluating reactivity of agricultural limestone. *Soil Sci. Soc. Am. J.* 56: 302-308.

- Higgins, S. S. Morrison, and C.J. Watson. 2012. Effect of annual applications of pelletized dolomitic lime on soil chemical properties and grass productivity. *Soil Use Management* 28:62–69.
- Iowa Department of Agriculture and Land Stewardship (IDALS). 2008. Determination of ECCE. pp. 8. *In* Chapter 43. Fertilizers and Agricultural Lime. Available at <http://www.legis.state.ia.us/asp/ACODOCS/DOCS/21.43.pdf> [cited 15 October 2016].
- Kelling, K.A. and E.E. Schulte. 1988. Pelletized lime for Wisconsin? Proceedings of the 1988 Wisconsin Forage Council's 12th Forage Production and Use Symposium. p. 147-149. Jan. 26-27, 1988. Wisconsin Dells, WI.
- Kelling, K.A. and E.E. Schulte. 1988. Pelletized lime for Wisconsin? *Soil Science Newsletter*. pp 1-5. November. Univ. Wisconsin, Madison, WI.
- Lentz, E.M., K.A. Diedrick, C.E. Dygert, D.C. Henry, and R.W. Mullen. 2010. Soil pH and corn grain yield response to low rates of pelletized lime and typical aglime. *National Assoc. County Agric. Agents Journal*. 3(1):1-4.
- Lindsay, W.L. 1979. *Chemical Equilibria in Soils*, *In*: John Wiley & Sons: New York.
- Lollato, R.P., J.T. Edwards, and H. Zhang. 2013. Effect of alternative soil acidity amelioration strategies on soil pH distribution and wheat agronomic response. *Soil Sci. Soc. Am. J.* 77:1831-1841.
- Meyer, T. A., and G.W. Volk. 1952. Effect of particle size of limestones on soil reaction, exchangeable cations, and plant growth. *Soil Science*. 73:37-52.
- Motto, H.L. and S.W. Melsted. 1960. The efficiency of various particle-size fractions of limestone. *Soil Sci. Soc. Am. J.* 24: 488.

- Motto, H., & Whiter, J. L. (1957, January). Specific surface and reaction rate of calcitic limestone in neutralizing soil acidity. In *Proceedings of the Indiana Academy of Science* (Vol. 67, pp. 237-242).
- Pagani, A. and A.P. Mallarino. 2012. Soil pH and crop grain yield as affected by the source and rate of lime. *Soil Sci. Soc. Am. J.* 76: 1877.
- Peters, J.B., M.V. Nathan, and C.A.M. Laboski. 2012. pH and Lime Requirement. Chapter 4, Revised Oct. 2012. p. 4.1-4.11. In: *Recommended chemical soil test procedures for the North Central region*. North Central Regional Publ. No. 221 (Rev.). Missouri Exp. Stn. Publ. SB 1001. Univ. of Missouri. Columbia.  
<http://extension.missouri.edu/explorepdf/specialb/sb1001.pdf>.
- Rippy, J., P. Nelson, D.L. Hesterberg and E. Kamprath. 2007. Reaction times of twenty limestones. *Commun. Soil Sci. Plant Anal.* 38: 1775-1783.
- Ruiz Diaz, D.A., J.E. Sawyer and A.P. Mallarino. 2008. Poultry manure supply of potentially available nitrogen with soil incubation. *Agron. J.* 100: 1310-1317.
- Sawyer, J.E., A.P. Mallarino, R. Killorn, and S.K. Barnhart. 2002. A general guide for crop nutrient and limestone recommendations in Iowa. Publ. Pm-1688. Iowa State Uni. Ext., Ames.
- SAS Institute. 2009. *The SAS system for Windows*. Version 9.2. SAS Institute, Cary, NC.
- Scott, B., M. Conyers, R. Fisher and W. Lill. 1992. Particle size determines the efficiency of calcitic limestone in amending acidic soil. *Aust. J. Agric. Res.* 43: 1175.
- Sikora, F.J. 2006. A buffer that mimics the SMP buffer for determining lime requirement of soil. *Soil Sci. Soc. Am. J.* 70:474-486.

- Stevens, J. and R.W. Blanchar. 1992. Soil-pH gradients near calcite and dolomite particles. *Soil Sci. Soc. Am. J.* 56: 967-972.
- Thomas, G. W., & Hargrove, W. L. (1984). The chemistry of soil acidity. *Soil acidity and liming, (soilacidityandliming)*, 3-56.
- Warncke, D.D. and F.J. Pierce. 1997. Pelletized lime reacts slower than dolomitic aglime. *Crop and Soil Sciences Newsletter*. 23 (231): 4-6. Michigan State University.
- Watson, M.E., and J.R. Brown. 1998. pH and lime requirement. p. 13-16. In J.R. Brown (ed.) *Recommended chemical soil test procedures for the North Central Region Publ. 221 (rev.)*. Publ. SB 1001. Missouri Exp. Stn., Columbia.
- Warncke, D., and J.R. Brown. 1998. Potassium and other basic cations. p. 31-34. In J.R. Brown (ed.) *Recommended chemical soil test procedures for the North Central Region Publ. 221 (rev.)*. Publ. SB 1001. Missouri Exp. Stn., Columbia.
- Wang, D., and D.W. Anderson. 1998. Direct measurement of organic carbon content in soils by the Leco CR-12 carbon analyzer. *Commun. Soil Sci. Plant Anal.* 29:15-21.

## TABLES AND FIGURES

Table 1. Properties of three soils used in the incubation.

Property	Soil		
	Nicollet	Otley	Fruitfield
Textural class	loam	loamy clay	sand
pH	5.2	5.4	6.0
Buffer pH	6.4	6.4	7.3
Mehlich-3 P, mg kg <sup>-1</sup>	21	27	71
K, mg kg <sup>-1</sup> †	145	156	102
Ca, mg kg <sup>-1</sup> †	2556	2470	615
Mg, mg kg <sup>-1</sup> †	491	481	102
Na, mg kg <sup>-1</sup> †	12	71	61
Clay, g kg <sup>-1</sup>	236	256	22.8
Silt, g kg <sup>-1</sup>	307	612	83
Organic matter, g kg <sup>-1</sup>	44	45.9	12.3
CEC cmol kg <sup>-1</sup>	24.5	23.9	0.85

† Ammonium acetate extraction.

Table 2. Laboratory analysis of the CaCO<sub>3</sub>, calcitic aglime, dolomitic aglime, and pelleted calcitic aglime sources.

Source	Ca	Mg	Passing 4 mesh	Passing 8 mesh	Passing 60 mesh	FF †	CCE	Moisture	ECCE ‡
	----- % -----								
CaCO <sub>3</sub>	99	< 1	100	100	100	100	99	< 1	99.0
Pelleted	45	0.2	100	100	97	98.2	94	1	92.3
Calcitic	42	0.2	100	99	37	61.9	95	< 1	58.8
Dolomitic	22	15	99	88	48	65.1	100	< 1	65.1

† Fineness according to the State of Iowa limestone analysis regulations (IDALS, 2008), with percentage of material passing sieves with Tyler mesh sizes 4, 8, and 60 (4.75, 2.38, and 0.25 mm, respectively). FF, fineness factor defined as amounts passing sieves with mesh 4, 8, and 60 multiplied by the factors of 0.1, 0.3, and 0.6, respectively.

‡ ECCE, effective calcium carbonate equivalent as defined in Iowa (IDALS, 2008)



Table 3. Laboratory analysis of the calcitic and dolomitic aglime fractions.

Mesh†	Calcitic aglime					Dolomitic aglime				
	Ca	Mg	FF‡	CCE §	ECCE¶	Ca	Mg	FF	CCE	ECCE
	----- % -----									
4	41	0.15	10	96	9.6	23	13	10	103	10.3
8	42	0.13	40	97	38.8	23	13	40	102	40.8
20	37	0.15	40	94	37.6	21	12	40	98	39.2
60	42	0.15	100	95	95.0	22	13	100	99	99.0
100	42	0.16	100	95	95.0	22	13	100	100	100

† Material passing through mesh 4 but not 8, through mesh 8 but not 20, through mesh 20 but not 60, through mesh 60 but not 100, and through mesh 100 (4.75, 2.38, 0.85, 0.25, and 0.15 mm, respectively).

‡ FF, fineness factor according to the State of Iowa limestone analysis regulations (IDALS, 2008), defined as amounts passing sieves with mesh 4, 8, and 60 multiplied by 0.1, 0.3, and 0.6, respectively.

§ CaCO<sub>3</sub>, calcium carbonate equivalent

¶ ECCE, effective calcium carbonate equivalent as defined in Iowa (IDALS, 2008).

# Moisture for all mesh sizes was < 1%

Table 4. Soil pH of three soils as affected by commercial liming sources and the incubation period.

Soil	Incubation Period	Source					LSD†
		CaCO <sub>3</sub>	Calcitic aglime	Dolomitic aglime	Pelleted aglime	Control	
	Days	----- Soil pH -----					
Fruitfield	0‡	6.0	6.0	6.0	6.0	6.0	
	7	7.0	6.6	6.1	6.3	6.0	0.24
	21	7.3	7.0	6.7	6.5	6.0	0.38
	35	7.4	6.9	6.9	6.9	5.9	0.40
	70	7.6	7.1	6.8	7.0	5.9	0.15
	105	7.7	7.2	7.0	7.2	6.0	0.20
	140	7.7	7.2	7.0	7.3	6.0	0.16
	175	7.7	7.2	7.0	7.3	6.0	0.06
	210	7.8	7.2	7.1	7.5	6.0	0.11
	Max/Plat§	31	48	210	48	NS¶	
Nicollet	0	5.2	5.2	5.2	5.2	5.2	
	7	6.9	5.6	5.5	6.5	5.2	0.33
	21	7.3	6.3	5.6	6.6	5.2	0.21
	35	7.3	6.5	5.7	6.6	5.2	0.36
	70	7.4	6.7	5.7	6.8	5.2	0.18
	105	7.6	6.7	5.7	7.0	5.2	0.16
	140	7.6	6.8	5.8	7.1	5.2	0.14
	175	7.6	6.8	6.0	7.2	5.2	0.07
	210	7.7	6.8	6.0	7.3	5.2	0.05
	Max/Plat	15	52	210	210	NS	
Otley	0	5.4	5.4	5.4	5.4	5.4	
	7	5.9	5.9	5.4	6.2	5.3	0.35
	21	6.3	6.0	5.5	6.1	5.2	0.27
	35	7.0	5.8	5.7	6.6	5.3	0.21
	70	7.1	5.8	5.8	6.8	5.3	0.29
	105	7.2	6.0	5.9	7.1	5.3	0.14
	140	7.3	6.1	6.1	7.2	5.3	0.23
	175	7.3	6.1	6.2	7.3	5.3	0.17
	210	7.4	6.3	6.2	7.3	5.3	0.21
	Max/Plat	59	210	210	120	NS	

† LSD ( $P \leq 0.05$ )

‡ Initial soil pH value for each soil.

§ Max/Plat, Date when either a maximum was reached by fitting an exponential rise to maximum model or when a plateau was reached by fitting a quadratic plateau model. All models fit ( $P \leq 0.05$ ).¶ NS, no significant model was found to fit ( $P \leq 0.05$ ).

Table 5. Soil pH of three soils as affected by liming with different particle sizes of calcitic and dolomitic aglime and the incubation period.

Soil	Incubation Period	Source												
		Calcitic Mesh Size						LSD†	Dolomitic Mesh Size					LSD
		4	8	20	60	100	4		8	20	60	100		
	Days	Soil pH												
Fruitfield	0‡	6.0	6.0	6.0	6.0	6.0		6.0	6.0	6.0	6.0	6.0		
	7	5.8	6.1	6.2	6.4	6.6	0.25	6.0	6.1	6.1	6.2	6.1	0.49	
	21	6.4	6.6	6.7	6.8	7.0	0.35	6.0	6.2	6.5	6.6	6.7	0.19	
	35	6.6	6.7	7.1	7.2	7.4	0.45	6.1	6.0	6.5	6.6	6.8	0.64	
	70	6.5	6.7	7.1	7.4	7.5	0.13	6.1	6.2	6.7	6.7	7.1	0.07	
	105	6.5	6.8	7.1	7.5	7.7	0.15	6.2	6.3	6.7	6.9	7.3	0.12	
	140	6.5	6.7	7.1	7.6	7.7	0.14	6.2	6.4	6.8	7.0	7.4	0.17	
	175	6.5	6.7	7.1	7.7	7.7	0.05	6.1	6.4	6.8	7.0	7.4	0.05	
	210	6.5	6.8	7.1	7.7	7.7	0.08	6.1	6.4	6.8	7.1	7.5	0.07	
	Max/Plat§		45	48	52	210	60		126	210	77	210	210	
Nicollet	0	5.2	5.2	5.2	5.2	5.2		5.2	5.2	5.2	5.2	5.2		
	7	5.4	5.7	5.8	6.1	6.2	0.48	5.2	5.3	5.3	6.1	6.2	0.36	
	21	5.4	5.6	6.4	6.8	7.2	0.62	5.2	5.3	5.5	6.1	6.3	0.53	
	35	5.5	5.7	6.4	6.6	7.1	0.25	5.3	5.5	5.7	6.2	6.5	0.26	
	70	6.0	6.1	6.5	6.9	7.2	0.18	5.4	5.6	5.7	6.3	6.7	0.12	
	105	6.0	6.1	6.8	7.0	7.4	0.19	5.4	5.7	5.8	6.6	7.0	0.19	
	140	6.1	6.1	6.9	7.1	7.5	0.16	5.5	5.7	5.9	6.6	7.1	0.25	
	175	6.1	6.2	6.8	7.1	7.5	0.05	5.5	5.7	6.0	6.7	7.2	0.05	
	210	6.1	6.2	6.8	7.2	7.6	0.07	5.6	5.7	6.0	6.8	7.2	0.07	
	Max/Plat		210	210	52	210	210		210	120	210	210	210	
Otley	0	5.4	5.4	5.4	5.4	5.4		5.4	5.4	5.4	5.4	5.4		
	7	5.4	5.4	5.5	5.6	6.2	0.30	5.4	5.3	5.4	5.8	6.0	0.21	
	21	5.4	5.4	5.9	6.0	6.6	0.23	5.5	5.5	5.5	6.0	6.2	0.19	
	35	5.6	5.5	6.2	6.3	6.7	0.11	5.5	5.6	5.9	6.1	6.6	0.18	
	70	5.6	5.8	6.2	6.3	6.9	0.17	5.5	5.6	6.1	6.3	6.8	0.18	
	105	5.7	5.9	6.3	6.5	7.1	0.17	5.5	5.7	6.3	6.6	7.1	0.14	
	140	5.7	6.0	6.3	6.6	7.2	0.16	5.6	5.7	6.3	6.7	7.2	0.17	
	175	5.7	6.0	6.3	6.6	7.3	0.06	5.6	5.7	6.3	6.7	7.2	0.05	
	210	5.7	6.0	6.3	6.7	7.3	0.12	5.5	5.7	6.3	6.8	7.2	0.08	
	Max/Plat		210	178	53	60	210		157	147	210	170	103	

† LSD ( $P \leq 0.05$ )

‡ Initial soil pH value for each soil.

§ Max/Plat, Date when either a maximum was reached by fitting an exponential rise to maximum model or when a plateau was reached by fitting a quadratic plateau model. All models fit ( $P \leq 0.005$ ).

Table 6. Efficiency of commercial liming sources at increasing soil pH compared to CaCO<sub>3</sub> for three soils and all incubation periods. †

Soil	Incubation Period Days	Source			LSD‡
		Calcitic aglime	Dolomitic aglime	Pelleted aglime	
Fruitfield	7	58	10	25	36.5
	21	79	58	40	44.1
	35	65	62	61	48.2
	70	68	50	61	10.0
	105	70	59	72	17.9
	140	71	61	76	10.0
	175	69	58	78	3.9
	210	66	61	85	12.2
	Max/Plat§	12	23	210	
Nicollet	7	22	15	79	28.8
	21	54	20	65	16.6
	35	59	24	66	18.9
	70	66	22	73	13.9
	105	63	23	76	9.8
	140	66	25	80	10.5
	175	67	32	81	3.3
	210	66	33	84	3.2
	Max/Plat	40	210	210	
Otley	7	61	10	94	50.3
	21	62	30	75	26.6
	35	24	35	77	12.3
	70	26	33	83	22.9
	105	37	37	95	13.8
	140	36	42	95	18.2
	175	39	44	97	4.7
	210	47	46	100	11.2
	Max/Plat	NS	210	NS	

† Efficiency was calculated using Equation 2 in the Materials and Methods section.

‡ LSD ( $P \leq 0.05$ )

§ Max/Plat, Date when either a maximum was reached by fitting an exponential rise to maximum model or when a plateau was reached by fitting a quadratic plateau model. All models fit ( $P \leq 0.005$ ).

¶ Mean across all soils

# NS, no model was found to statistically fit ( $P \leq 0.005$ ).

Table 6. (Continued).

Soil	Incubation Period Days	Source			LSD
		Calcitic aglime	Dolomitic aglime	Pelleted aglime	
		-----%-----			
Mean	7	47	12	66	24.8
	21	65	36	60	13.7
	35	49	40	68	12.9
	70	53	35	72	9.5
	105	57	40	81	7.6
	140	58	43	84	4.5
	175	59	44	85	1.6
	210	60	47	90	6.6
	Max/Plat	NS	210	210	

Table 7. Efficiency of particle size fractions of calcitic and dolomitic aglime at increasing soil pH compared to CaCO<sub>3</sub> for three soils and all incubation periods. †

Soil	Incubation Period	Source											
		Calcitic Mesh Size						Dolomitic Mesh Size					
		4	8	20	60	100	LSD‡	4	8	20	60	100	LSD
	Days	-----%-----						-----%-----					
Fruitfield	7	-19	9	22	40	56	24.2	-4	11	13	18	11	49.5
	21	31	43	51	63	77	42.6	-2	12	36	47	58	30.9
	35	39	45	76	83	95	39.7	3	1	35	41	56	44.0
	70	30	44	66	86	94	15.8	8	13	42	44	69	9.6
	105	29	44	65	90	96	19.6	11	18	41	52	77	15.2
	140	31	40	67	95	101	11.0	14	23	48	58	81	10.6
	175	29	43	64	99	100	2.3	5	23	46	59	82	2.7
	210	29	42	64	96	97	4.8	5	23	45	63	85	4.7
	Max/Plat§	22	7	129	155	7		126	210	210	210	210	
Nicollet	7	11	30	33	53	62	28.6	-1	4	8	54	62	23.6
	21	9	19	57	74	95	29.7	0	6	14	41	50	25.2
	35	13	22	54	66	90	14.3	2	13	22	46	62	14.9
	70	38	40	61	76	90	8.4	8	19	24	50	68	6.8
	105	33	38	67	74	92	7.7	9	20	26	57	73	8.3
	140	36	39	68	79	95	7.7	12	20	28	59	78	10.7
	175	37	40	65	78	96	2.7	14	21	32	63	83	2.1
	210	38	42	66	82	98	3.1	15	21	34	64	81	2.8
	Max/Plat	210	210	56	210	21		210	103	210	210	210	
Otley	7	3	12	17	49	91	37.7	12	-3	15	76	108	44.7
	21	7	9	58	69	83	14.2	11	11	14	65	81	13.6
	35	13	10	52	59	83	14.5	11	14	30	45	72	14.3
	70	16	27	47	54	86	11.5	9	15	44	56	84	14.5
	105	18	30	50	63	95	8.9	8	18	50	66	94	7.9
	140	17	33	49	65	95	10.6	11	19	49	67	94	12.0
	175	18	34	49	63	96	3.3	12	18	50	68	93	3.3
	210	19	33	50	65	97	5.8	10	17	49	70	94	3.5
	Max/Plat	93	178	17	14	128		115	43	115	86	16	

† Efficiency was calculated by the use of Equation 2 in the Materials and Methods section.

‡ LSD ( $P \leq 0.05$ )

§ Max/Plat, Date when either a maximum was reached by fitting an exponential rise to maximum model or when a plateau was reached by fitting a quadratic plateau model. All models fit ( $P \leq 0.005$ ).

¶ Mean across all soils

Table 7. (Continued).

		Source											
		Calcitic Mesh Size						Dolomitic Mesh Size					
Soil	Incubation Period	4	8	20	60	100	LSD	4	8	20	60	100	LSD
		-----%-----						-----%-----					
Mean	7	-1	17	24	47	70	18.5	2	4	12	50	60	25.0
	21	16	24	55	69	85	23.2	3	10	21	51	63	11.1
	35	22	26	61	69	89	13.8	5	9	29	44	63	13.8
	70	28	37	58	72	90	7.1	8	16	37	50	74	6.3
	105	27	37	61	75	95	5.6	9	19	39	58	81	5.6
	140	28	37	61	79	97	5.8	12	20	42	61	84	5.6
	175	28	39	59	80	97	1.7	10	21	43	63	86	1.2
	210	29	39	60	81	97	1.8	10	20	43	66	86	2.3
	Max/Plat	53	103	29	210	210		153	165	99	210	201	

Table 8. Mean soil pH across three soils for the two longest incubation periods as affected by the liming source and drying/rewetting.

Incubation Period		Source					LSD†
Days	Moisture	CaCO <sub>3</sub>	Calcitic aglime	Dolomitic aglime	Pelleted aglime	Control	
----- pH -----							
175	Constant‡	7.55a	6.72a	6.38a	7.26a	5.54a	0.05
	Dry/rewet	7.64a	6.77b	6.52b	7.41b	5.47a	0.08
210	Constant	7.59a	6.76a	6.44a	7.37a	5.50a	0.06
	Dry/rewet	7.69b	6.84b	6.58b	7.46b	5.41b	0.05
----- pH -----							
		Calcitic Mesh Size					
		4	8	20	60	100	
----- pH -----							
175	Constant	6.10a	6.31a	6.73a	7.13a	7.50a	0.03
	Dry/rewet	6.20b	6.39b	6.80a	7.20a	7.57b	0.09
210	Constant	6.13a	6.33a	6.76a	7.18a	7.54a	0.04
	Dry/rewet	6.25b	6.45b	6.85b	7.24b	7.61b	0.06
----- pH -----							
		Dolomitic Mesh Size					
		4	8	20	60	100	
----- pH -----							
175	Constant	5.74a	5.94a	6.37a	6.82a	7.27a	0.02
	Dry/rewet	5.81b	6.10b	6.46b	6.89a	7.38b	0.08
210	Constant	5.73a	5.94a	6.39a	6.88a	7.30a	0.04
	Dry/rewet	5.85b	6.18b	6.51b	6.92a	7.42b	0.05

† LSD ( $P \leq 0.05$ )‡ pH values with the same letter are not statistically ( $P \leq 0.05$ ) different within each respective source-date combination.



Table 9. Equations that describe relationships in Figs 1-3 between soil pH and incubation period length for fourteen lime treatments (means across three soils).

Source	Fineness	Equation coefficients and statistics †						
		Y0	a	b	R <sup>2</sup> ‡	Model	Max/Plat Date§	Max/Plat pH¶
CaCO <sub>3</sub>	As is	5.61	1.88	0.08	0.96	Exp	210	7.5
Pelleted aglime	As is	5.75	1.50	0.03	0.91	Exp	210	7.2
Calcitic aglime	As is	5.55	0.07	-0.001	0.92	QP	33	6.6
	Pass mesh 4, not 8	5.49	0.01	-0.00007	0.99	QP	94	6.1
	Pass mesh 8, not 20	5.58	0.01	-0.00007	0.98	QP	105	6.3
	Pass mesh 20, not 60	5.52	0.05	-0.0004	0.99	QP	52	6.7
	Pass mesh 60, not 100	5.58	1.50	-0.04	0.98	Exp	210	7.1
	Pass mesh 100	5.59	1.83	-0.06	0.97	Exp	210	7.4
	Dolomitic aglime	As is	5.62	0.01	-0.00004	0.92	QP	137
Pass mesh 4, not 8		5.51	0.003	-9.30E-06	0.98	Quad	162	5.8
Pass mesh 8, not 20		5.54	0.005	-1.49E-05	1.00	Quad	167	6.0
Pass mesh 20, not 60		5.55	0.01	-5.50E-05	0.99	QP	120	6.4
Pass mesh 60, not 100		5.69	1.12	-0.02	0.94	Exp	210	6.8
Pass mesh 100		5.67	1.58	-0.03	0.97	Exp	210	7.2

† Exponential rise to a maximum (Exp),  $Y = Y_0 + a*(1-\exp(-b*X))$ ; Quadratic (Quad),  $Y = Y_0 + aX + bX^2$ ; or Quadratic Plateau (QP),  $Y = Y_0 + aX + bX^2$  for  $X \leq$  the two portions of the model join. All equations fit at  $P \leq 0.001$ .

‡ Adjusted by degrees of freedom.

§ Max/Plat Date, Date when either a maximum was reached by fitting an exponential rise to maximum or quadratic model, or when a plateau was reached by fitting a quadratic plateau model. All models fit ( $P \leq 0.005$ ).

¶ Max/Plat pH, pH when either a maximum was reached by fitting an exponential rise to maximum or quadratic model, or when a plateau was reached by fitting a quadratic plateau model. All models fit ( $P \leq 0.005$ ).

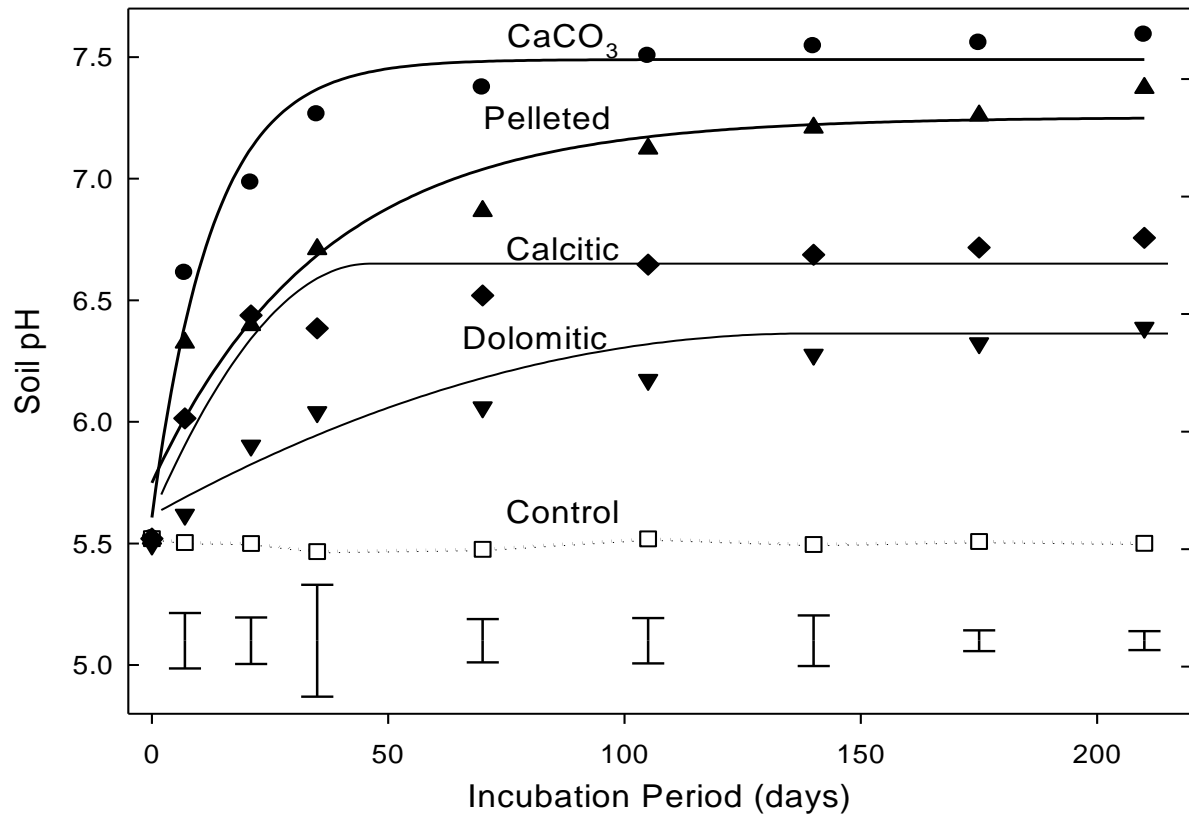


Figure 1. Effect of CaCO<sub>3</sub>, calcitic aglime, dolomitic aglime, pelleted calcitic aglime, and an untreated control on soil pH over time (averages across three soils). Vertical bars represent least significant differences (LSD) for each incubation period ( $P \leq 0.05$ ).

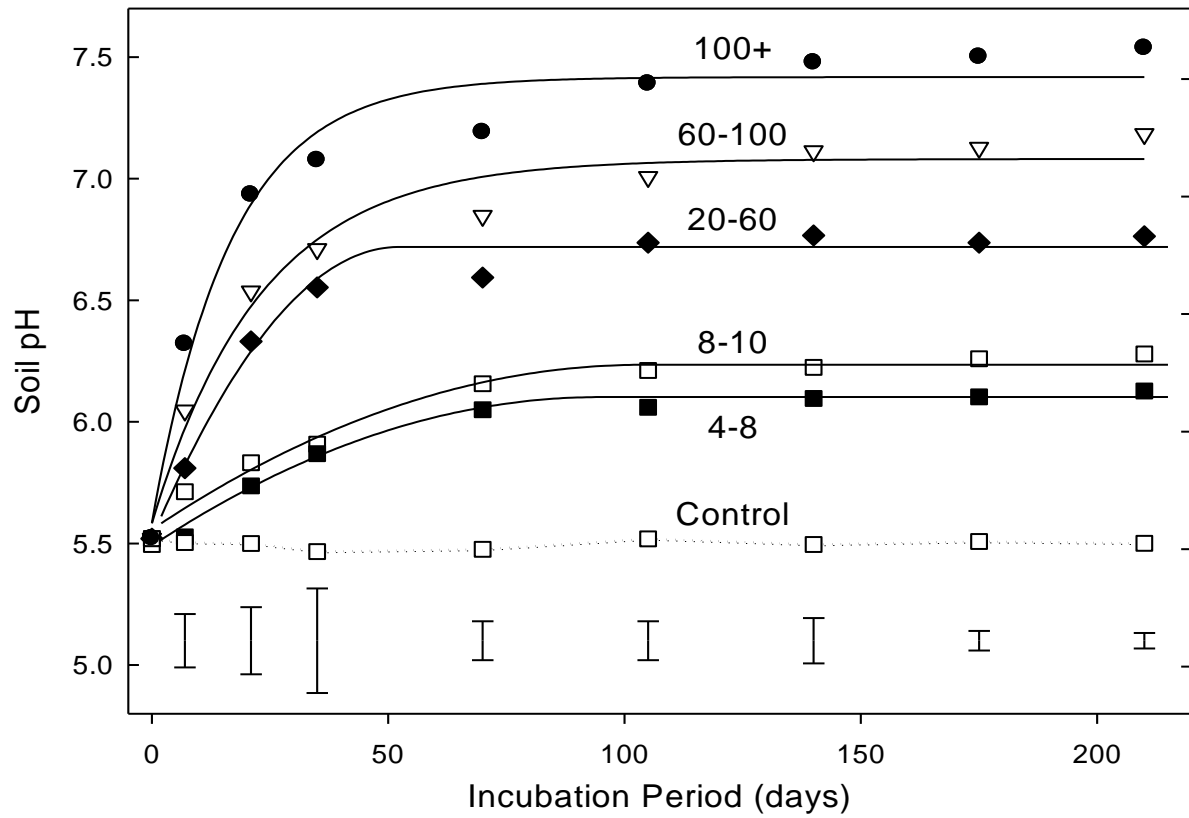


Figure 2. Effect of five fineness fractions of calcitic aglime and an untreated control on soil pH over time (averages across three soils). Vertical bars represent least significant differences (LSD) for each incubation period ( $P \leq 0.05$ ).

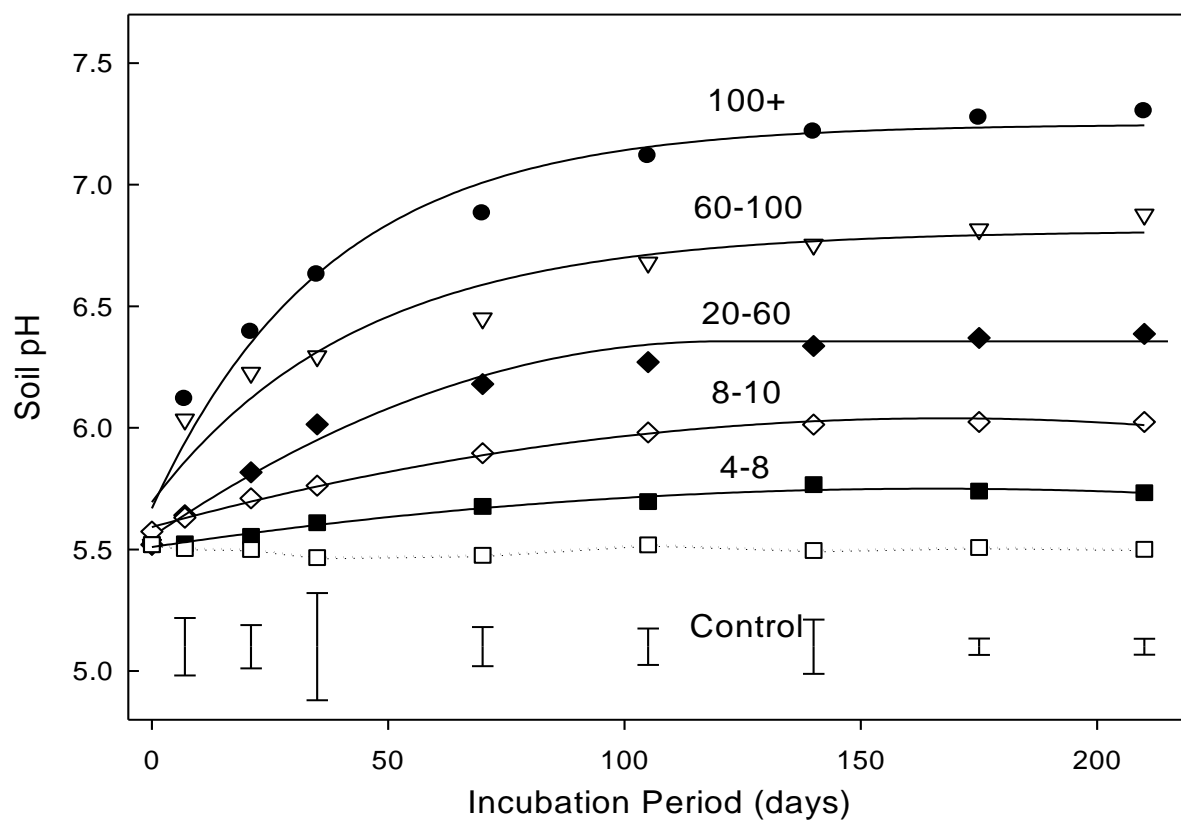


Figure 3. Effect of five fineness fractions of dolomitic aglime and an untreated control on soil pH over time (averages across three soils). Vertical bars represent least significant differences (LSD) for each incubation period ( $P \leq 0.05$ ).

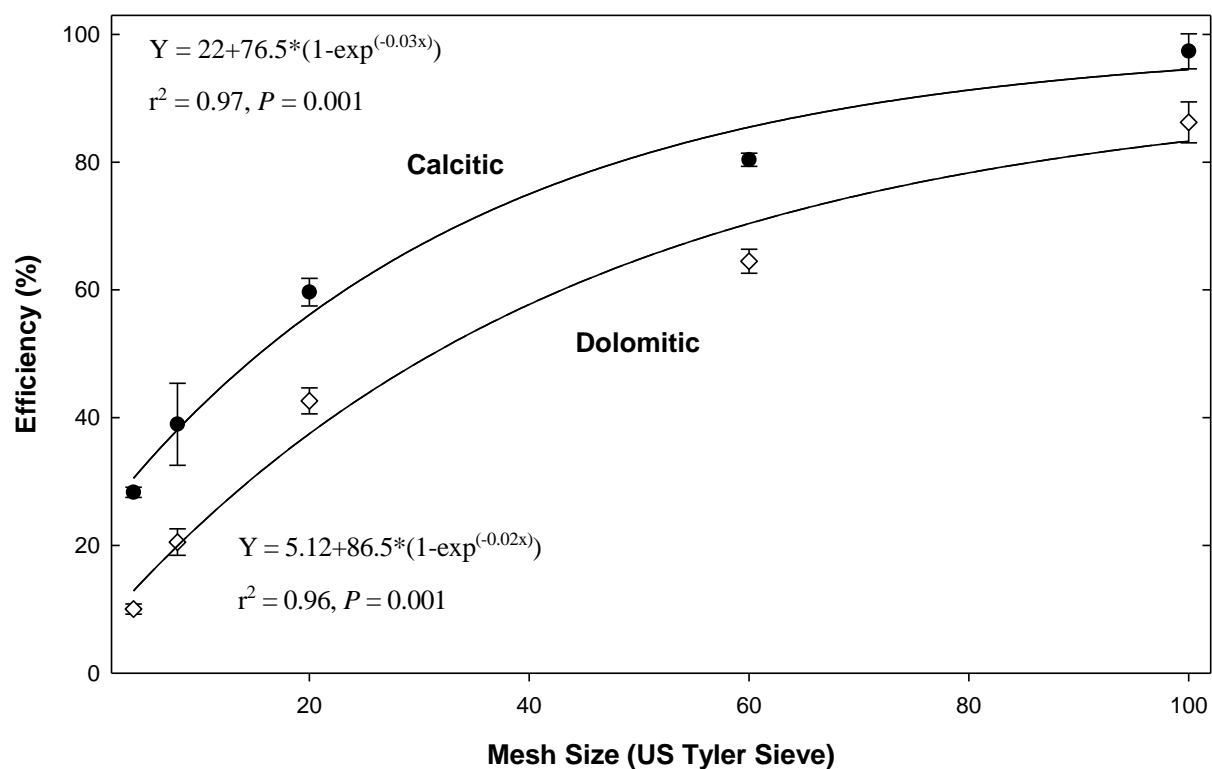


Figure 4. Efficiency of different fineness fractions of calcitic and dolomitic aglime at increasing soil pH. Averages for the two longest incubation periods (25 and 30 weeks) and across three soils. Vertical bars represent least significant differences (LSD) for each fineness fraction ( $P \leq 0.05$ ).

### CHAPTER 3. GENERAL CONCLUSION

The objective of this study was to evaluate the effect of particle size on efficiency at increasing soil pH of commercial calcitic and dolomitic agricultural lime (aglime) compared with pure ground  $\text{CaCO}_3$  and a commercial calcitic pelleted lime. Both aglime sources were fractionated to pass five mesh fractions of varying sizes. All commercial lime sources and the calcitic and dolomitic fineness fractions increased soil pH above the control by the longest incubation period.  $\text{CaCO}_3$  increased pH the most rapid and reached the greatest maximum for all sources. Pelleted aglime increased soil pH more than both aglime sources, and was statistically significant to the  $\text{CaCO}_3$  for one soil. The calcitic and dolomitic aglime sources were significantly similar for two of the three soils, but the calcitic aglime reached a plateau more quickly for all soils when means of the three soils were fit to models. Models fit to means across soils showed that from the 70-day incubation and longer, all commercial sources differed and the  $\text{CaCO}_3$  and pelleted aglime exponentially increased to a maximum at the longest date. The fineness of each mesh size fractions influenced the maximum pH attained for both calcitic and dolomitic sources, but the time to reach either maximum values or plateaus varied across treatments. Means across soils for both calcitic and dolomitic fractions showed that the two finest fractions continued to increase pH to the longest period, while the three coarsest fractions either reached plateaus or pH began to decrease. The efficiency of all fineness fractions for both sources increased exponentially with decreasing increments toward a maximum as mesh size increased (particle size decreased). The calcitic mesh fractions were always more efficient than the comparable dolomitic fraction of the same size. The results from this study show that soil, aglime source, particle fineness, and the duration that the material reacts with the soil are essential variables when using liming material for agricultural soil pH management.

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