

**Searching for the Best Methodology to  
Determine Lime Requirement of Selected Puerto Rican Soils**

By

Emmanuel Feliciano Justiniano

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Approved by:

\_\_\_\_\_  
Julia M. O'Hallorans, Ph.D.  
Member, Graduate Committee

\_\_\_\_\_  
Date

\_\_\_\_\_  
Victor Snyder, Ph.D.  
Member, Graduate Committee

\_\_\_\_\_  
Date

\_\_\_\_\_  
Miguel A. Muñoz, Ph.D.  
President, Graduate Committee

\_\_\_\_\_  
Date

\_\_\_\_\_  
Sandra L. Maldonado, Ph.D.  
Graduate Studies Representative

\_\_\_\_\_  
Date

\_\_\_\_\_  
Hipólito O'Farril, Ph.D.  
Department Director

\_\_\_\_\_  
Date

## Abstract

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The accuracy of six methods to estimate lime requirement was evaluated using ten acid soil series from Puerto Rico. The methods selected for the research were soil-lime incubation, buffer solutions (Shoemaker-McLean-Pratt, Sikora, Adams-Evans and Mehlich) and an estimate based on exchangeable  $Al^{3+}$  content. Soil samples of Consumo (*Typic Haplohumults*), Corozal (*Typic Hapludults*), Lares (*Aquic Paleudults*), Humatas (*Typic Haplohumults*), Catalina (*Typic Hapludox*), Los Guineos (*Humic Hapludox*), Bayamón (*Typic Hapludox*), Dagüey (*Inceptic Hapludox*), Alonso (*Oxic Dystrudepts*) and Múcara (*Dystric Eutrudepts*) series were collected at two depths (0-20 cm and 20-40 cm). Lime requirement values were estimated using a target pH of 6.5. The soil-lime incubation was the reference method to perform the statistical analysis.

The soil-lime incubation method showed lime requirement values ranging from 3.94 to 38.88 Mg ha<sup>-1</sup>. Adams-Evans buffer showed lime requirement values varying from 3.60 to 12 Mg ha<sup>-1</sup>. Mehlich buffer recommended lime in a range from 1.70 to 25.80 Mg ha<sup>-1</sup>. Exchangeable  $Al^{3+}$  method showed lime requirement values ranging from 0.22 to 16.57 Mg ha<sup>-1</sup>. SMP buffer showed lime requirement estimates varying from 5.60 to 41.60 Mg ha<sup>-1</sup>. Sikora buffer showed lime requirement values ranging from 4.70 to 41.66 Mg ha<sup>-1</sup>. Adams-Evans buffer, Mehlich buffer and exchangeable  $Al^{3+}$  methods provided lower lime requirement values than soil-lime incubation method for all soils. The highest lime requirement values were obtained with the SMP and Sikora buffers. Both of these methods gave similar lime requirement values. Pearson correlation coefficients indicated a good correlation between soil-lime incubation method and the SMP (0.88) and Sikora (0.85) buffer methods. Both methods also showed good linear relation with soil-lime incubation method. Sikora buffer seems to be the best alternative to estimate lime requirement of the soils included in this research due to its notable advantages.

## Resumen

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La efectividad de seis métodos para estimar el requisito de encalado fue evaluada utilizando diez series de suelos ácidos de Puerto Rico. Los métodos seleccionados para la investigación fueron incubación suelo-cal, soluciones amortiguadoras (Shoemaker-McLean-Pratt [SMP], Sikora, Adams-Evans y Mehlich) y un estimado del requisito de encalado basado en el contenido de  $Al^{3+}$  intercambiable del suelo. Los suelos analizados correspondían a las series Consumo (*Typic Haplohumults*), Corozal (*Typic Hapludults*), Lares (*Aquic Paleudults*), Humatas (*Typic Haplohumults*), Catalina (*Typic Hapludox*), Los Guineos (*Humic Hapludox*), Bayamón (*Typic Hapludox*), Dagüey (*Inceptic Hapludox*), Alonso (*Oxic Dystrudepts*) and Múcara (*Dystric Eutrudepts*). Todos los suelos fueron colectados a dos profundidades (0-20 cm y 20-40 cm). Los valores del requisito de encalado fueron estimados utilizando un pH óptimo de 6.5. El método incubación suelo-cal fue utilizado como el método de referencia para realizar los análisis estadísticos.

El método incubación suelo-cal mostró valores del requisito de encalado en un rango de 3.94 a 38.88 Mg ha<sup>-1</sup>. La solución amortiguadora Adams-Evans mostró estimados del requisito de encalado variando desde 3.60 hasta 12.0 Mg ha<sup>-1</sup>. En cuanto a la solución amortiguadora Mehlich, este método recomendó cal en un rango de 1.70 hasta 25.80 Mg ha<sup>-1</sup>. El método  $Al^{3+}$  intercambiable mostró valores del requisito de encalado en un rango de 0.22 hasta 16.57 Mg ha<sup>-1</sup>. La solución amortiguadora SMP mostró estimados del requisito de encalado variando de 5.60 hasta 41.60 Mg ha<sup>-1</sup>. La solución amortiguadora Sikora mostró valores del requisito de encalado en un rango de 4.70 hasta 41.66 Mg ha<sup>-1</sup>. Las soluciones amortiguadoras Adams-Evans y Mehlich, y el método  $Al^{3+}$  intercambiable mostraron valores de requisito de encalado menores que el método incubación suelo-cal para todos los suelos. Por el contrario, las soluciones

amortiguadoras SMP y Sikora estimaron valores de requisito de encalado mayores que el método incubación suelo-cal. Estas soluciones amortiguadoras mostraron valores similares de requisito de encalado. El análisis de correlación Pearson mostró altos coeficientes de correlación entre el método incubación suelo-cal y las soluciones amortiguadoras SMP y Sikora (0.88 y 0.85, respectivamente). Ambas soluciones presentaron buena relación lineal con el método incubación suelo-cal. La solución amortiguadora Sikora parece ser la mejor alternativa para realizar recomendaciones de encalado para los suelos incluidos en esta investigación debido a sus notables ventajas.

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## Introduction

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Soil acidity is one of the most common problems in many tropical and temperate regions. Approximately 25 to 30% of worldwide soils are acids and occur in some of the world most important food-producing regions (Havlin et al., 1999). In the tropics, acid soils represent one third or 1.7 billion hectares (Harter, 2002). In Puerto Rico, there are about 50 soil series with low pH values, where crop production will be limited significantly. It is important to understand the causes and effects of the acidification process. The main sources of soil acidity are the effect of respiration and nutrient uptake processes by plants, organic matter decomposition, oxidation reactions, fertilization (especially fertilizers with ammonium and phosphate) and weathering processes (Harter, 2002). Among the conditions associated with an acid soil are loss of soil negative charge, low availability of basic ions and phosphorus, and high concentration of exchangeable aluminum. Also, under extremely acid conditions some micronutrients in the soil solution can reach toxic levels to plants. In addition, acid soils represent an adverse environment for most microorganisms.

Soil acidity can be reduced by the application of liming materials, such as calcium carbonate ( $\text{CaCO}_3$ ), calcium hydroxide [ $\text{Ca}(\text{OH})_2$ ], calcium oxide ( $\text{CaO}$ ) and dolomite [ $\text{CaMg}(\text{CO}_3)_2$ ]. The selection of the best amendment greatly depends on availability and cost of these materials. How much liming material is needed to reduce soil acidity is determined by soil type. This quantity is typically called *lime requirement*. Sims (1996) introduced a most complete definition for lime requirement:

“... is defined as the amount of agricultural limestone or other basic material needed to increase the pH of the soil from an unacceptably acidic condition to a value that is considered optimum for the desired use of the soil.”

Several methods have been proposed to estimate lime requirement for soils, including field studies, soil-lime incubations, soil-base titrations, buffer solutions, exchangeable aluminum content and estimates based on soil properties (McLean, 1982; Sims, 1996). The effectiveness of each technique greatly depends on soil properties. Failure in determining the exact lime requirement of a particular soil will induce negative results. For example, low lime recommendations may result in time and economical losses, whereas high quantities may result in overliming. The application of excessive amounts of lime may decrease soil permeability and drainage, and increase some ion concentrations to toxic levels.

In Puerto Rico, there is not reliable and recent published data on the best methods to determine lime requirement. The techniques used at present are variants of the soil-lime incubation method (Riera, 1946; Abruña and Vicente, 1955; Muñiz, 1987). These techniques are tedious, time consuming and the results vary significantly depending on the period of incubation. There is a need for methodology less time consuming, reliable and easy to perform under laboratory conditions. The objectives of this study were to evaluate the accuracy of different methods to estimate the lime requirement of acid soils from Puerto Rico, and to provide a fast, simple and effective test for lime requirement recommendations.

## Considerations about the Methods

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Several techniques have been developed to estimate the lime requirement of soils. The most recognized methods include the following: field studies, soil–lime incubations, soil–base titrations, buffer solutions, exchangeable aluminum content and estimates based on selected soil properties (McLean, 1982; Sims, 1996). The accuracy of all methods is associated with soil characteristics. However, each technique presents advantages and limitations that control its use in soil testing laboratories.

Field lime response studies (Figure 1) are realized by adding increasing quantities of lime to the soil, allowing sufficient time for soil–lime reaction and measuring the change in soil pH at each lime level (Sims, 1996). The data obtained (soil pH and lime quantity) is used to create a curve from which the lime requirement is determined. It is maybe the most accurate method because the study is carried out under the environmental conditions prevailing in the zone of interest. The main limitations of field studies are the high cost and time involved, and the inability to analyze a great number of soils at the same time. This method is not appropriate for routine use, however, field lime response studies are useful to corroborate other lime requirement tests.

Soil–lime incubations are similar to field studies in terms of the procedure. The difference is that soil–lime incubations use a specific weight of soil mixed with increasing proportions of lime (Figure 2). The mixture is incubated in appropriated containers under laboratory conditions and moisture adjusted to field capacity. The incubation period can be for several weeks or months. At the end of the incubation period, changes in soil pH are determined and a lime curve is developed with pH and lime rates. The lime requirement is obtained from the curve. This technique is very useful to estimate lime requirement of soils with different physical

and chemical properties (Sims, 1996). In contrast to field studies, several soils can be evaluated simultaneously with this method. The problem with soil-lime incubations is the inadequacy for



Figure 1. Lime application to Corozal soil.

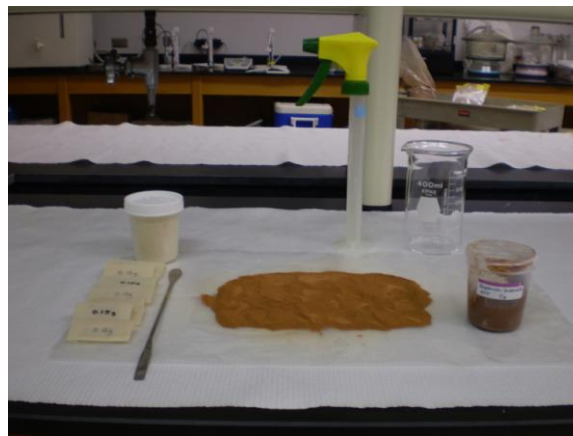


Figure 2. Materials used in soil-lime incubation method.

routine use in laboratories because the long time required to reach equilibrium between soil and liming material. Also, there is not a pre-established period of time for incubation and results can vary depending on the soil type.

Soil–base titrations consist of equilibrating soils with a basic solution to reach both active and potential acidity (Figure 3). This technique can be performed by suspending the soil with an unbuffered concentrated salt solution (for example KCl), adding a basic solution to the soil–salt mixture, waiting enough time for soil–base equilibration to take place and determine soil pH (Sims, 1996). Lime requirement is calculated from a titration curve prepared with soil pH and the quantity of base added. The basic solution, usually calcium hydroxide or sodium hydroxide, will be added by direct titration or by increasing levels of base used to equilibrate separate portions of soil–salt mixture. The latter procedure is the most utilized. Soil–base titrations present the same limitation of soil–lime incubations, the long time required for the soil and base mixture to achieve equilibrium (Abruña and Vicente, 1955). Another problem with soil–base titrations is the

need of conversion factors to correctly estimate lime requirements values. Despite limitations, titration and incubation procedures are very important to calibrate rapid lime requirement tests. Liu et al. (2004) presented a simplified titration method that could be used as fast test by soil testing laboratories. The method consists of adding a few aliquots of a base [ $\text{Ca}(\text{OH})_2$ ] to a soil sample in 30 min intervals and generate a curve with the obtained pH values and the applied amounts of the base. The curve is used to estimate the lime requirement of the soil by linear extrapolation.

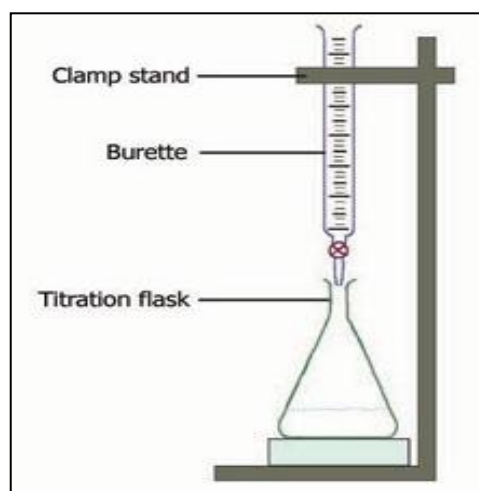


Figure 3. Instruments used in soil-base titration studies.

From the 1940s to 1970s, there was an effort to eliminate the problem with field, incubation and titration techniques. Buffer methods were introduced as a substitute procedure to determine lime requirement (Woodruff, 1948; Shoemaker et al., 1961; Adams and Evans, 1962; Yuan, 1974; Mehlich, 1976; McLean et al., 1977). Buffer methods or soil-buffer equilibrations consist of a mixture of the soil sample with a buffer solution (Figure 4), followed by an equilibration period of several minutes and measurement of the pH of the soil-buffer mixture (McLean, 1982; Sims, 1996). For each buffer method, there is a calibration table where the lime

requirement for attaining a desired soil pH can be determined based on the measured soil–buffer pH. The buffer pH decreases in a linear manner as soil acidity reacts with the solution (Sims, 1996), thus the decrease in buffer pH is a direct measure of the acidity to be neutralized and soil lime requirement.

The most utilized buffer methods in the USA are the Shoemaker, McLean and Pratt (SMP) single buffer method (Shoemaker et al., 1961) and the Adams-Evans buffer method (Adams and Evans, 1962). SMP buffer is used in the western region while Adams-Evans buffer is used in the southeastern and mid–Atlantic regions. The SMP method is recommended for soils



Figure 4. Buffer solution used to determine lime requirement.

with a lime need  $> 4.5 \text{ Mg ha}^{-1}$ , pH values  $< 5.8$ , organic matter contents  $< 10 \%$  and appreciable quantities of extractable Al (McLean et al., 1966; Sims, 1996). The Adams-Evans method is especially adapted for soils with low buffer capacity, which means soils with low cation exchange capacity, small amounts of 2:1 clays and low organic matter contents (Sims, 1996). Some researchers have developed “double buffer methods” with the intention of obtain more accurate lime recommendations (Yuan, 1974; McLean et al., 1977). Nevertheless, these modified

procedures involve more reagents, equipment, time and complex calculations that exclude its use in routine soil testing laboratories. Certainly, the single buffer methods, if properly conducted, bring very accurate lime requirements values (Tran and van Lierop, 1982).

Buffer solutions methods present several advantages. First, these tests are reliable, easy to perform and provide results in a short period of time. Second, buffer methods allow to analyze many soil samples and different soils at the same time. Finally, it does not require complicated calculations. However, some researchers questioned the use of buffer solutions because of the toxicity of some chemical components. These components are p-nitrophenol, barium and chromium (Liu et al., 2004; Huluka, 2005; Sikora, 2006; Sikora and Moore, 2008).

New buffer solutions have been developed without hazardous chemicals. Huluka (2005) replaced p-nitrophenol in the Adams-Evans buffer with monobasic potassium phosphate ( $\text{KH}_2\text{PO}_4$ ). This modification of the Adams-Evans buffer showed to be as effective as the original solution in the determination of lime requirement for 407 Alabama soil samples. Sikora (2006) found that chromium and p-nitrophenol in the SMP buffer can be replaced by 2-(N-morpholino)ethanesulfonic acid monohydrate (MES) and imidazole, respectively. The new buffer developed by Sikora produced a similar soil-buffer pH as the SMP buffer on 255 Kentucky soils and 87 North American Proficiency Testing (NAPT) soils and showed no change in effectiveness after a long period of storage. Sikora and Moore (2008) modified the Adams-Evans buffer by replacing p-nitrophenol with 3-(N-morpholino) propanesulfonic acid (MOPS) and MES. They found 44% of 222 South Carolina soils and 41 NAPT soils showed no difference in lime requirement among the two buffers.

Several studies have been conducted to compare different buffer methods. Alabi et al. (1986) evaluated the effectiveness of eight buffer methods (SMP single buffer, SMP double buffer, SMP adaptation method, Adams-Evans buffer, original Woodruff buffer, modified



Woodruff method, Yuan buffer and Peech buffer) to predict lime requirement in coarse textured soils. Lime requirement values determined by the three SMP methods and the Adams-Evans method were the most highly correlated with the lime values from incubation method. Lime requirements from the other methods presented less correlation with those from the incubation technique. Tran and van Lierop (1982) studied the ability of the SMP, Yuan, Woodruff and Mehlich buffer methods to measure the lime requirements needed to attain soil pH values of 5.5 and 6.0. The precision of the SMP and Yuan buffer methods increased as the initial buffer pH approached the desired soil pH. The Woodruff method was effective to estimate lime requirements to attain pH 6.0, whereas the Mehlich buffer was very precise to determine lime requirements for pH 5.5. Other research findings in this topic are presented by McLean et al. (1966), Webber et al. (1977), Fox (1980), Ssali and Nuwamanya (1981), Tran and van Lierop (1981), Doerge and Gardner (1988) and Godsey et al. (2007).

Another technique to estimate lime requirement for soils is to apply sufficient lime to neutralize exchangeable aluminum, which is the  $Al^{3+}$  fraction extracted with a neutral unbuffered salt solution like 1 N KCl (Kamprath, 1970; Reeve and Sumner, 1970; McLean, 1982; Sims, 1996). This method is utilized for highly weathered acid soils (Ultisols and Oxisols), where  $Al^{3+}$  is the predominant exchangeable cation when soil pH is 5.0 or less. A high  $Al^{3+}$  concentration in the soil solution is associated with poor plant growth because the detrimental effect of  $Al^{3+}$  on the root elongation (Kamprath, 1970; Evans and Kamprath, 1970). This is the reason why some researchers argue that if  $Al^{3+}$  is the primary yield-limiting factor in soil, the concentration of this element will be used as a good index for the required lime to improve soil conditions. When this method is used, a lower soil pH is attained than the values obtained by other techniques because exchangeable  $Al^{3+}$  is practically neutralized at pH 5.5. This procedure is really appropriate for

areas with limited quantities of liming materials (Sims, 1996) or when the cost of liming material is too high.

Despite the apparent advantages of the exchangeable  $\text{Al}^{3+}$  content method, the opinions of researchers are divided. Kamprath (1970) noted the convenience of using exchangeable  $\text{Al}^{3+}$  as a criterion for estimate lime requirements of highly weathered soils. In the study, Kamprath mentioned that optimum growth of several crops occurs when pH is in the range of 5.6 – 6.0. At these pH values almost all of the exchangeable  $\text{Al}^{3+}$  is neutralized. Also, Kamprath showed that a factor of 1.5 or 2 should be used to obtain better lime recommendations and low  $\text{Al}^{3+}$  saturation for crops with certain tolerance and crops very sensitive to  $\text{Al}^{3+}$ , respectively. Reeve and Sumner (1970) found that lime rates higher than values required to inactivate exchangeable  $\text{Al}^{3+}$  did not increased the available P fraction in soils. In addition, the lime requirement at which the maximum yield of *Sorghum sudanense* occurred was in good agreement with lime required to neutralize exchangeable  $\text{Al}^{3+}$ .

McLean (1970) questioned the use of exchangeable  $\text{Al}^{3+}$  as an index to estimate lime requirements of soils and presented three reasons for applying more lime than the amount required to eliminate exchangeable  $\text{Al}^{3+}$  in soils. The reasons are: (1) more Ca and Mg are available for plants, (2) at higher pH values the supplies of Ca, Mg, P, K, S, B, Cu and Zn by the soil increase and (3) biological activity is increased (McLean, 1970). Sims (1996) suggested that exchangeable  $\text{Al}^{3+}$  content method is not used by soil testing laboratories because the time and the high cost of analyzing soil samples and the presence of other yield-limiting factors. These factors include high concentrations of other toxic elements (Mn), low levels of exchangeable bases, reduced biological activity and lower efficacy of pesticides (Sims, 1996). Amedee and Peech (1976b) evaluated the use of KCl as extractant for exchangeable  $\text{Al}^{3+}$  and found that concentration of the salt directly affect the amount of extracted  $\text{Al}^{3+}$ . The authors concluded the

use of KCl-extracted  $\text{Al}^{3+}$  may be an erroneous evaluation of lime requirement for soils of the humid tropics. Moreover, in another study Amedee and Peech (1976a) noted that the amount of exchangeable  $\text{Al}^{3+}$  extracted by 1 N KCl underestimated the lime requirement of highly weathered tropical soils.

A less common technique to estimate the lime needs of acid soils is to use some chemical and physical properties of soil, which are associated with its buffer capacity. Typically these properties are soil pH, texture, cation exchange capacity and organic matter content. The basis of this method is to correlate measured soil properties with lime requirement obtained by another technique, normally incubation method, and then develop an equation that shows this relation. Keeney and Corey (1963) evaluated the effect of several soils properties on the lime requirements of Wisconsin soils and found that pH along with organic matter content were the best factors predicting lime needs of these soils. Lugo et al. (1952) analyzed 17 soils from Puerto Rico and noted that lime requirements were well correlated with soil pH and cation exchange capacity when the predominant clay mineral was kaolinite. Ross et al. (1964) studied the ability of some soil properties to predict lime requirement of nine Michigan soils. They concluded that clay content, organic matter, exchangeable hydrogen and cation exchange capacity are in good correlation with lime requirement determined by incubation. Curtin et al. (1984) found a significant correlation between lime requirement and organic matter.

## Materials and Methods

### I. Lime Requirement Methods

Six lime requirement methods were evaluated in this study. These methods were the soil-lime incubation, SMP buffer, Adams-Evans buffer, Mehlich buffer, Sikora buffer and exchangeable  $Al^{3+}$  content.

The soil-lime incubation method was performed mixing 75 g of soil with increasing quantities of agricultural limestone with 99 % of calcium carbonate (Figure 5). The quantities of agricultural limestone used were (grams): 0, 0.015, 0.030, 0.045, 0.060, 0.075, 0.15, 0.30, 0.45, 0.60, 0.80, 1.0, 1.5 and 2.0. These quantities are equivalent to limestone applications of 0 to 60  $Mg\ ha^{-1}$ . After mixing, the samples were moistened with distilled water to reach field capacity, placed in 120 mL polyethylene containers (Figure 6) and weighted. The containers were covered with perforated parafilm to allow gas exchange and incubated for four weeks. Every four days, the sample's moisture content was adjusted to field capacity. At the end of incubation period, the samples were allowed to dry at room temperature and ground. The pH of soil-lime mixtures was determined in a



Figure 5. Agricultural limestone used in soil-lime incubation.



Figure 6. Soil samples under incubation process.

1:1 soil:distilled water ratio and measured using an Orion Model 310 pH meter. A calibration curve was prepared plotting pH against applied lime quantity (Figure 7). Lime requirement to achieve a soil pH of 6.5 was obtained from the calibration curve. The 6.5 value was selected because at this pH most crops perform best, toxicity problems of Al and Mn are nil as well as deficiency of macro and micronutrients.

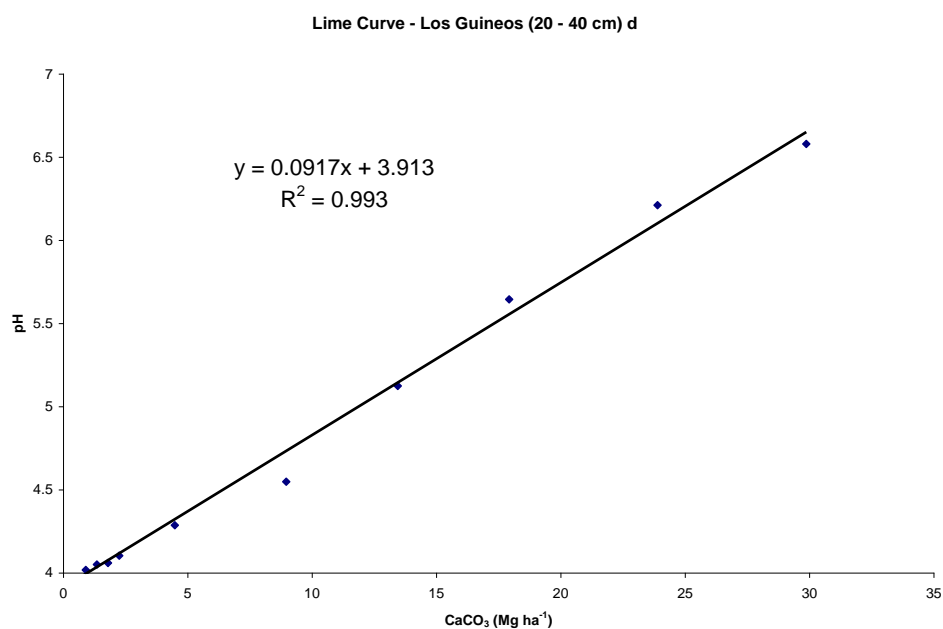


Figure 7. An example of a calibration curve used in soil-lime incubation studies to determine lime requirement. Calibration curves for all soils are showed in Appendix I.

The Adams-Evans buffer solution was prepared as described by Sims (1996). Buffer components are potassium chloride (KCl), potassium hydroxide (KOH), p-nitrophenol ( $\text{OH}\cdot\text{C}_6\text{H}_4\cdot\text{NO}_2$ ) and boric acid ( $\text{H}_3\text{BO}_3$ ). Buffer pH was adjusted to  $8.0 \pm 0.1$ . The Adams-Evans method was performed placing 10 g of soil into 50 mL centrifuge tubes. Ten milliliters of distilled water were added to the tubes and were shaken for 10 minutes. Soil pH was measured using the same pH meter previously mentioned. Ten milliliters of the Adams-Evans buffer were added to soil-water mixture. The samples

were shaken for 10 minutes and allowed to stand for 30 minutes. Soil-buffer mixtures pH was determined. Both values, soil-water pH and soil-buffer pH, were used to estimate soil lime requirement from the calibration table (Table 1). Target pH was 6.5.

Table 1. Calibrations to determine soil lime requirement using the Adams-Evans buffer method (Sims, 1996).

Soil pH in Water	Soil pH in Adams-Evans Buffer Solution				
	7.8	7.6	7.4	7.2	7.0
----- Ag-ground Limestone -----					
<u>Target pH in Water = 6.0</u>					
5.9	0.2	0.4	0.5	0.7	0.9
5.7	0.5	1.0	1.4	1.0	2.4
5.5	0.7	1.5	2.2	2.9	3.7
5.3	1.0	1.9	2.9	3.8	4.8
5.1	1.2	2.3	3.4	4.6	5.7
4.9	1.3	2.6	4.0	5.3	6.6
4.7	1.5	3.0	4.5	6.0	7.5
4.5	1.7	3.3	5.0	6.7	8.4
<u>Target pH in Water = 6.5</u>					
6.3	0.5	1.0	1.5	2.0	2.5
6.1	0.9	1.7	2.6	3.5	4.4
5.9	1.2	2.3	3.5	4.7	5.9
5.7	1.4	2.8	4.3	5.7	7.1
5.5	1.6	3.3	4.9	6.5	8.1
5.3	1.8	3.6	5.4	7.2	9.0
5.1	2.0	3.9	5.9	7.9	9.8
4.9	2.1	4.2	6.3	8.4	10.5
4.7	2.2	4.5	6.7	9.0	11.2
4.5	2.4	4.8	7.2	9.6	12.0

The SMP buffer solution was prepared as described by Sims (1996). Chemical constituents of this buffer are: p-nitrophenol ( $\text{OH}\cdot\text{C}_6\text{H}_4\cdot\text{NO}_2$ ), potassium chromate ( $\text{K}_2\text{CrO}_4$ ), calcium chloride dehydrate ( $\text{CaCl}_2\cdot 2\text{H}_2\text{O}$ ), calcium acetate [ $\text{Ca}(\text{OAc})_2$ ], and triethanolamine [ $\text{N}(\text{CH}_2\text{CH}_2\text{OH})_3$ ]. Buffer pH was adjusted to  $7.5 \pm 0.02$ . The SMP buffer was stored in a polyethylene bottle connected to two 2 $\frac{5}{8}$ " x 11 $\frac{3}{8}$ " cylinders of

drierite and a 2<sup>5</sup>/<sub>8</sub>” x 11<sup>3</sup>/<sub>8</sub>” cylinder of ascarite to avoid contamination of the solution with CO<sub>2</sub> and H<sub>2</sub>O vapor (Figure 8). The SMP method was performed placing 5 g of soil into 50 mL centrifuge tubes. Five milliliters of distilled water were added to the tubes and samples were shaken for 10 minutes. After shaking, samples pH was measured with the same instrument previously described. Ten milliliters of the SMP buffer were added to the tubes. The samples were shaken for 10 minutes and allowed to stand for 30 minutes. The soil-buffer pH was determined. Lime requirement to attain pH 6.5 was estimated from the calibration table (Table 2) using soil-buffer pH values.



Figure 8. SMP buffer storage using drierite (blue) and ascarite cylinders to protect against CO<sub>2</sub> and H<sub>2</sub>O vapor contamination.

The Mehlich buffer solution contained glacial acetic acid (CH<sub>3</sub>COOH), triethanolamine [N(CH<sub>2</sub>·CH<sub>2</sub>OH)<sub>3</sub>], ammonium chloride (NH<sub>4</sub>Cl), barium chloride dehydrate (BaCl<sub>2</sub>·2H<sub>2</sub>O) and sodium glycerophosphate [(HOCH<sub>2</sub>)<sub>2</sub>CHOPO<sub>3</sub>Na<sub>2</sub>·5H<sub>2</sub>O]. Sims (1996) presents the amounts of each reagent required to prepare the solution. The Mehlich buffer pH was adjusted to 6.60 ± 0.04. This method was performed mixing 10 g

Table 2. Calibrations to determine soil lime requirement using the SMP buffer method (Sims, 1996).

Soil-Buffer pH	Quantity of liming material (Mg ha <sup>-1</sup> ) required to reach desired pH				
	7.0	<u>Mineral Soils</u>		<u>Organic Soils</u>	
		7.0	6.5	6.0	5.2
	Pure CaCO <sub>3</sub>	----- Ag-ground Limestone† -----			
6.8	2.4	3.2	2.7	2.3	1.5
6.7	4.1	5.3	4.7	3.8	2.9
6.6	5.3	7.6	6.5	5.3	4.0
6.5	7.0	10.1	8.5	7.0	5.3
6.4	9.0	12.3	10.5	8.5	6.5
6.3	10.5	14.6	12.3	10.1	7.8
6.2	12.1	16.8	14.3	11.6	9.0
6.1	13.4	19.2	16.1	13.2	10.3
6.0	15.2	21.5	18.1	14.8	11.4
5.9	17.2	23.8	20.1	16.3	12.8
5.8	18.6	26.2	21.9	17.9	13.9
5.7	20.1	28.5	23.9	19.5	15.0
5.6	21.8	30.6	26.0	21.0	16.3
5.5	23.3	33.2	28.0	22.8	17.5
5.4	25.3	35.4	30.0	24.4	18.8
5.3	26.7	37.8	31.8	26.0	19.9
5.2	28.5	40.1	33.8	27.6	21.0
5.1	30.2	42.5	35.8	29.1	22.4
5.0	31.8	44.8	37.8	30.6	23.5
4.9	33.6	47.2	39.9	32.3	24.7
4.8	34.9	49.5	41.6	33.8	26.0

† Ag-ground lime of > 90% total neutralizing power (TNP) or CaCO<sub>3</sub> equivalent, and fineness of 40% < 0.15 mm, 50% < 0.25 mm, 70% < 0.85 mm and 95% < 2.36 mm. Values are based on the amount of lime required for the top 20 cm of soil. For other depths, increase or decrease the values in table proportionate to the deviation in soil depth from 20 cm. The amounts of pure CaCO<sub>3</sub> required to bring the soil to pH 7.0 are given as points of reference in case one wish to use another grade of lime than Ag-ground lime.

of soil with 10 mL of distilled water into a 50 mL centrifuge tube. Samples were shaken for 10 minutes and allowed to stand for 30 minutes before measuring the pH. Ten milliliters of the Mehlich buffer were added to the samples. The soil-buffer mixtures were shaken for 10 minutes and allowed to stand for an hour. Soil-buffer pH values were



determined and lime requirement to achieve soil pH 6.5 was estimated from calibration table (Table 3).

Table 3. Relationships between soil-buffer pH and lime requirements for pH values of 5.5, 6.0 and 6.5 for mineral soils with the Mehlich buffer (Sims, 1996).

Soil Buffer pH	Lime Requirement			
	Mehlich†	pH 5.5	pH 6.0	pH 6.5
	----- Mg ha <sup>-1</sup> -----			
6.5	0.4	0	0	0
6.4	0.9	0	0.2	0.3
6.3	0.9	0	1.4	1.2
6.2	1.9	0.2	2.6	2.2
6.1	2.4	1.1	3.8	3.2
6.0	3.0	2.0	4.9	4.3
5.9	3.6	2.9	6.1	5.4
5.8	4.2	3.8	7.3	6.6
5.7	4.9	4.6	8.5	7.9
5.6	5.6	5.5	9.6	9.2
5.5	6.3	6.4	10.8	10.6
5.4	7.1	7.3	12.0	12.0
5.3	7.9	8.2	13.2	13.6
5.2	8.7	9.1	14.4	15.1
5.1	9.6	10.0	15.5	16.7
5.0	10.5	10.9	15.5	16.7
4.9	11.4	11.7	17.9	20.2
4.8	12.4	12.6	19.0	22.0
4.7	13.4	13.5	20.2	23.9
4.6	14.4	14.4	21.4	25.8
4.5	15.5	15.3	22.6	27.8
4.4	16.5	16.2	23.7	29.8
4.3	17.7	17.0	24.9	32.0
4.2	18.8	18.0	26.1	34.1
4.1	20.0	18.8	27.3	36.4
4.0	21.2	19.7	28.4	38.7
3.9	22.5	20.6	29.6	41.0

† Lime requirement calibrations for Mehlich lime requirement values were obtained from Mehlich (1976) based on optimizing crop yields. Lime requirement values to soil pH 5.5 and 6.0 were developed by Tran and van Lierop (1982), and to soil pH 6.5 by Ssali and Nuwamanya (1981).

The Sikora buffer solution was prepared as described by Sikora (2006). Buffer components are potassium chloride (KCl), glacial acetic acid ( $\text{CH}_3\text{COOH}$ ), 2-(N-morpholino)ethanesulfonic acid monohydrate (MES) ( $\text{C}_6\text{H}_{13}\text{NO}_4\text{S}\cdot\text{H}_2\text{O}$ ), imidazole ( $\text{C}_3\text{H}_4\text{N}_2$ ), triethanolamine [ $\text{N}(\text{CH}_2\cdot\text{CH}_2\text{OH})_3$ ] and sodium hydroxide (NaOH). The buffer pH was adjusted to  $7.70 \pm 0.01$ . The Sikora method was performed placing 10 g of soil into 50 mL centrifuge tube. Ten milliliters of distilled water were added, samples were shaken for 10 minutes and pH was determined. Ten milliliters of the Sikora buffer were added to the samples. The mixture was shaken for 10 minutes and pH was immediately measured. Lime requirement to obtain pH 6.5 was estimated from calibration table (Table 4) presented by the Soil and Plant Analysis Council (2000, table 12.3).

Exchangeable aluminum method was performed extracting  $\text{Al}^{3+}$  with 1M KCl (Bertsch and Bloom, 1996). Five grams of soil were placed into a 50 mL centrifuge tube. Twenty five milliliters of 1M KCl were added to the tubes. Samples were shaken for 30 minutes and centrifuged for 10 minutes at 3,500 rpm. The supernatant was filtered through a Whatman no. 42 filter paper. The filtrate was acidified to  $\text{pH} < 3.0$  with concentrated nitric acid ( $\text{HNO}_3$ ) and stored in 20 mL polyethylene vials. Exchangeable  $\text{Al}^{3+}$  concentration was determined by atomic absorption spectrometry using a Perkin Elmer Model AAnalyst 300 spectrophotometer. Lime requirement was estimated multiplying exchangeable  $\text{Al}^{3+}$  concentration ( $\text{cmol}_c \text{ kg}^{-1}$ ) by a factor of 1.5 to account for the acidity generated by pH dependent charges and organic matter. Lime requirement values were expressed in  $\text{Mg ha}^{-1}$  units.

Table 4. Amounts of limestone required to bring mineral and organic soils to the indicated pH according to Sikora buffer method (Soil and Plant Analysis Council, 2000).

Soil-Buffer pH	Mineral Soils				Organic Soils
	7.0	7.0	6.5	6.0	5.2
	Pure CaCO <sub>3</sub>		Ag-ground Limestone†		
	-----		Tons A <sup>-1</sup> -----		
6.8	1.1	1.4	1.2	1.0	0.7
6.7	1.8	2.4	2.1	1.7	1.3
6.6	2.4	3.4	2.9	2.4	1.8
6.5	3.1	4.5	3.8	3.1	2.4
6.4	4.0	5.5	4.7	3.8	2.9
6.3	4.7	6.5	5.5	4.5	3.5
6.2	5.4	7.5	6.4	5.2	4.0
6.1	6.0	8.6	7.2	5.9	4.6
6.0	6.8	9.6	8.1	6.6	5.1
5.9	7.7	10.6	9.0	7.3	5.7
5.8	8.3	11.7	9.8	8.0	6.2
5.7	9.0	12.7	10.7	8.7	6.7
5.6	9.7	13.7	11.6	9.4	7.3
5.5	10.4	14.8	12.5	10.2	7.8
5.4	11.3	15.8	13.4	10.9	8.4
5.3	11.9	16.9	14.2	11.6	8.9
5.2	12.7	17.9	15.1	12.3	9.4
5.1	13.5	19.0	16.0	13.0	10.0
5.0	14.2	20.0	16.9	13.7	10.5
4.9	15.0	21.1	17.8	14.4	11.0
4.8	15.6	22.1	18.6	15.1	11.6

† Ag-ground limestone of 90% plus total neutralizing power (TNP) or CaCO<sub>3</sub> equivalent, and fineness of 40% < 100 mesh, 50% < 60 mesh, 70% < 20 mesh and 95% < 8 mesh.

## II. Soil Samples

Ten acid soil series with agricultural value in Puerto Rico were selected for this study. Soil series were Consumo, Corozal, Lares, Humatas, Catalina, Los Guineos, Bayamón, Dagüey, Alonso and Múcara. Table 5 shows taxonomic classification of these soil series according to Soil Taxonomy system. In this system, the first four series are

Ultisols, the following four series belong to the order Oxisol and the last two series are Inceptisols (USDA, 1975; USDA, 1982).

Soil samples were collected at two depths (0-20 cm and 20-40 cm) to expand the range on soil properties. The samples were allowed to dry at room temperature, ground to pass a 2 mm sieve and stored in plastic bags.

Table 5. Taxonomic classification of soil series according to Soil Taxonomy system (Beinroth et al., 2003).

<b>Soil</b>	<b>Taxonomic Class</b>
Consumo	Fine, mixed, semiactive, isohyperthermic Typic Haplohumults
Corozal	Very-fine, parasesquic, isohyperthermic Typic Hapludults
Lares	Very-fine, mixed, semiactive, isohyperthermic Aquic Paleudults
Humatas	Very-fine, parasesquic, isohyperthermic Typic Haplohumults
Catalina	Very-fine, ferruginous, isohyperthermic Typic Hapludox
Los Guineos	Very-fine, kaolinitic, isothermic Humic Hapludox
Bayamón	Very-fine, kaolinitic, isohyperthermic Typic Hapludox
Dagüey	Very-fine, kaolinitic, isohyperthermic Inceptic Hapludox
Alonso	Very-fine, parasesquic, isohyperthermic Oxidic Dystrudepts
Múcara	Fine-loamy, mixed, superactive, isohyperthermic Dystric Eutrudepts

### **III. Soil Properties**

Selected characteristics of soils used in this research are presented in Table 6. Soil pH was determined in a 1:1 soil:distilled water ratio and measured using an Orion Model

310 pH meter. Soil organic matter (SOM) was determined by the Walkley-Black method as described by Nelson and Sommers (1996). Exchangeable bases were extracted with 0.2M ammonium chloride ( $\text{NH}_4\text{Cl}$ ) and base concentrations were estimated by atomic absorption spectrometry using a Perkin Elmer Model AAnalyst 300 spectrophotometer (Sumner and Miller, 1996). Effective cation exchange capacity (ECEC) was estimated by the sum of exchangeable bases and exchangeable  $\text{Al}^{3+}$ . Clay and sand percentages were determined by hydrometer method.

#### **IV. Statistical Analysis**

Lime requirement methods were compared by linear regression, Pearson correlation coefficients and multiple comparisons (Tukey Test) analyses using the statistical program InfoStat. Soil-lime incubation was used as the reference method. There were four repetitions of each soil for all methods. The  $n$  value was 80.

## Results and Discussion

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Soils in this study showed a high variation in properties which affect their buffer capacity and consequently their lime requirement (Table 6). Soil pH ranged from 4.25 (extremely acid) to 5.43 (strongly acid) with exception of Catalina (0-20 cm) soil, with pH of 6.93. This soil was probably recently limed. Eight of the original ten soil series showed lower pH values at 20-40 cm of depth excluding Lares and Humatas soils. SOM varied from 0.33 to 4.41 %. Higher SOM was observed at 0-20 cm of depth for eight soil series. The Corozal soil at a 20-40 cm depth showed no detectable SOM by the Walkley-Black method, because this soil is an eroded Corozal clay. Clay percentages ranged from 34.44 to 85.96 %. Sand percentages ranged from 1.15 to 65.35 %. Nine of the ten soil series showed texture dominated by the clay fraction, while one of the ten soil series was a sandy soil. Exchangeable bases varied from 0.76 to 21.64  $\text{cmol}_c \text{ kg}^{-1}$ . Nine of the ten soil series showed higher exchangeable bases at 0-20 cm of depth. Exchangeable  $\text{Al}^{3+}$  content ranged from 0 to 9.86  $\text{cmol}_c \text{ kg}^{-1}$ . Soils collected at 0-20 cm depth showed the lowest exchangeable  $\text{Al}^{3+}$  values excluding Lares and Humatas soils. ECEC varied from 1.83 to 22.48  $\text{cmol}_c \text{ kg}^{-1}$ . Seven of the ten soil series showed higher ECEC values at 0-20 cm of depth.

Soil lime requirement values obtained by the six methods are presented in Table 7. Soil-lime incubation method showed lime requirement values ranging from 3.94 to 38.88  $\text{Mg ha}^{-1}$ . The Adams-Evans buffer, Mehlich buffer and exchangeable  $\text{Al}^{3+}$  methods showed lower lime requirement values than soil-lime incubation method for all soils (Table 7). The Adams-Evans and Mehlich buffers showed higher lime requirement values than exchangeable  $\text{Al}^{3+}$  method. The SMP and Sikora buffers showed higher lime requirement values than soil-lime incubation method for all soils (Table 7). Lime requirement values obtained by these two buffer solutions were similar for all soils. Similar results were obtained by Sikora (2006).

Table 6. Selected chemical and physical properties of soils.

Soil	Depth (cm)	pH	Bases <sup>†</sup>	Al <sup>3+††</sup>	ECEC <sup>‡</sup>	SOM <sup>‡‡</sup>	Clay	Sand
			.....cmol <sub>c</sub> kg <sup>-1</sup> .....	.....	.....	-----%-----	.....	.....
Consumo	0 - 20	5.26	8.09	0.54	8.63	1.65	76.18	11.76
	20 - 40	5.13	6.06	1.40	7.46	0.70	77.02	10.84
Corozal	0 - 20	4.56	4.15	8.01	12.16	0.33	60.90	22.86
	20 - 40	4.51	1.77	9.86	11.63	ND*	56.12	25.18
Lares	0 - 20	5.26	17.32	1.41	18.73	2.49	50.86	27.79
	20 - 40	5.43	21.64	0.84	22.48	1.28	53.61	27.51
Humatas	0 - 20	5.02	10.29	0.71	11.0	2.69	72.40	13.15
	20 - 40	5.12	7.67	0.25	7.92	2.04	79.18	6.50
Catalina	0 - 20	6.93	16.32	0	16.32	4.06	84.89	4.89
	20 - 40	4.95	3.85	0.63	4.48	4.41	85.96	1.70
Los Guineos	0 - 20	4.54	6.39	1.83	8.22	2.38	72.41	13.79
	20 - 40	4.25	2.76	4.60	7.36	2.41	75.39	8.27
Bayamón	0 - 20	5.24	1.97	0.13	2.10	0.87	34.44	65.35
	20 - 40	4.87	1.49	0.34	1.83	0.38	39.36	61.67
Dagüey	0 - 20	4.71	2.73	2.26	4.99	4.02	79.72	11.08
	20 - 40	4.63	1.71	3.58	5.29	3.27	82.16	1.15
Alonso	0 - 20	4.85	5.32	2.51	7.83	2.81	66.40	21.97
	20 - 40	4.72	3.03	4.16	7.19	0.84	63.96	18.63
Múcara	0 - 20	4.81	2.14	4.12	6.26	2.00	68.88	14.90
	20 - 40	4.80	0.76	6.32	7.08	0.62	64.69	10.19

†Exchangeable Bases; ††Exchangeable Al<sup>3+</sup>; ‡Effective Cation Exchange Capacity; ‡‡Soil Organic Matter; \*Not detectable.

Table 7. Soil lime requirement values obtained by the selected methods.

Soil	Depth (cm)	Lime Requirement (Mg ha <sup>-1</sup> )					
		Incubation	SMP <sup>†</sup>	Sikora	AE <sup>‡</sup>	Mehlich	Al <sup>3+</sup>
Consumo	0 - 20	10.34	18.60	19.66	8.94	7.90	0.92
	20 - 40	10.86	18.10	20.16	9.62	9.20	2.34
Corozal	0 - 20	24.97	38.32	39.37	10.85	21.10	13.45
	20 - 40	38.88	41.60	41.66	11.20	25.80	16.57
Lares	0 - 20	27.78	26.00	28.00	9.40	13.60	2.37
	20 - 40	19.25	21.00	23.97	9.09	10.60	1.40
Humatas	0 - 20	20.12	21.00	18.14	9.56	7.90	1.18
	20 - 40	25.70	18.10	18.14	8.62	6.60	0.42
Catalina	0 - 20	0.00	0.00	0.00	0.00	0.00	0.00
	20 - 40	36.72	33.80	25.98	9.80	14.72	1.06
Los Guineos	0 - 20	26.11	30.00	29.01	12.00	15.10	3.07
	20 - 40	28.39	37.80	36.34	12.00	20.20	7.72
Bayamón	0 - 20	3.94	5.60	4.70	3.60	1.70	0.22
	20 - 40	5.92	5.60	6.50	5.48	1.95	0.58
Dagüey	0 - 20	32.35	33.30	31.36	11.60	15.10	3.80
	20 - 40	31.76	34.80	33.82	11.60	16.70	6.02
Alonso	0 - 20	23.21	34.80	28.00	10.59	15.10	4.22
	20 - 40	21.85	35.30	31.36	10.94	16.70	6.98
Múcara	0 - 20	25.87	35.80	35.84	10.85	16.70	6.92
	20 - 40	29.29	37.80	35.84	10.76	16.70	10.48

<sup>†</sup>SMP = Shoemaker-McLean-Pratt buffer; <sup>‡</sup>AE = Adams-Evans buffer.



Table 8 showed a multiple comparisons analysis (Tukey Test) performed on the lime requirement values obtained by the six methods. Lime requirement values showed by the Adams-Evans buffer, Mehlich buffer and exchangeable  $Al^{3+}$  methods were significantly lower than values obtained by the soil-lime incubation method. The SMP buffer method showed significantly higher lime requirement values than the soil-lime incubation method. The Sikora buffer method was not significantly different from the soil-lime incubation method. This method also was not significantly different from the SMP buffer method. The SMP and Sikora buffer methods showed significantly higher lime requirement values than the Adams-Evans buffer, Mehlich buffer and exchangeable  $Al^{3+}$  methods. The Adams-Evans buffer method was not significantly different from the Mehlich buffer method. These two buffer methods showed significantly higher lime requirement values than the exchangeable  $Al^{3+}$  method.

Table 8. Multiple comparisons analysis performed on the six methods.

Methods	Means	N <sup>§</sup>	Tukey Test <sup>*</sup>
$Al^{3+}$	4.49	80	A
AE <sup>‡</sup>	9.33	80	B
Mehlich	12.67	80	B
Incubation	22.17	80	C
Sikora	25.39	80	C D
SMP <sup>†</sup>	26.37	80	D

§Number of repetitions; \*Different letters means significant differences among the methods ( $p \leq 0.05$ ). Alfa = 0.05. LSD = 4.05409; ‡Adams-Evans buffer; †Shoemaker-McLean-Pratt buffer.

The differences observed among lime requirement methods can be explained on the nature and properties of the soils, and on the nature, properties and purposes of the

methodologies. The Adams-Evans buffer was designed to determine lime requirement of soils with low CEC, low SOM, and a mineralogy dominated by 1:1 clays (Sims, 1996). The Mehlich buffer was designed to estimate lime requirement needed to neutralize exchangeable acidity ( $\text{Al}^{3+}$  and  $\text{H}^+$ ), so attained pH is slightly above 5.5. Similarly, exchangeable  $\text{Al}^{3+}$  method takes as a target the neutralization of toxic levels of exchangeable  $\text{Al}^{3+}$ . The neutralization of this fraction of soil  $\text{Al}^{3+}$  occurs at pH values near to 5.5, so exchangeable  $\text{Al}^{3+}$  method was expected to estimate lower lime requirements than the other methods which were evaluated at pH 6.5. The SMP buffer was developed for soils with high buffer capacity (high CEC, high SOM and high exchangeable  $\text{Al}^{3+}$ ). The Sikora buffer was intended to mimic the SMP buffer, using reactants more friendly to the environment. The high variation on the buffer capacity of the soils is probably the major factor contributing to the differences observed among methods (Table 9). Each method was proposed for a specific group of soils, but in a small geographical area with great soil diversity, it is desired that researches focus on finding the best methodology.

Pearson correlation coefficients are presented in Table 10. The SMP buffer showed the highest correlation coefficient with soil-lime incubation method. The Sikora and Mehlich buffers also showed high correlation coefficients with soil-lime incubation method. The lowest correlation coefficient was showed by exchangeable  $\text{Al}^{3+}$  method (Table 10). The SMP buffer showed high correlation with the Sikora and Mehlich buffers. SMP also showed an acceptable correlation with Adams-Evans buffer, but poor correlation coefficient with exchangeable  $\text{Al}^{3+}$  method. The Adams-Evans buffer showed an acceptable correlation with the Sikora and Mehlich buffers, but low correlation coefficient with exchangeable  $\text{Al}^{3+}$  method. The Mehlich buffer showed high correlation coefficient with the Sikora buffer and an acceptable correlation with exchangeable  $\text{Al}^{3+}$  method. The Sikora buffer showed an acceptable correlation with exchangeable  $\text{Al}^{3+}$  method.

Table 9. Buffer capacity of soils.

<b>Soil</b>	<b>Depth (cm)</b>	<b>Buffer Capacity<sup>†</sup></b>
Consumo	0 - 20	0.1383
	20 - 40	0.1410
Corozal	0 - 20	0.0864
	20 - 40	0.0529
Lares	0 - 20	0.0431
	20 - 40	0.0449
Humatas	0 - 20	0.0449
	20 - 40	0.0525
Catalina	0 - 20	ND <sup>‡</sup>
	20 - 40	0.0417
Los Guineos	0 - 20	0.0864
	20 - 40	0.0911
Bayamón	0 - 20	0.0342
	20 - 40	0.0508
Dagüey	0 - 20	0.0550
	20 - 40	0.0581
Alonso	0 - 20	0.0819
	20 - 40	0.0910
Múcara	0 - 20	0.0714
	20 - 40	0.0688

<sup>†</sup>Buffer capacity refers to the natural resistance of soils to pH changes. This soil property was estimated from the line slope of the calibration curves.

<sup>‡</sup>ND = no detectable.

Table 10. Pearson correlation coefficients for the evaluated methods.

Methods	Pearson Correlation Coefficients					
	Incubation	SMP <sup>†</sup>	Sikora	AE <sup>‡</sup>	Mehlich	Al <sup>3+</sup>
<b>Incubation</b>	1.00					
<b>SMP</b>	0.88	1.00				
<b>Sikora</b>	0.85	0.97	1.00			
<b>AE</b>	0.79	0.89	0.89	1.00		
<b>Mehlich</b>	0.84	0.96	0.97	0.83	1.00	
<b>Al<sup>3+</sup></b>	0.57	0.75	0.79	0.53	0.84	1.00

<sup>†</sup>Shoemaker-McLean-Pratt buffer; <sup>‡</sup>Adams-Evans buffer

Figure 9 shows the relationship between lime requirement determined by the SMP buffer method and lime requirement determined by the soil-lime incubation method. A theoretical line was traced for comparison and was identified in the figure as “1:1 line”. The SMP buffer showed the highest linear relationship with the soil-lime incubation method as the line slope and  $R^2$  values are very close to one (0.99 and 0.77, respectively). Figure 9 also showed the SMP buffer estimated more lime than incubation method for almost all soils since the points are above the 1:1 line. These findings are similar to what other researchers have found (Webber et al., 1977; Fox, 1980; Alabi et al., 1986), because the SMP buffer method overestimated the lime requirement for the soils.

In addition to the SMP buffer method, the Sikora buffer showed a high linear relationship with the soil-lime incubation method as presented in Figure 10. The line slope is 0.91 and the  $R^2$  value is 0.72. Similarly to the SMP buffer method, the Sikora buffer estimated more lime than soil-lime incubation as showed by the line above the 1:1 line. However such relation was closer at higher values of lime requirement.

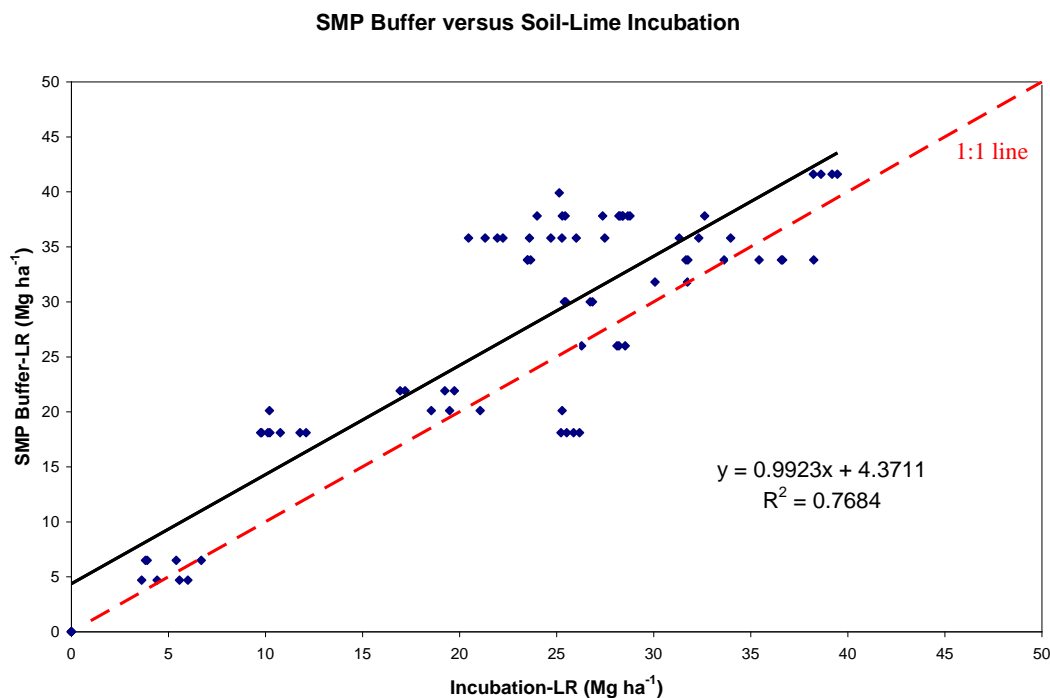


Figure 9. Comparison of lime requirement values (LR) determined by the SMP buffer and the soil-lime incubation method.

The Adams-Evans and Mehlich buffers estimated lower lime requirement values than soil-lime incubation method for all soils as showed by the lines below the 1:1 line (Figures 11 and 12, respectively). Both methods also showed poor linear relationships with the soil-lime incubation method. The Adams-Evans buffer line showed a slope of 0.22 and  $R^2$  value of 0.63. The Mehlich buffer line showed a slope of 0.53 and  $R^2$  value of 0.71. The poorest linear relationship with the soil-lime incubation method was showed by the exchangeable  $Al^{3+}$  method (Figure 13). The line slope was 0.24 and the  $R^2$  value was 0.32. The figure also showed exchangeable  $Al^{3+}$  method estimated lower lime requirement values than the soil-lime incubation method since the line is below the 1:1 line. The exchangeable  $Al^{3+}$  method also estimated lower lime requirement values than other methods.

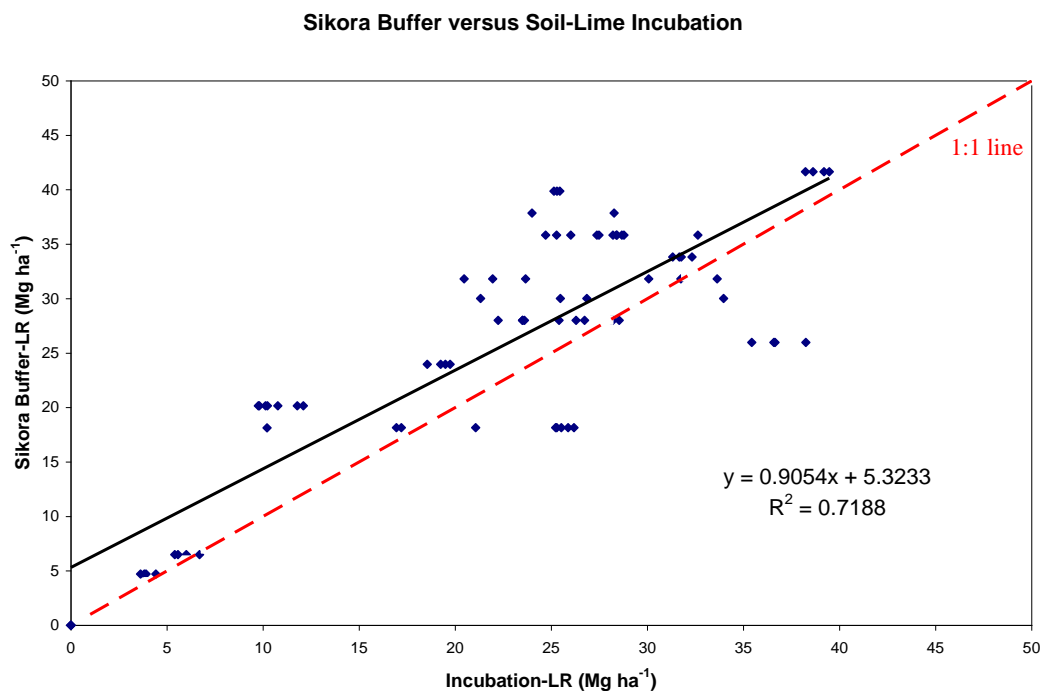


Figure 10. Comparison of lime requirement values (LR) determined by the Sikora buffer and the soil-lime incubation method.

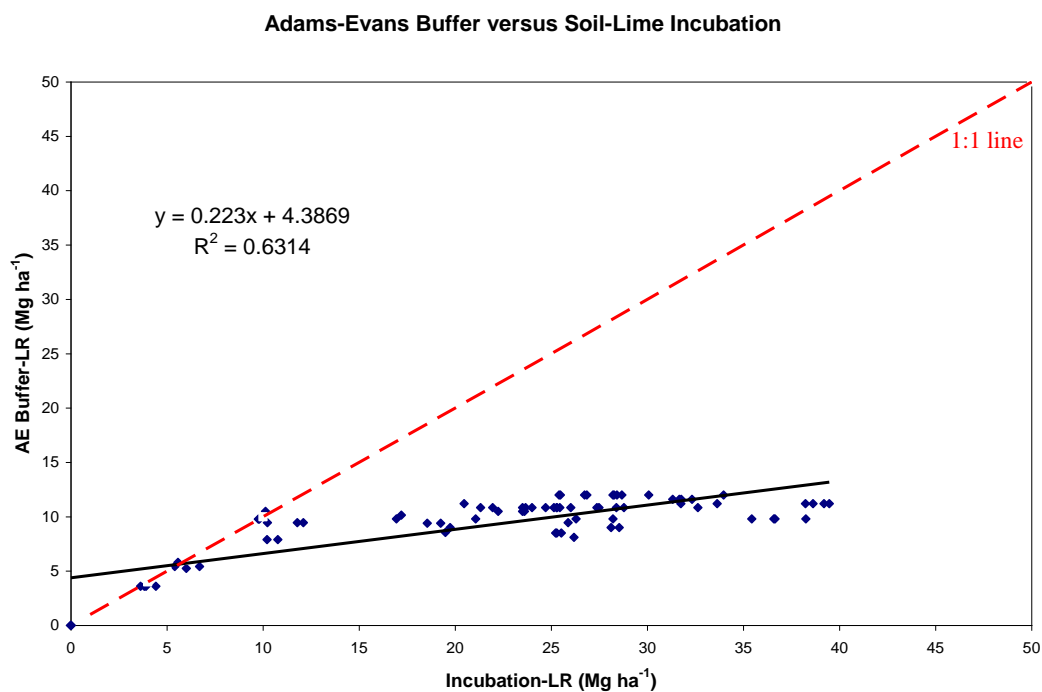


Figure 11. Comparison of lime requirement values (LR) determined by the Adams-Evans buffer and the soil-lime incubation method.

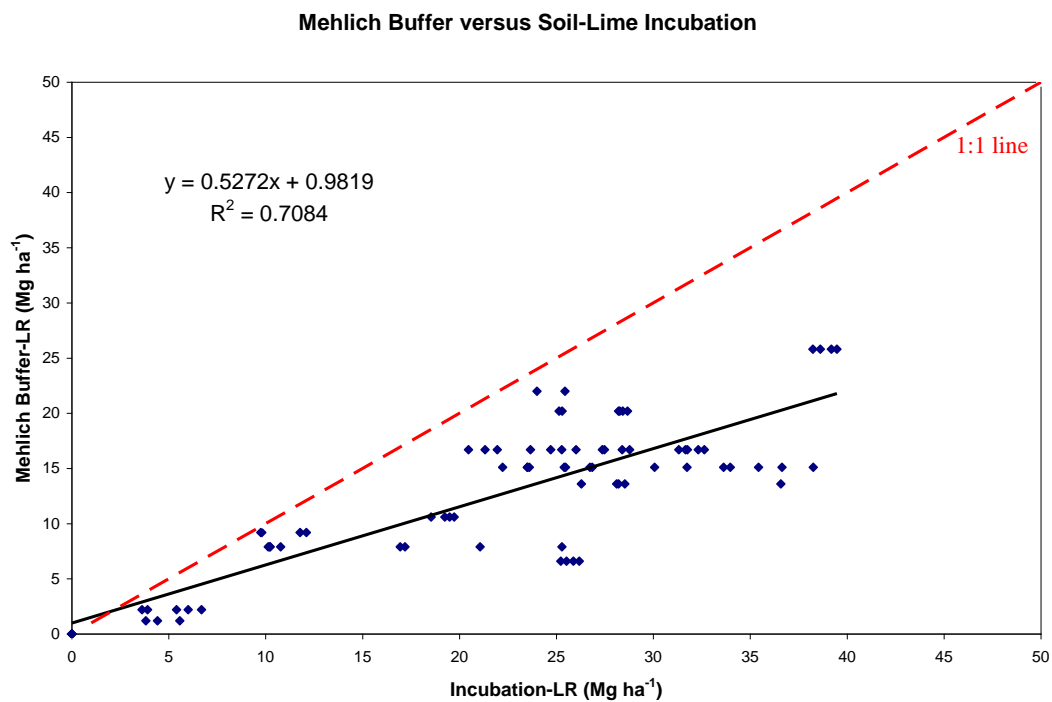


Figure 12. Comparison of lime requirement values (LR) determined by the Mehlich buffer and the soil-lime incubation method.

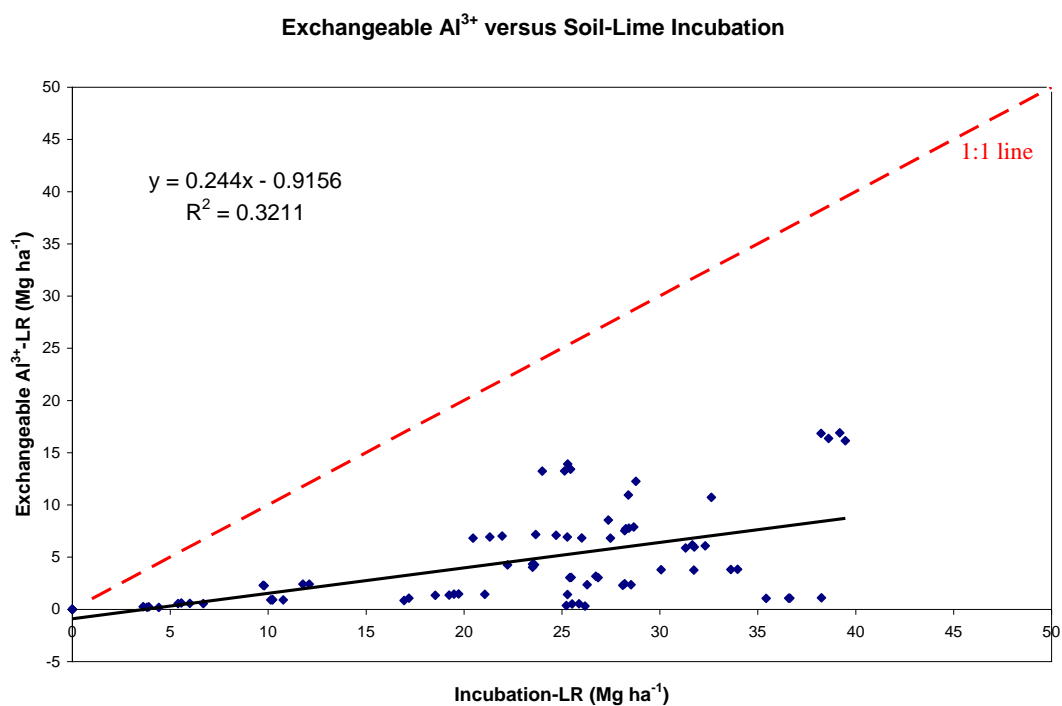


Figure 13. Comparison of lime requirement values (LR) determined by the exchangeable  $\text{Al}^{3+}$  method and the soil-lime incubation method.

Lime requirement values obtained by the exchangeable  $\text{Al}^{3+}$  method were compared with values obtained by the soil-lime incubation method determined at pH 5.5. The Tukey test shows that lime requirement obtained by the exchangeable  $\text{Al}^{3+}$  method were significantly lower than the values obtained by the soil-lime incubation method. However, Pearson correlation coefficient was improved from 0.57 to 0.75. Figure 14 shows the relationship between lime requirement values determined by both methods. Exchangeable  $\text{Al}^{3+}$  method showed poor linear relationship with the soil-lime incubation method (pH 5.5) because of the low slope and  $R^2$  values. The figure also presents exchangeable  $\text{Al}^{3+}$  method determine lower lime requirement values than the soil-lime incubation method (pH 5.5).

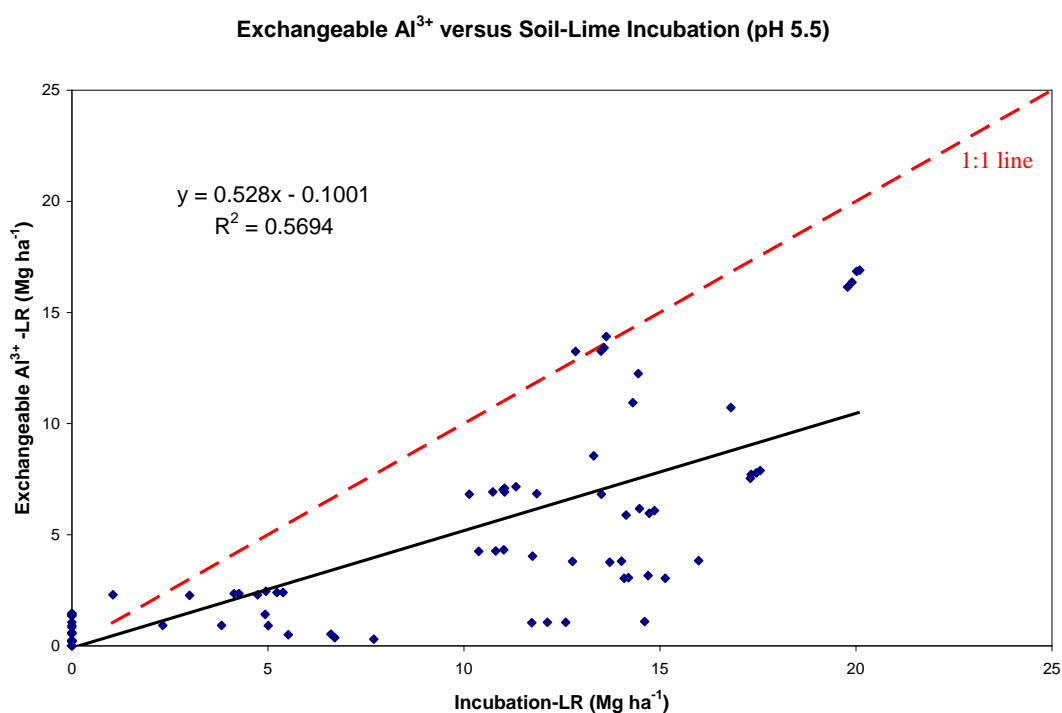


Figure 14. Comparison of lime requirement values (LR) determined by the exchangeable  $\text{Al}^{3+}$  method and the soil-lime incubation method at pH 5.5.



## Conclusions

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Results indicate that the Adams-Evans buffer, Mehlich buffer and exchangeable  $Al^{3+}$  methods estimate low lime requirements for soils in this study. These methods also showed poor linear relationships and poor Pearson correlation coefficients with the soil-lime incubation method. The Adams-Evans buffer showed good correlation with the Mehlich buffer and low correlation with the exchangeable  $Al^{3+}$  method. The Mehlich buffer showed good correlation with the exchangeable  $Al^{3+}$  method. These results suggest that these three methods are not suitable for lime requirement determinations of acid soils from Puerto Rico if the target pH is around 6.5.

The SMP and Sikora buffers predicted larger lime requirement values than the soil-lime incubation method. However both buffers showed high linear relationships and Pearson correlation coefficients with the soil-lime incubation method. These results suggest that SMP and Sikora buffers are appropriate methods to make lime recommendations for acid soils in Puerto Rico. The Sikora method has an advantage over the SMP buffer since no hazardous chemicals are used. This method is more environmental friendly than the SMP buffer.

The Sikora buffer seems to be the best alternative to estimate lime requirement for the soils studied in this research. Also, lime requirement values obtained by the Sikora buffer can be adjusted to the soil-lime incubation data using the equation of the linear regression analysis performed for both methods. The equation is

$$Y = 0.9054X + 5.3233,$$

where  $Y$  is lime requirement from the Sikora buffer and  $X$  is lime requirement from the soil-lime incubation method.

## Recommendations

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Further studies including more soil series are recommended to improve the accuracy of the Sikora buffer to predict lime requirement of acid soils in Puerto Rico and to be applied to a broader spectra of soils. Field studies are also necessary to verify the efficacy of the Sikora buffer method.

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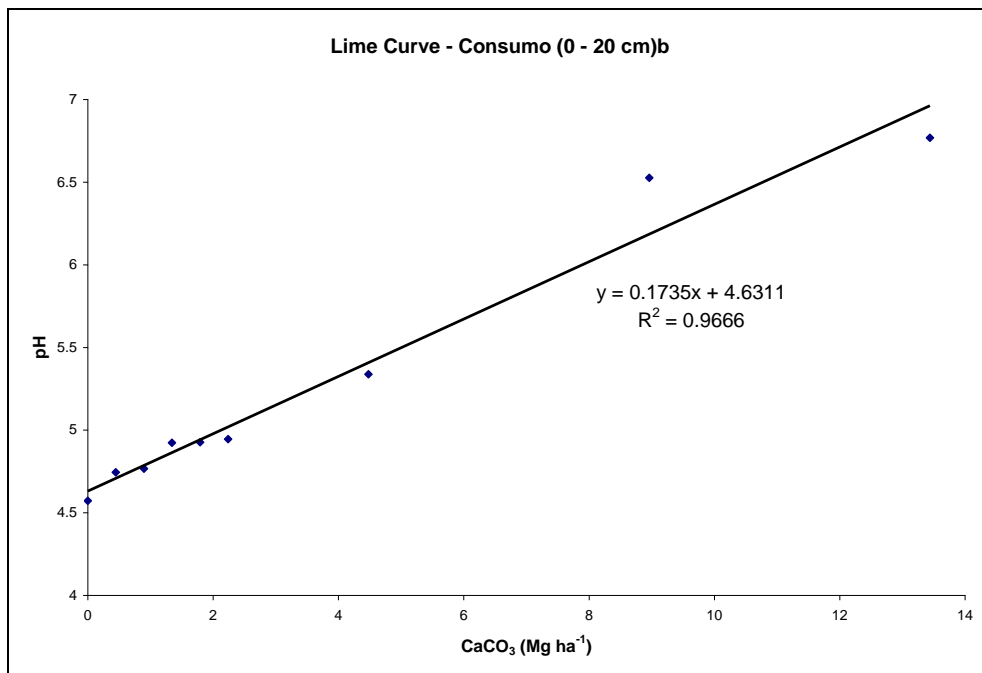
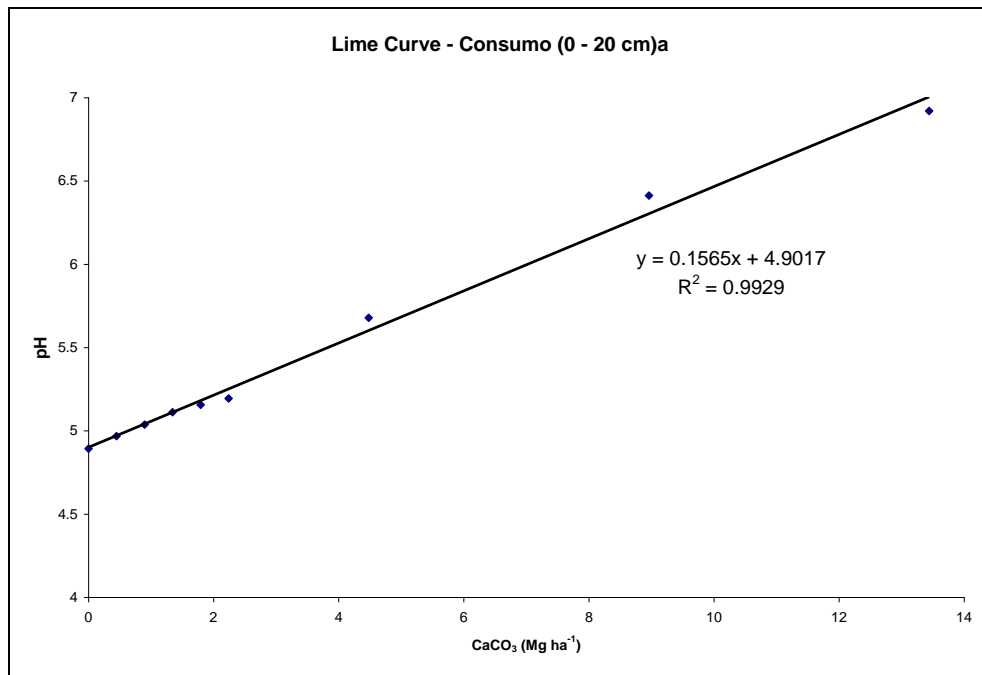
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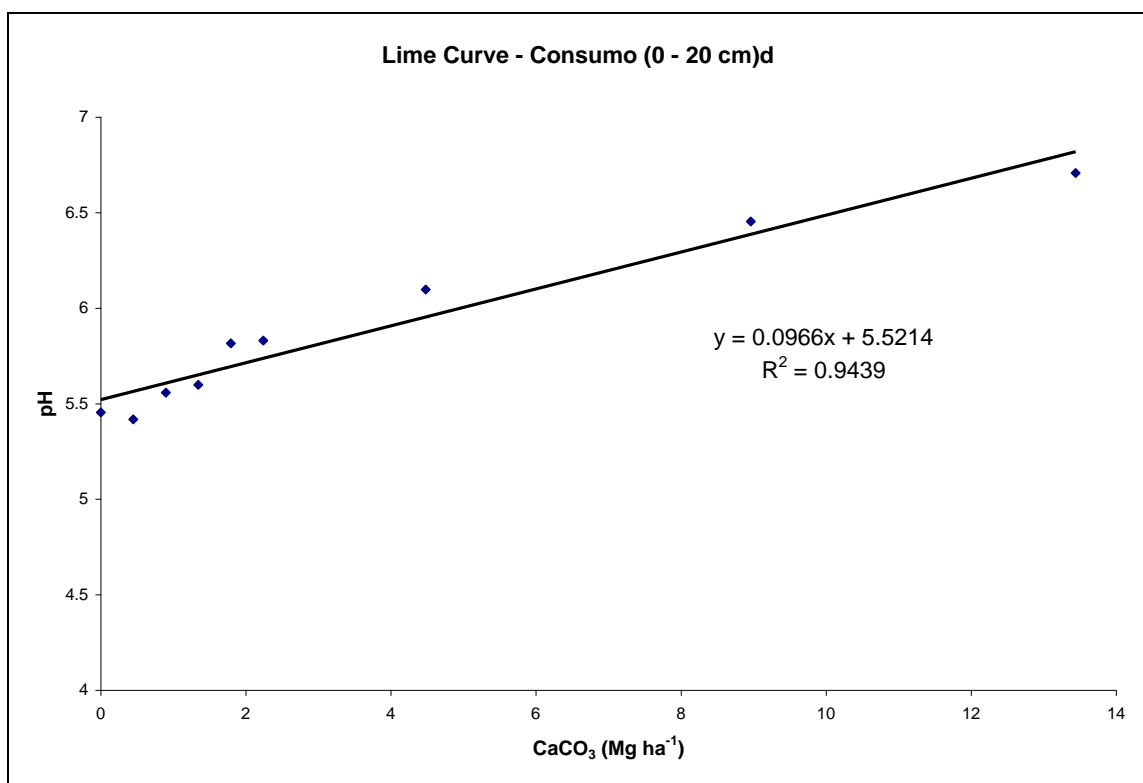
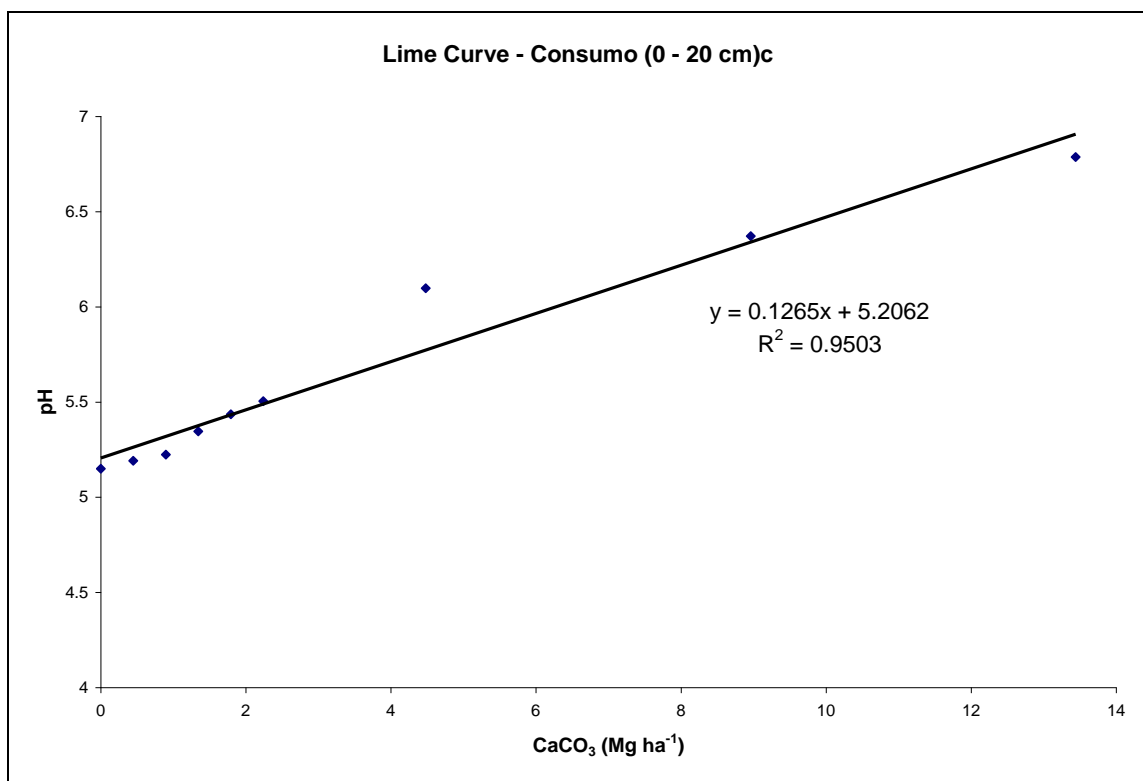
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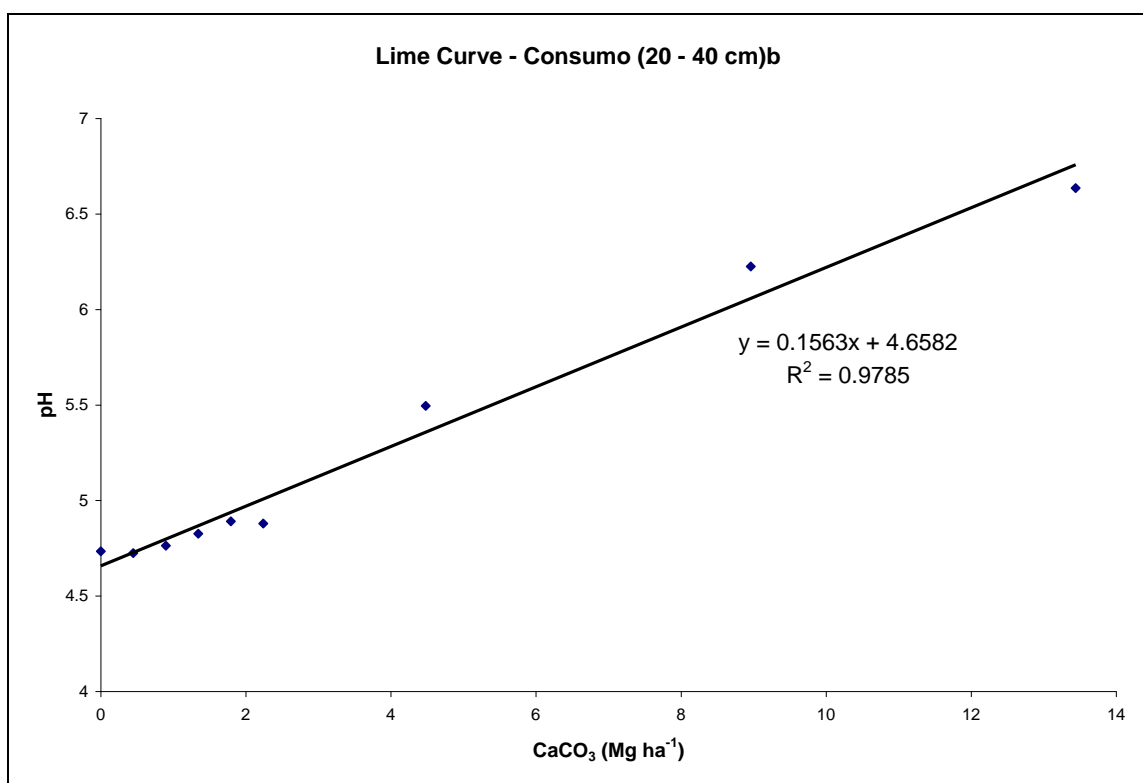
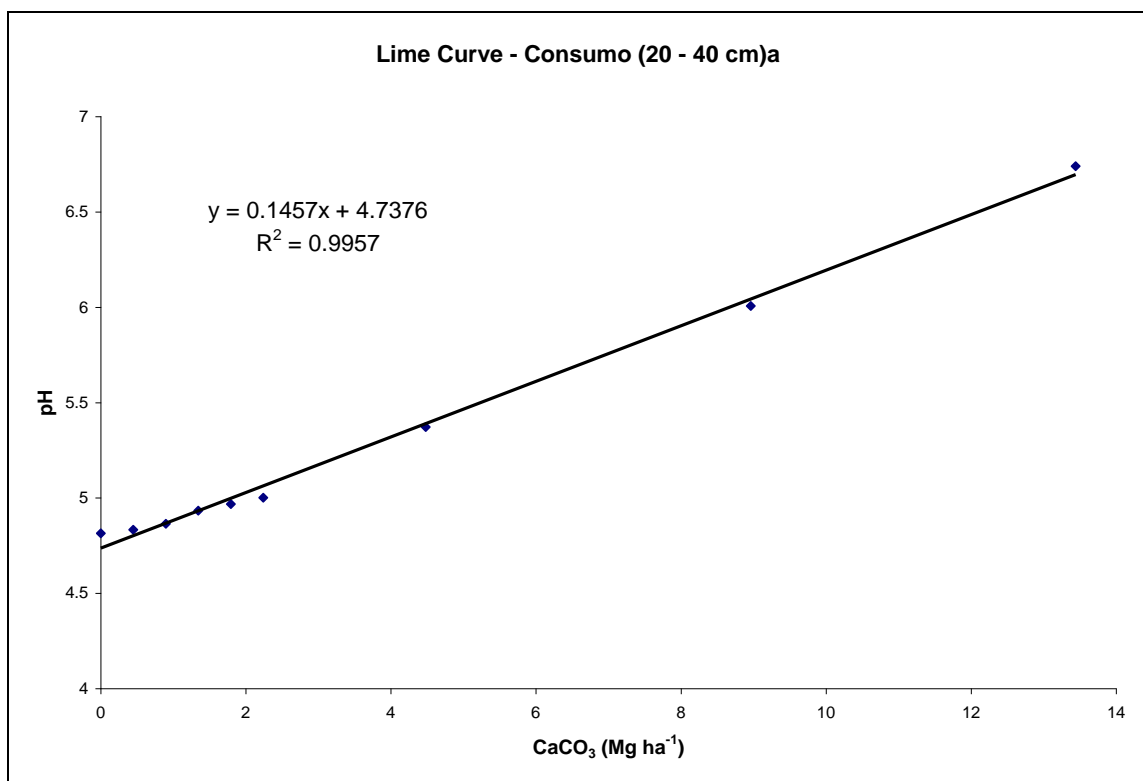
## Appendix

### I. Calibration curves used to determine lime requirement by the soil-lime incubation method.

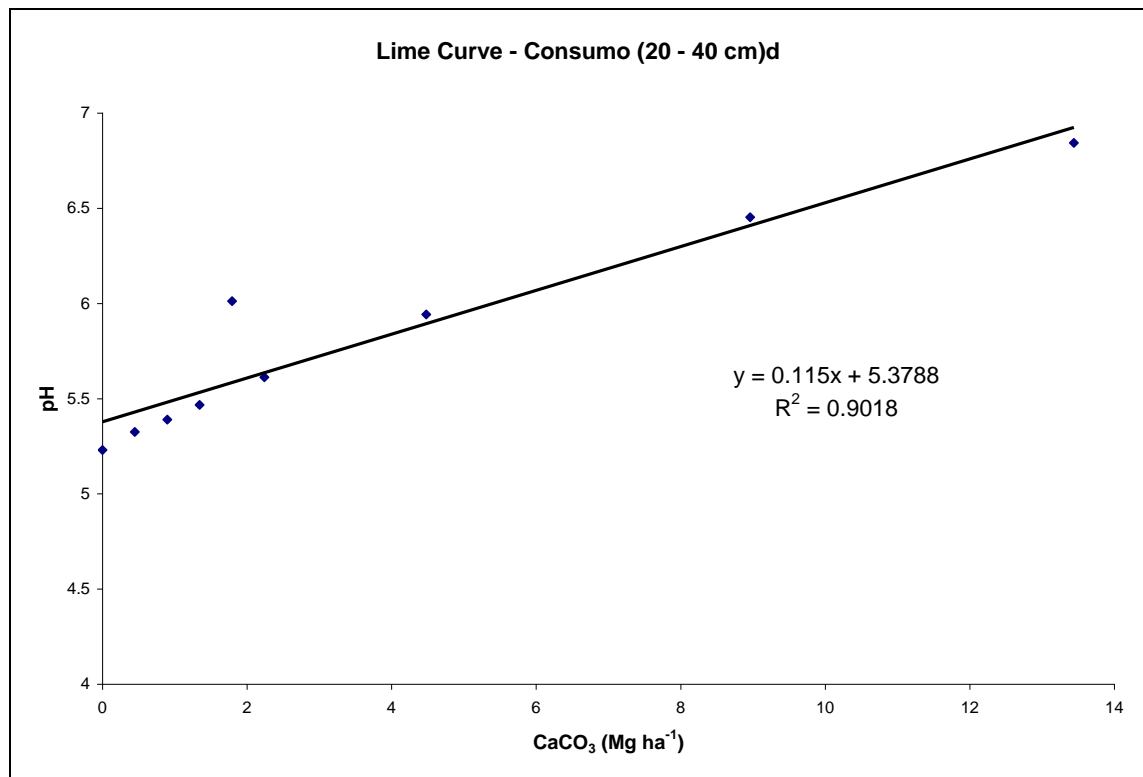
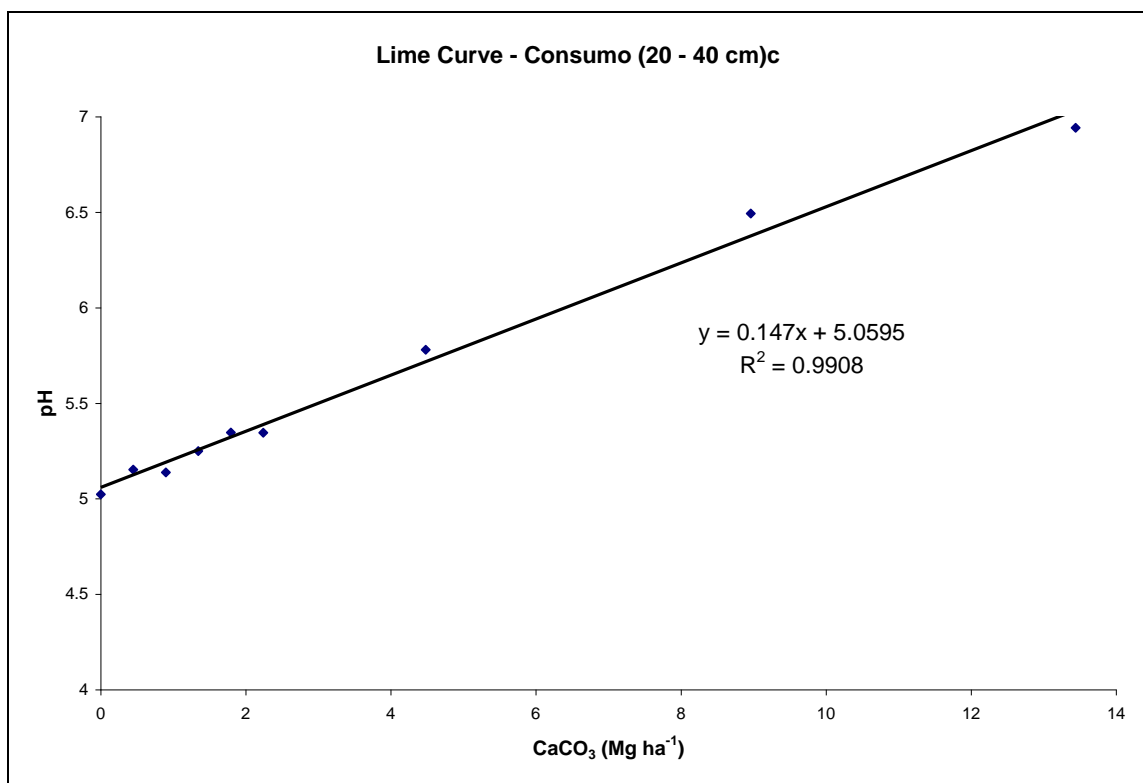
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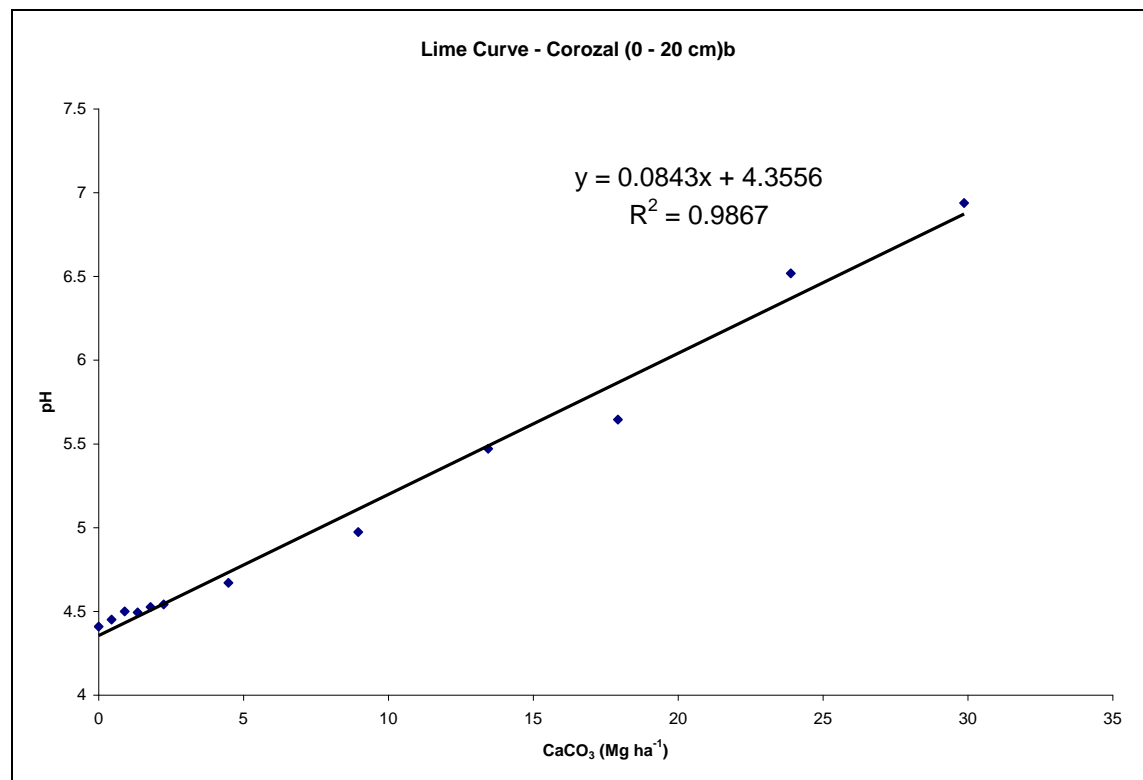
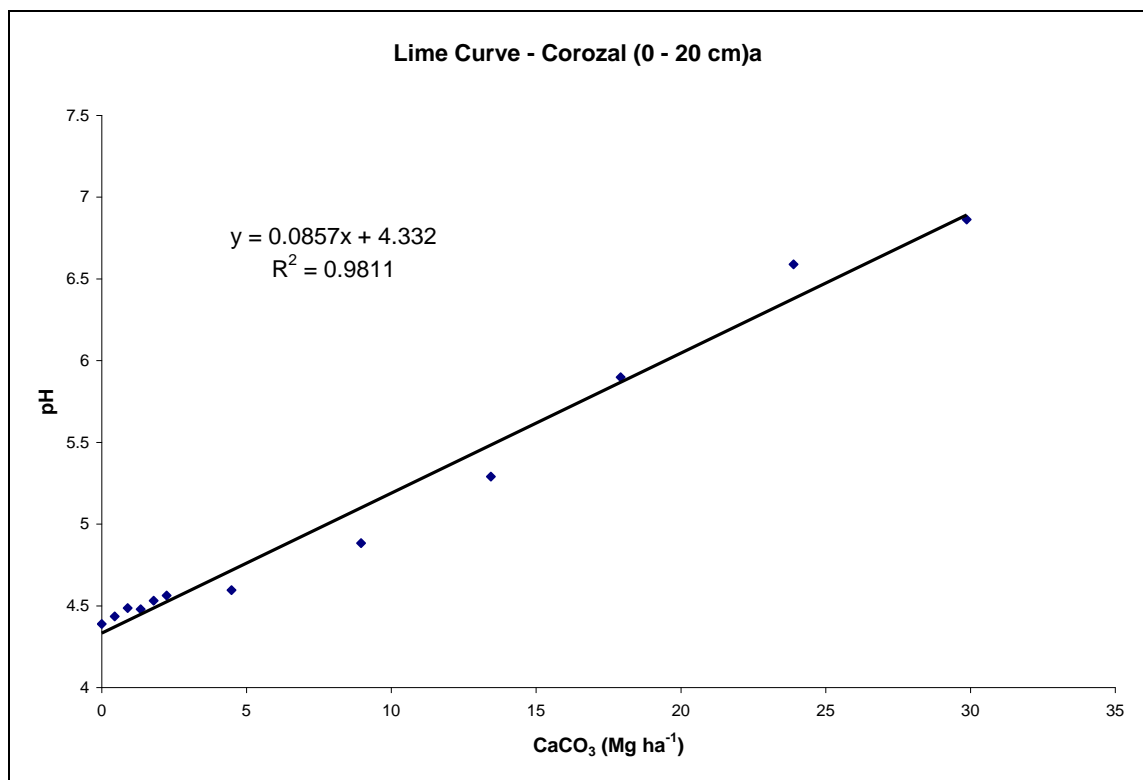


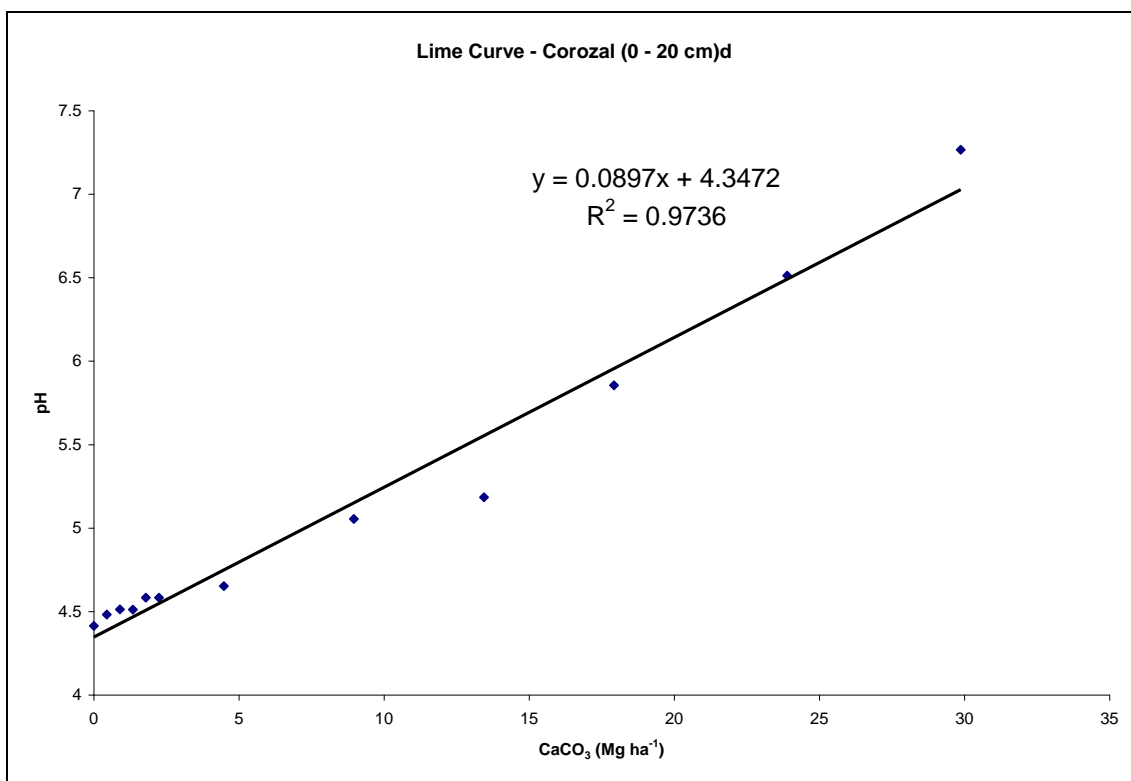
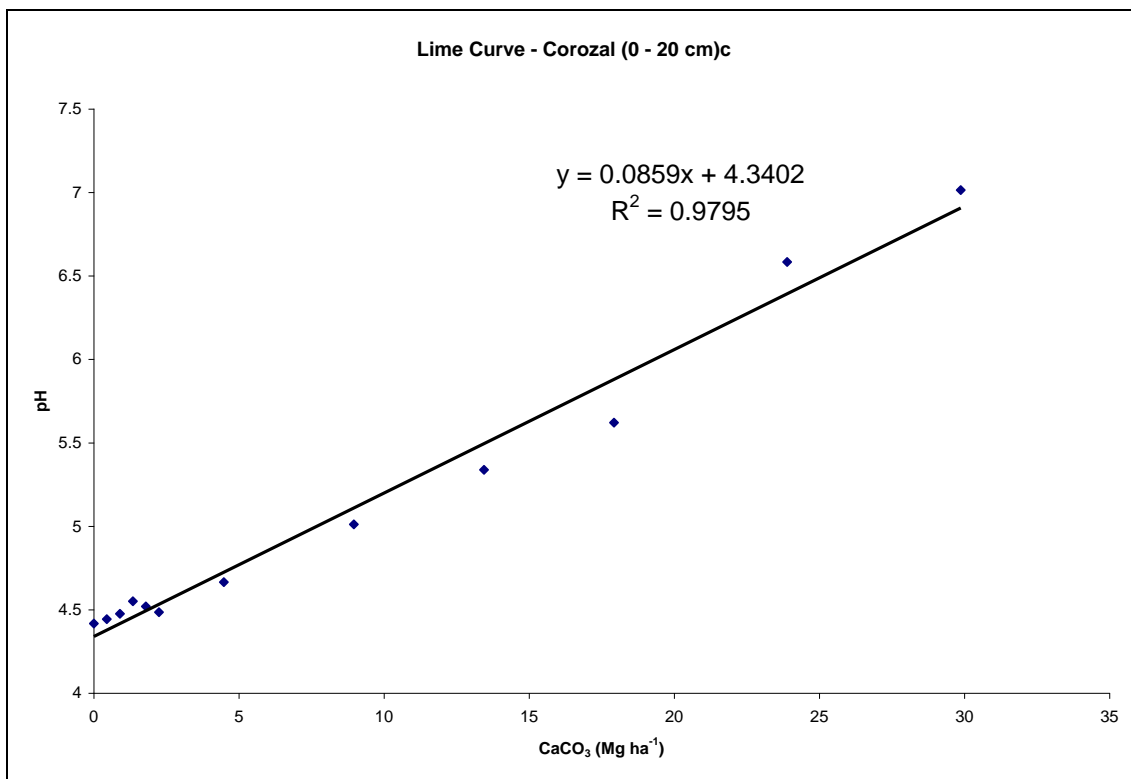


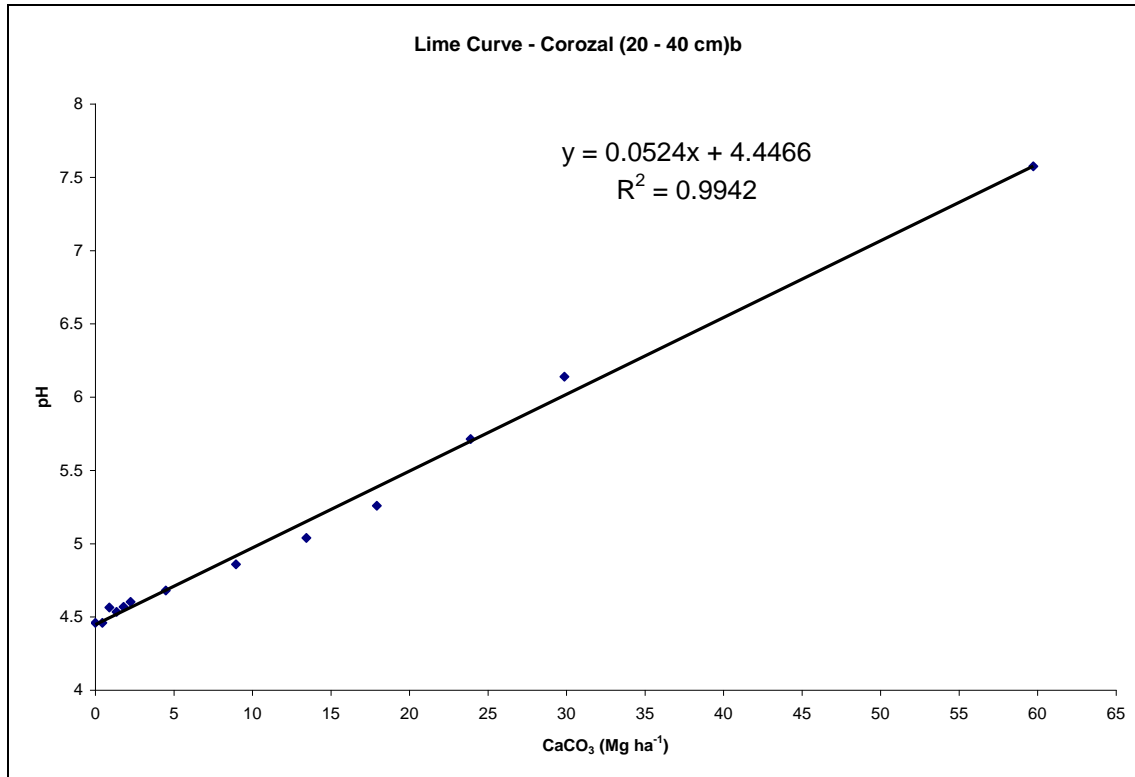
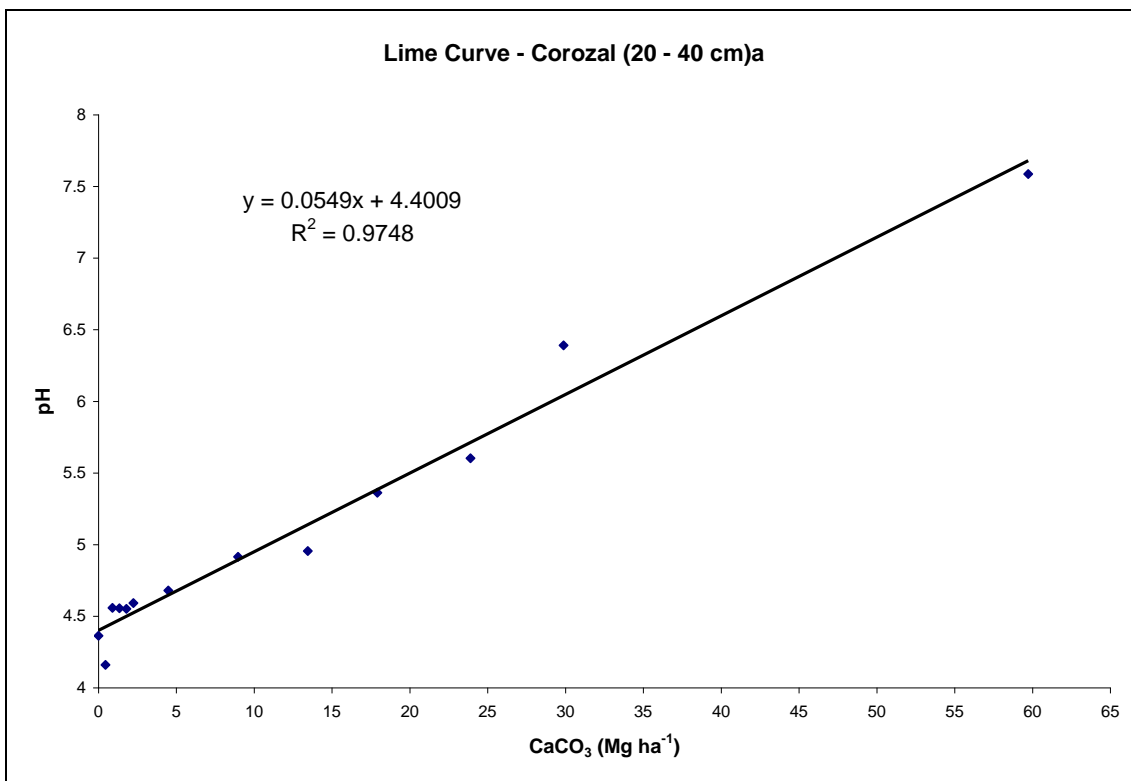


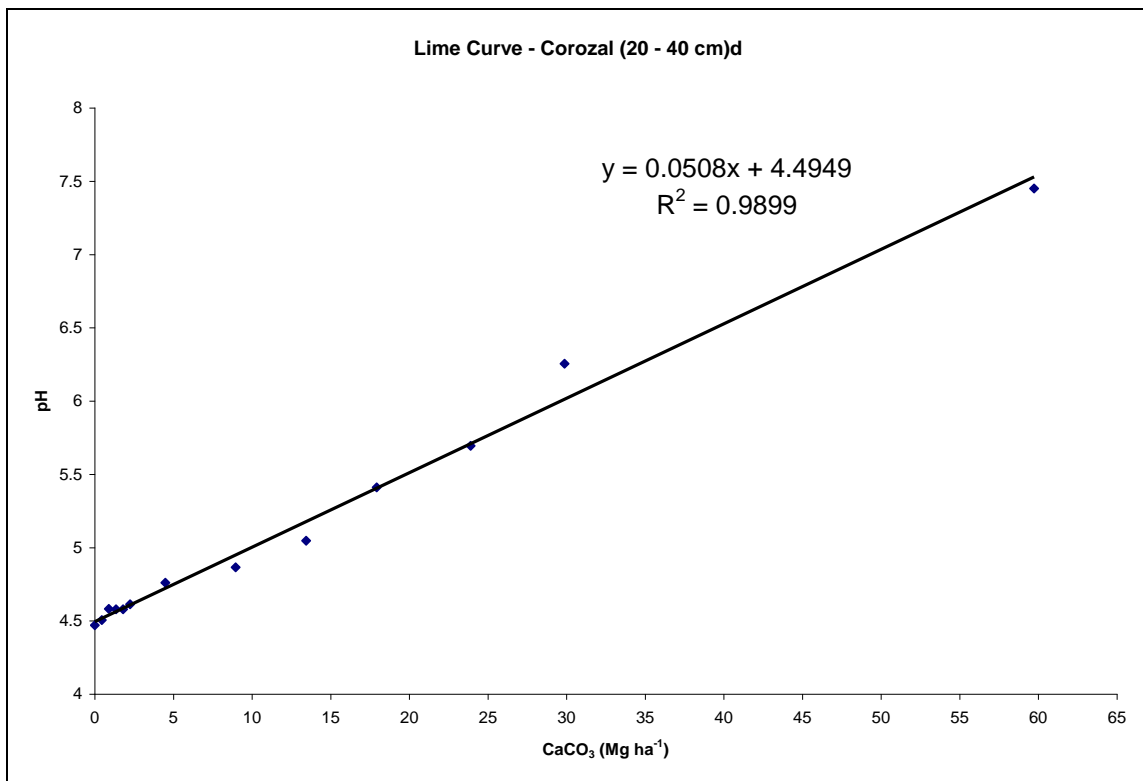
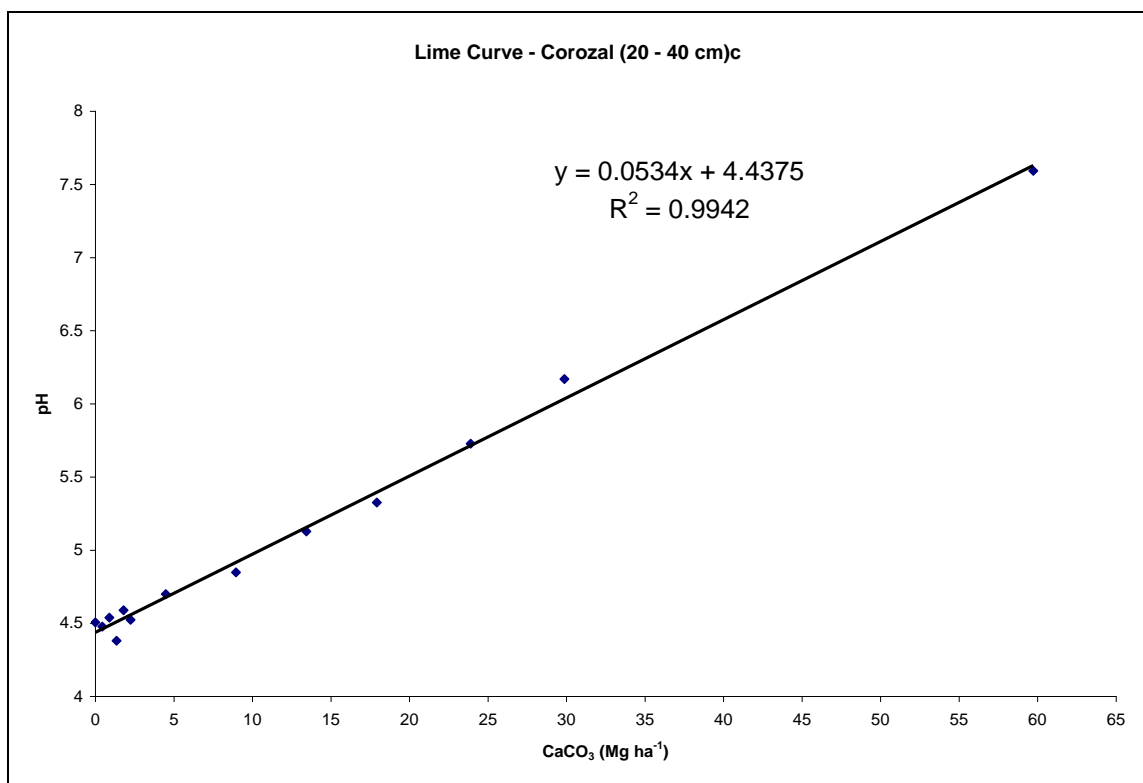


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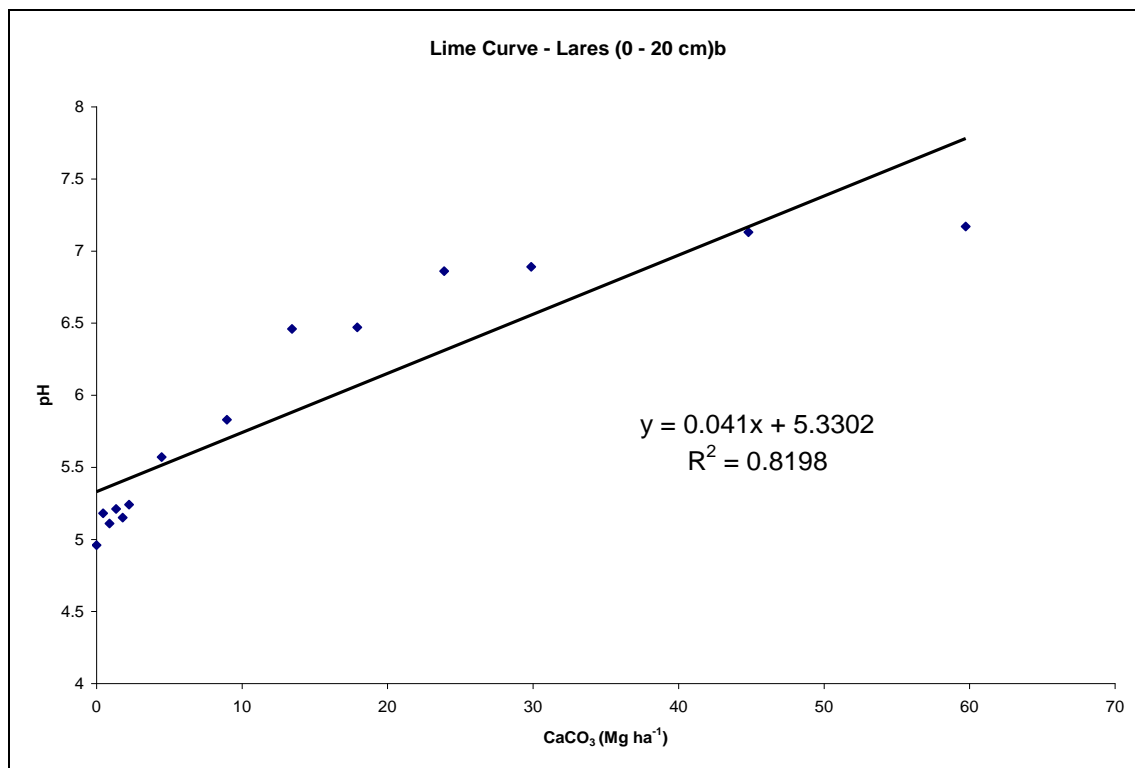
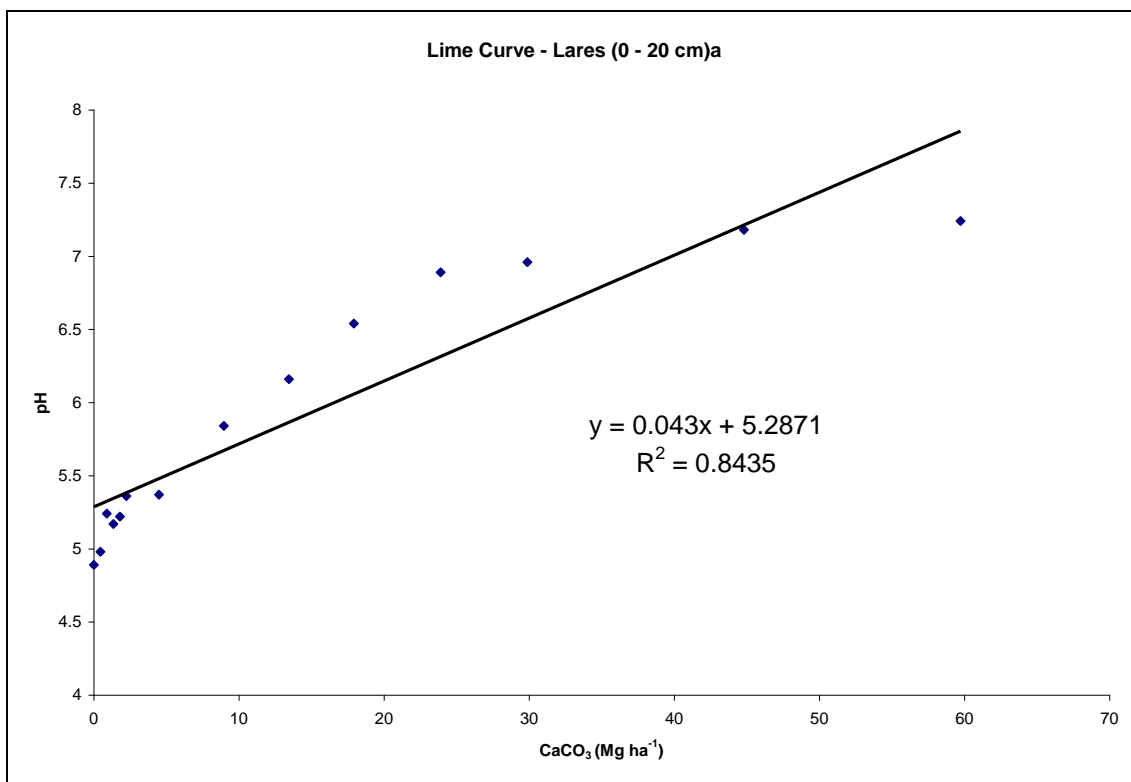


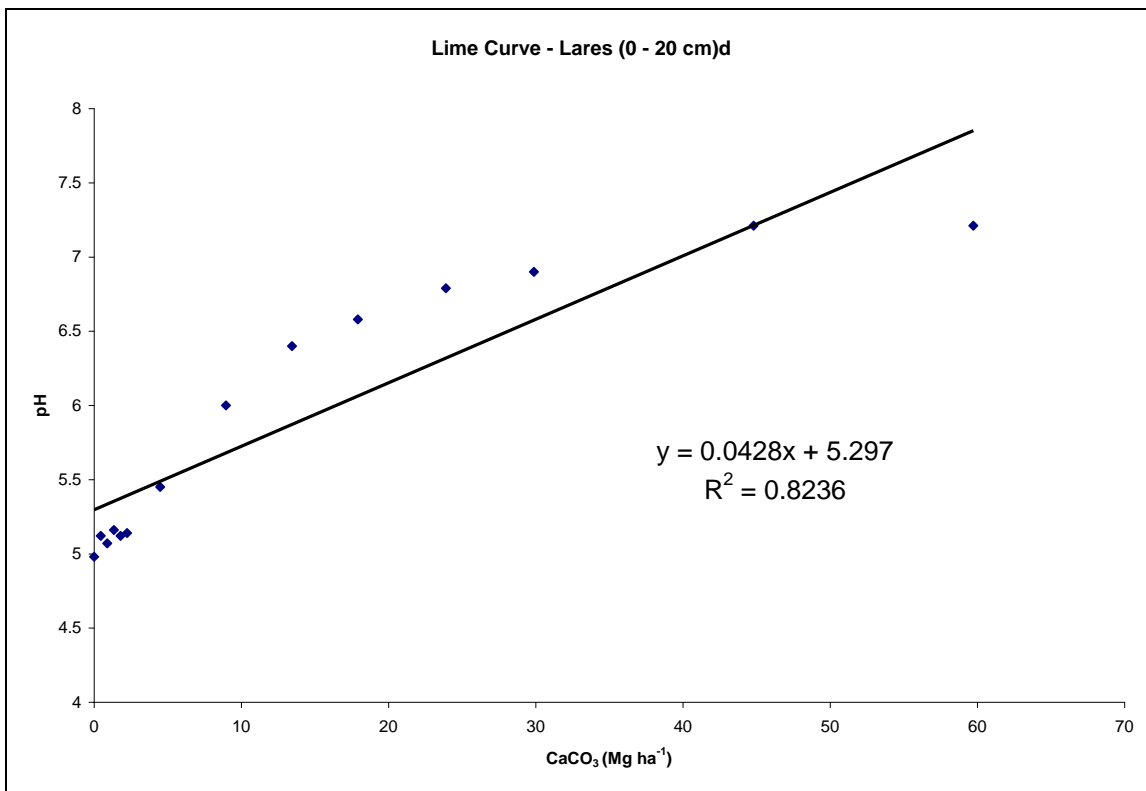
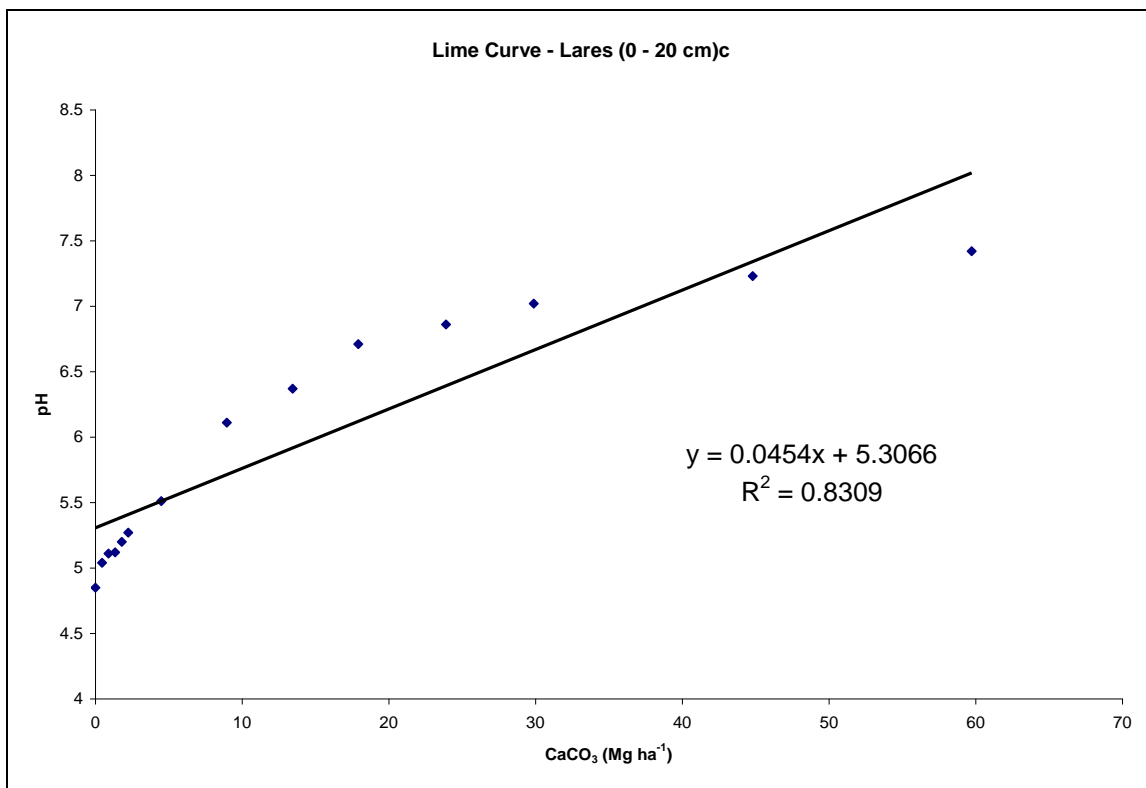


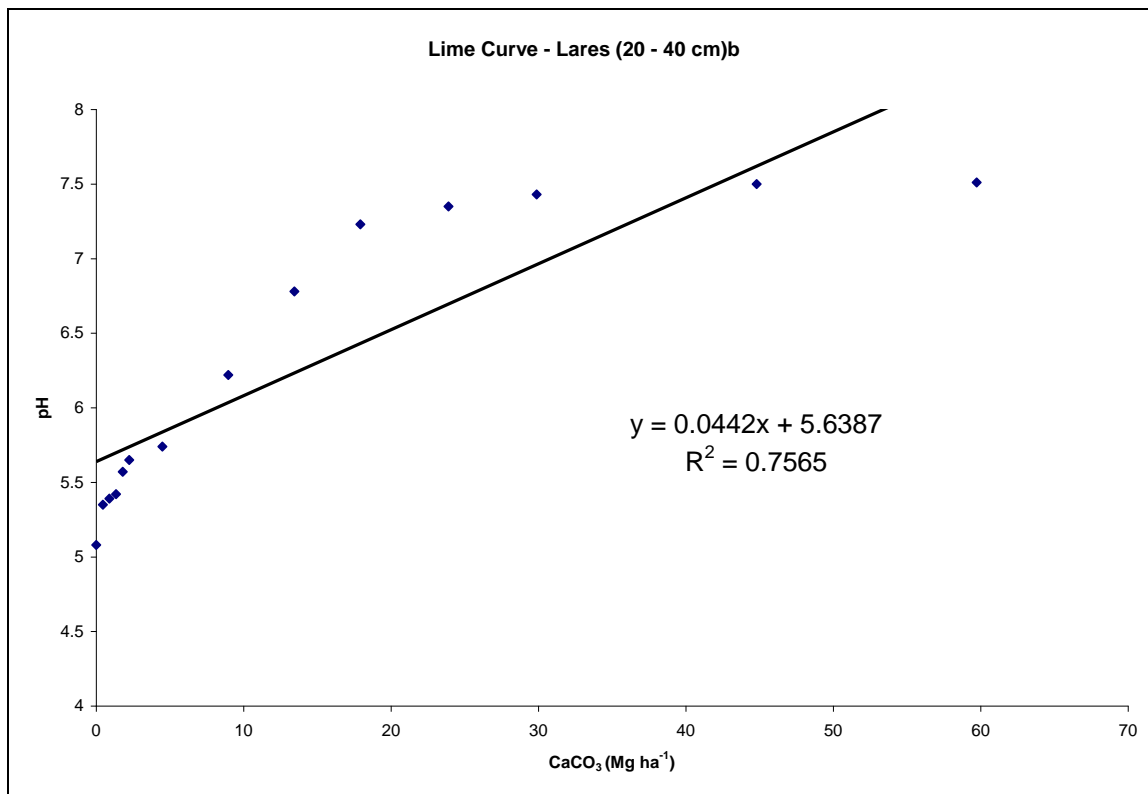
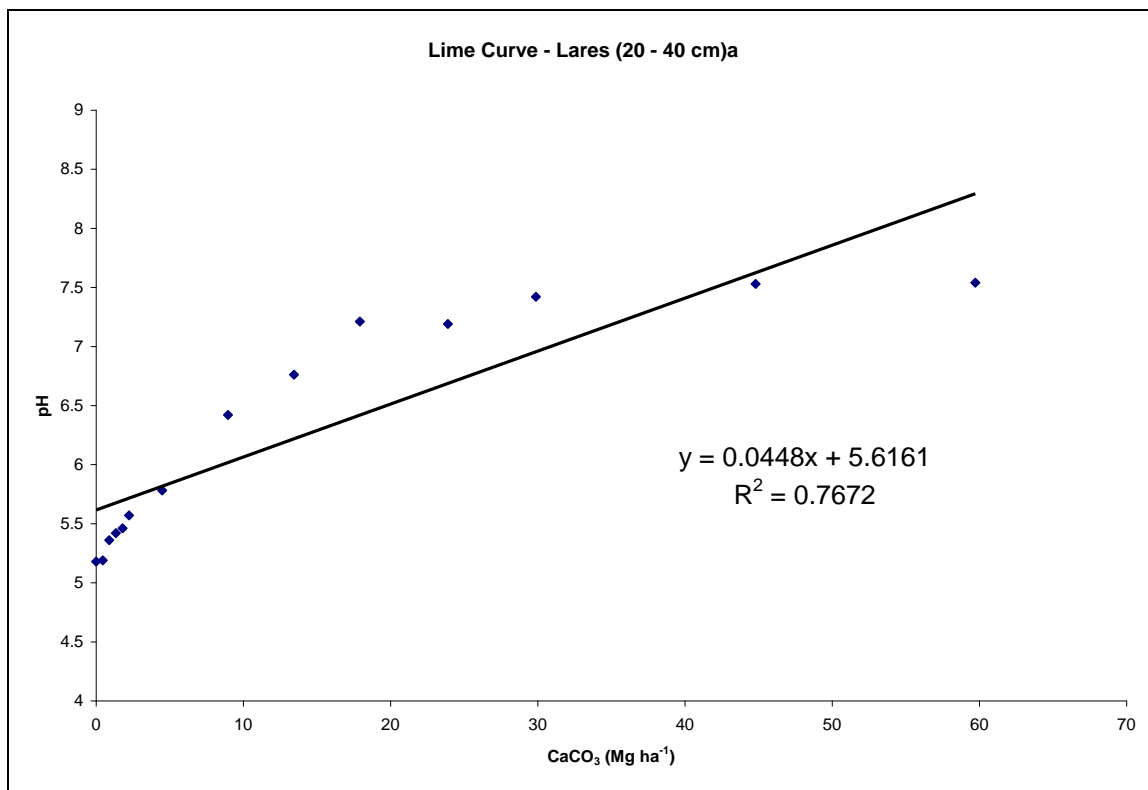




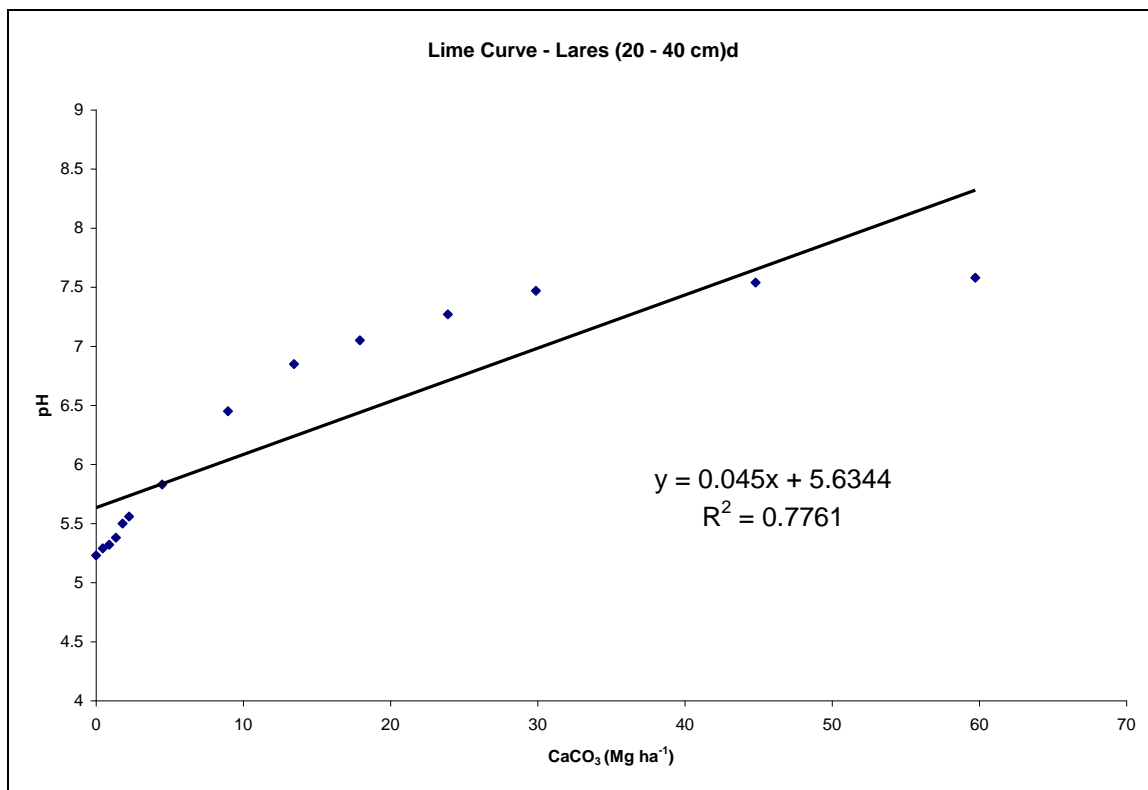
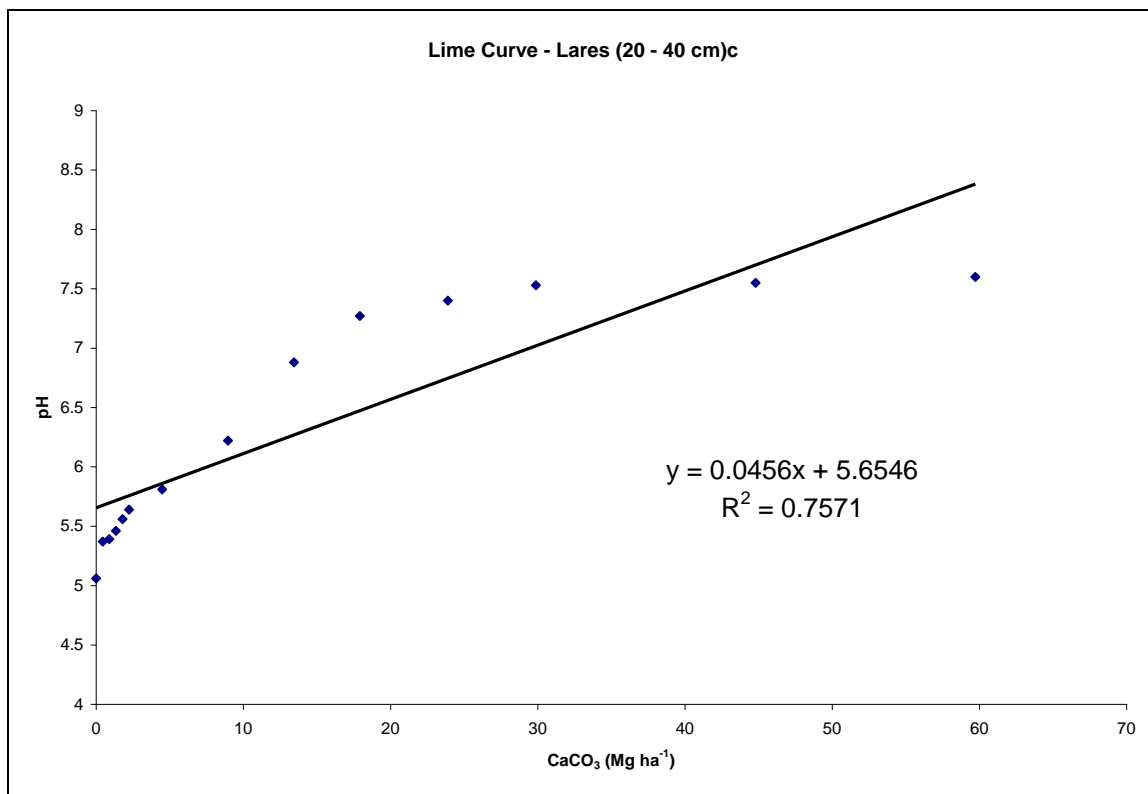
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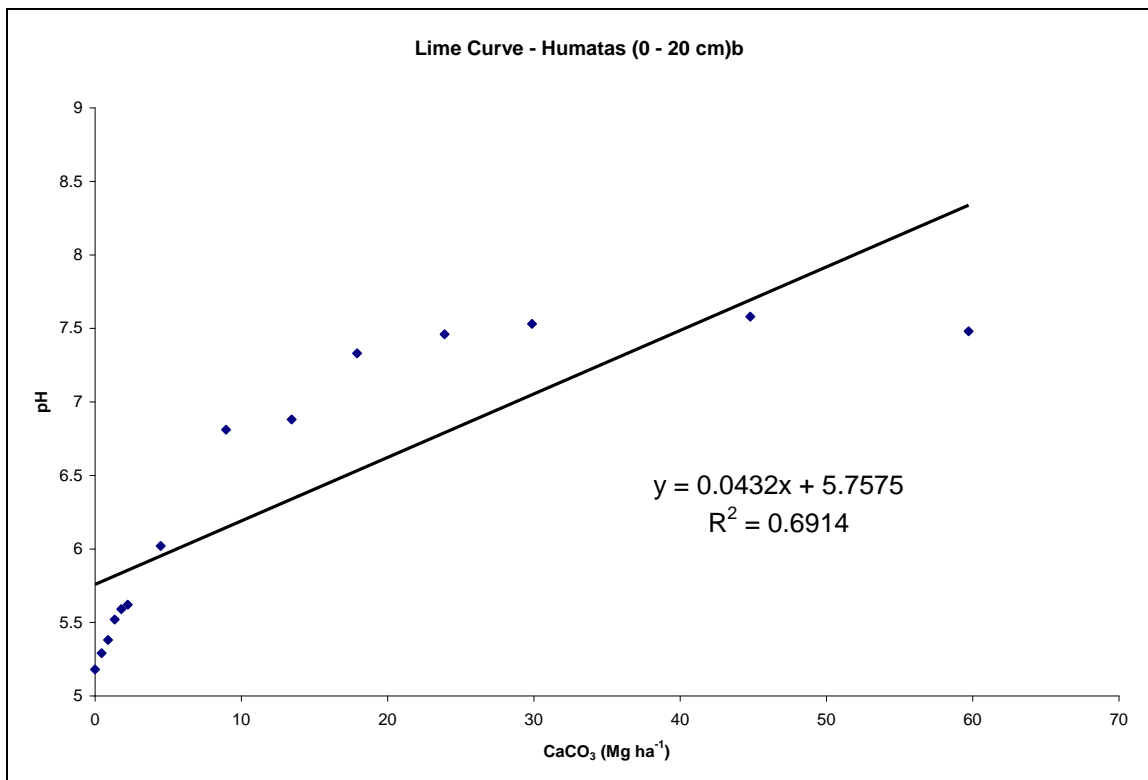
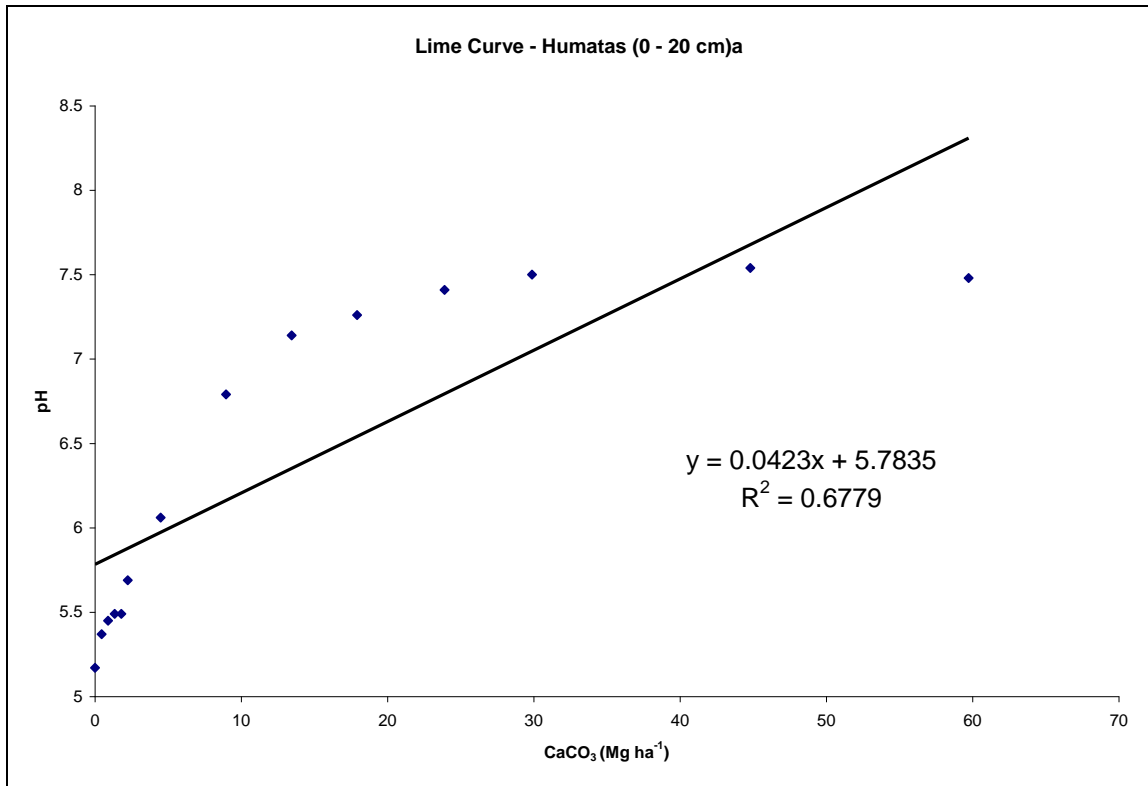


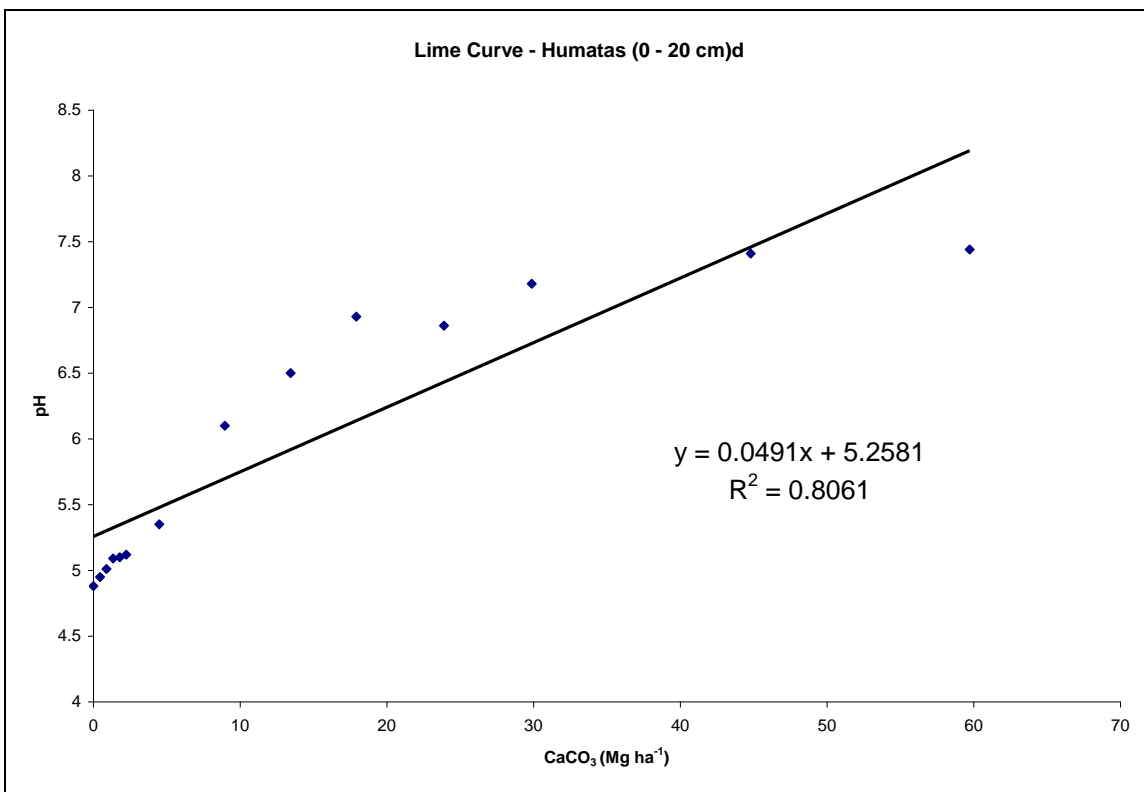
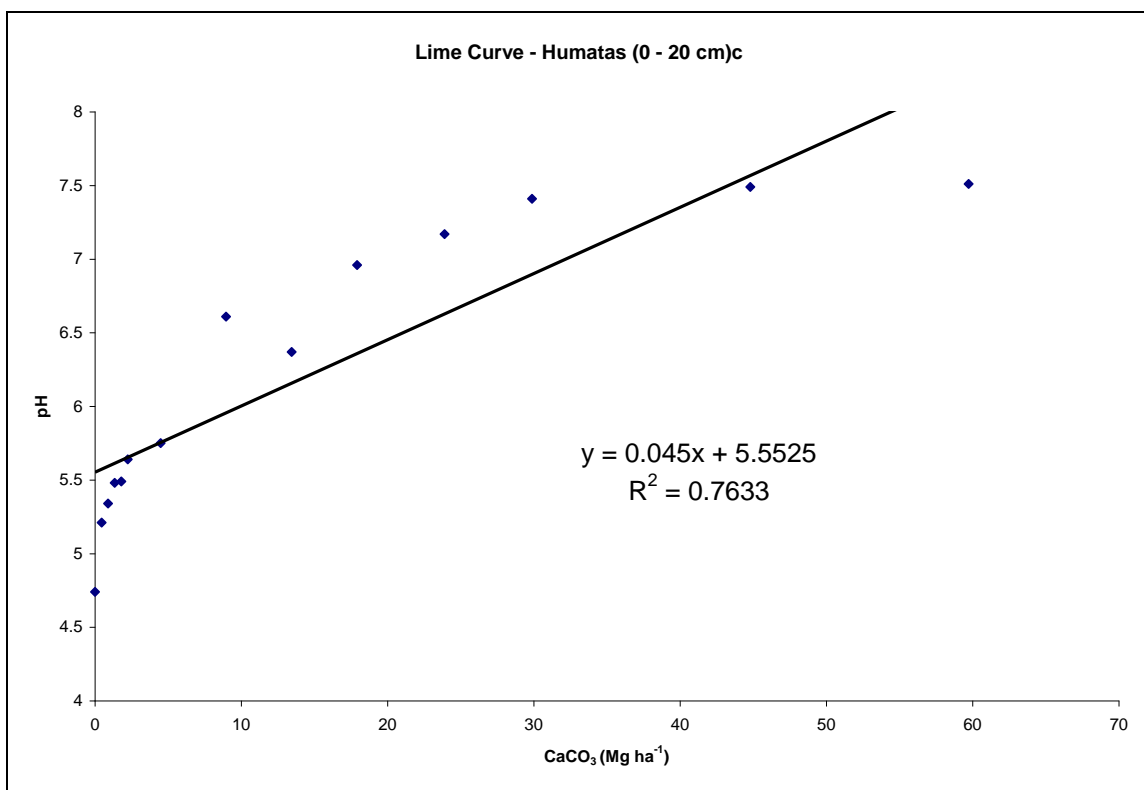


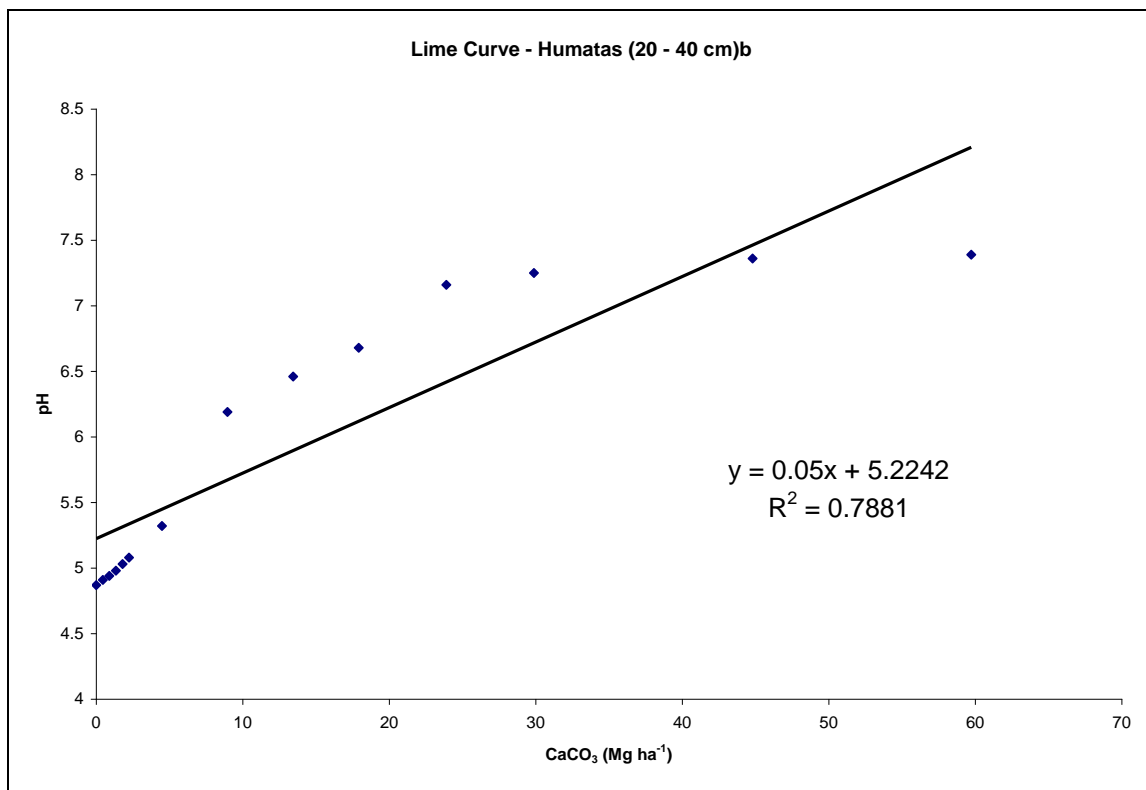
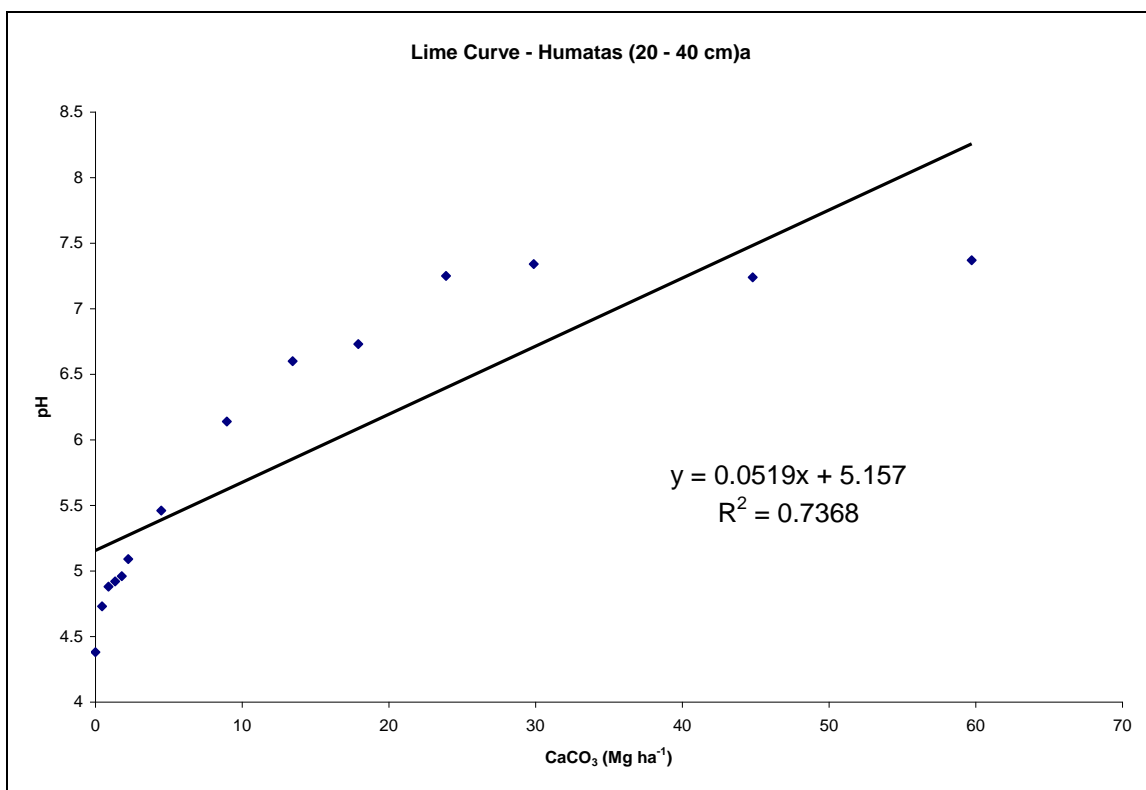


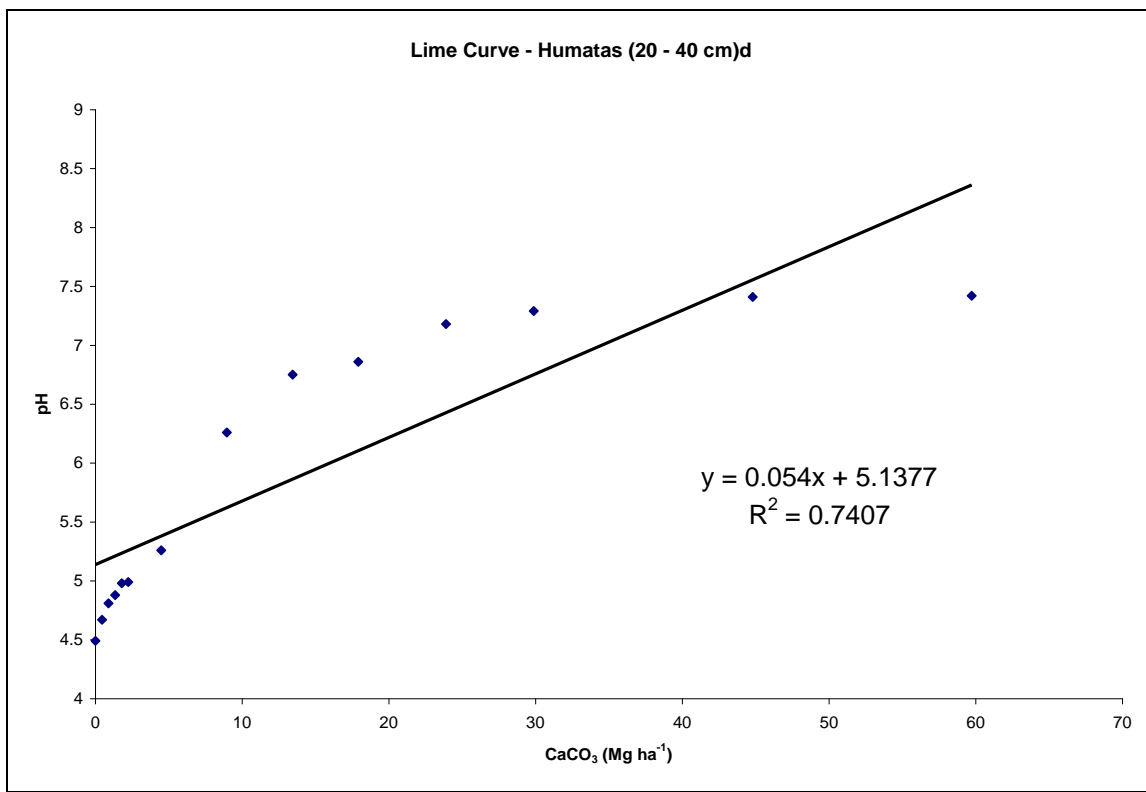
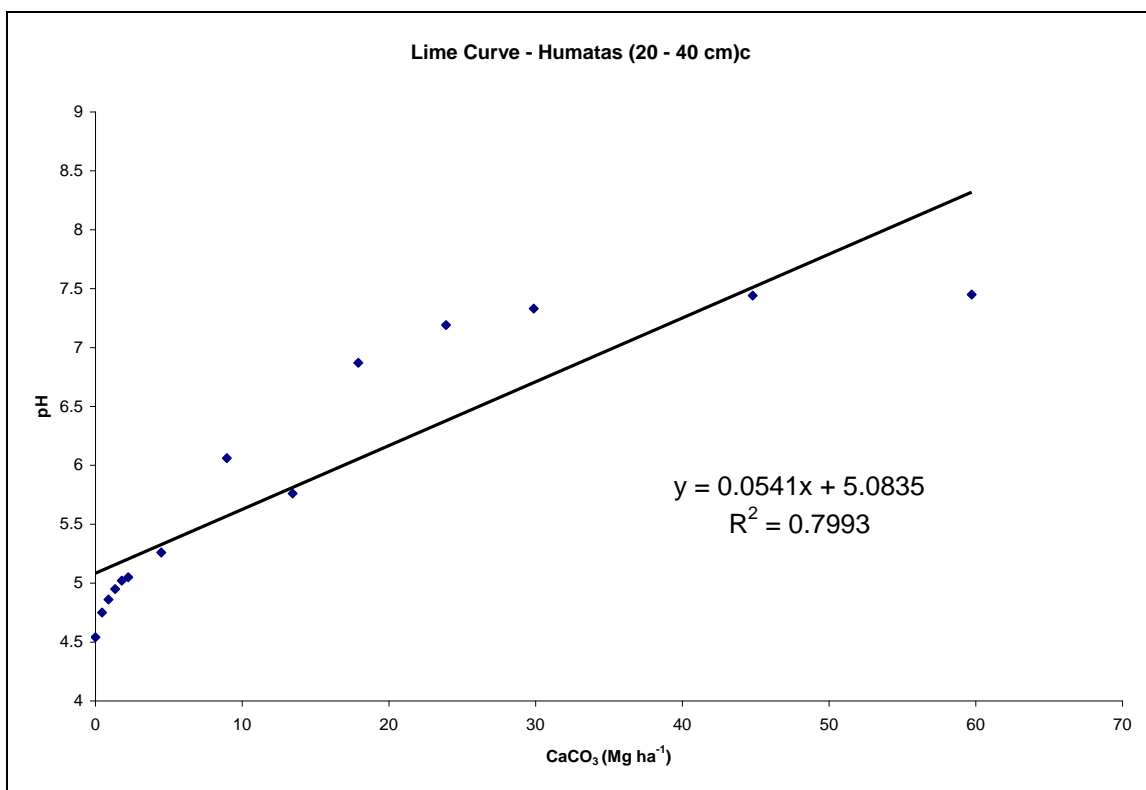


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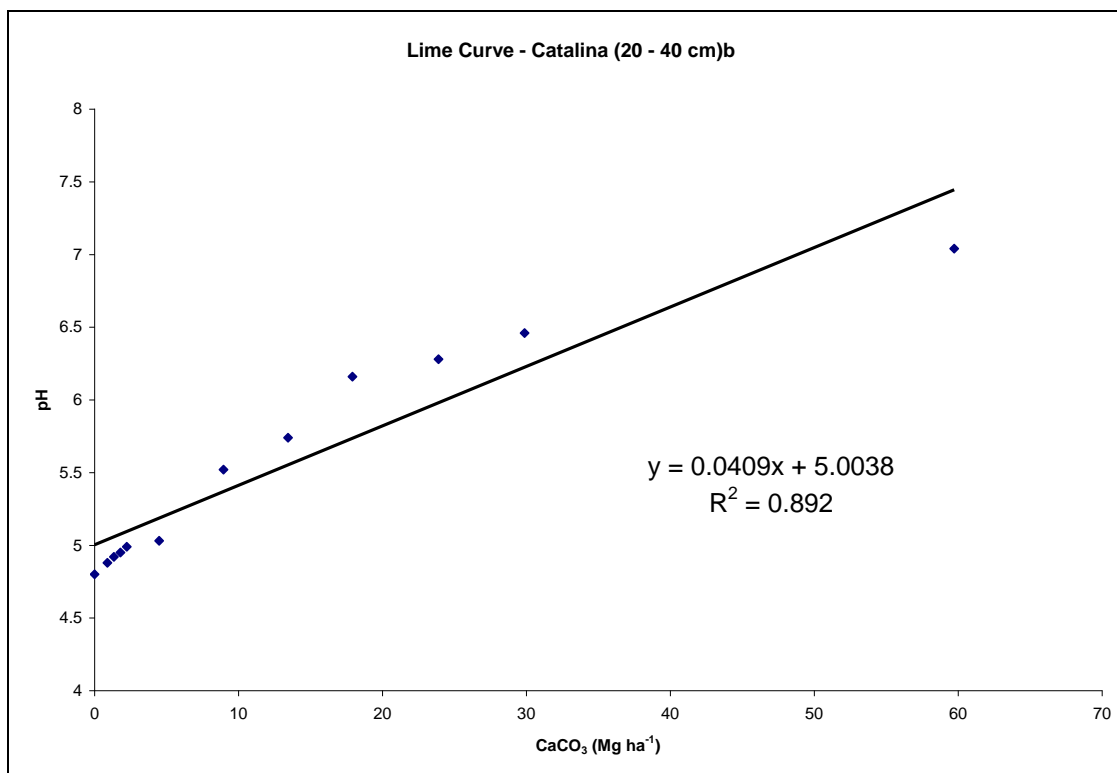
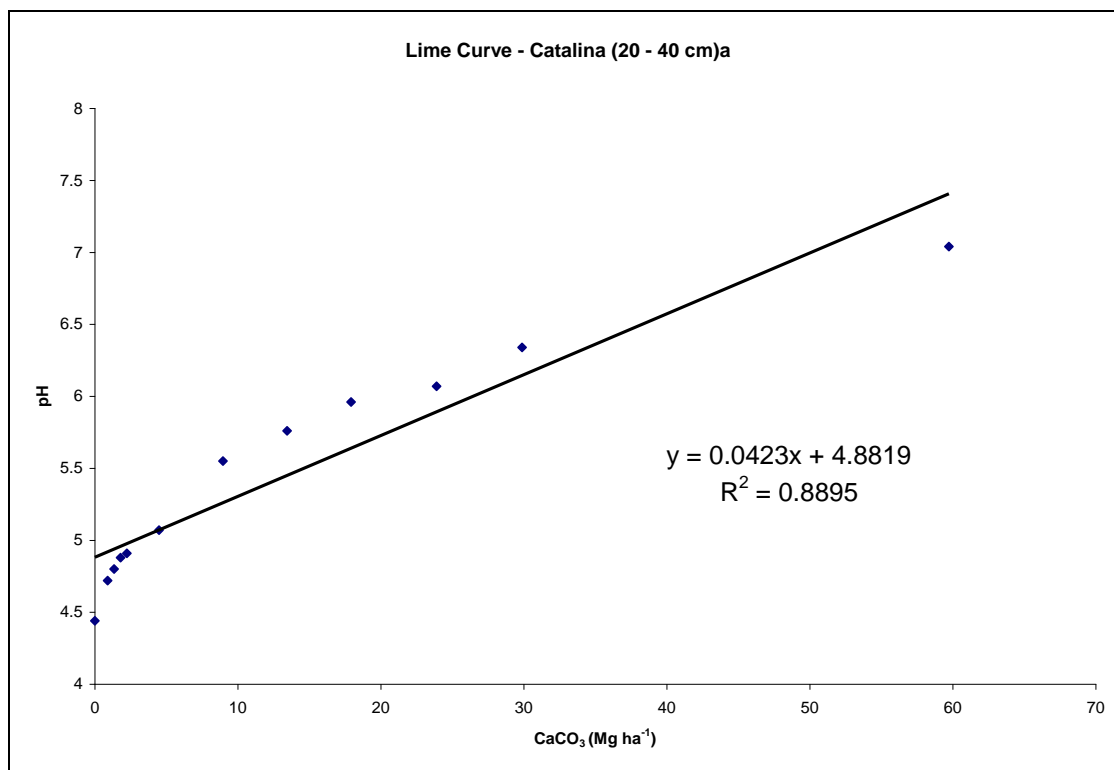


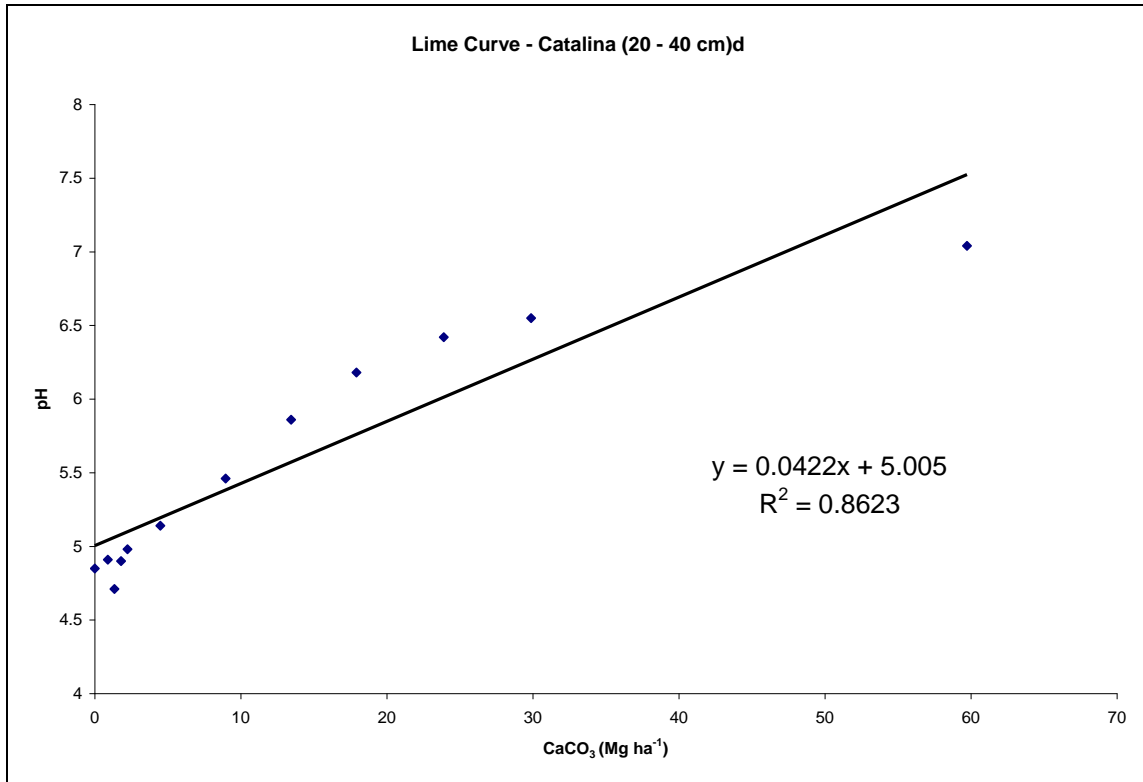
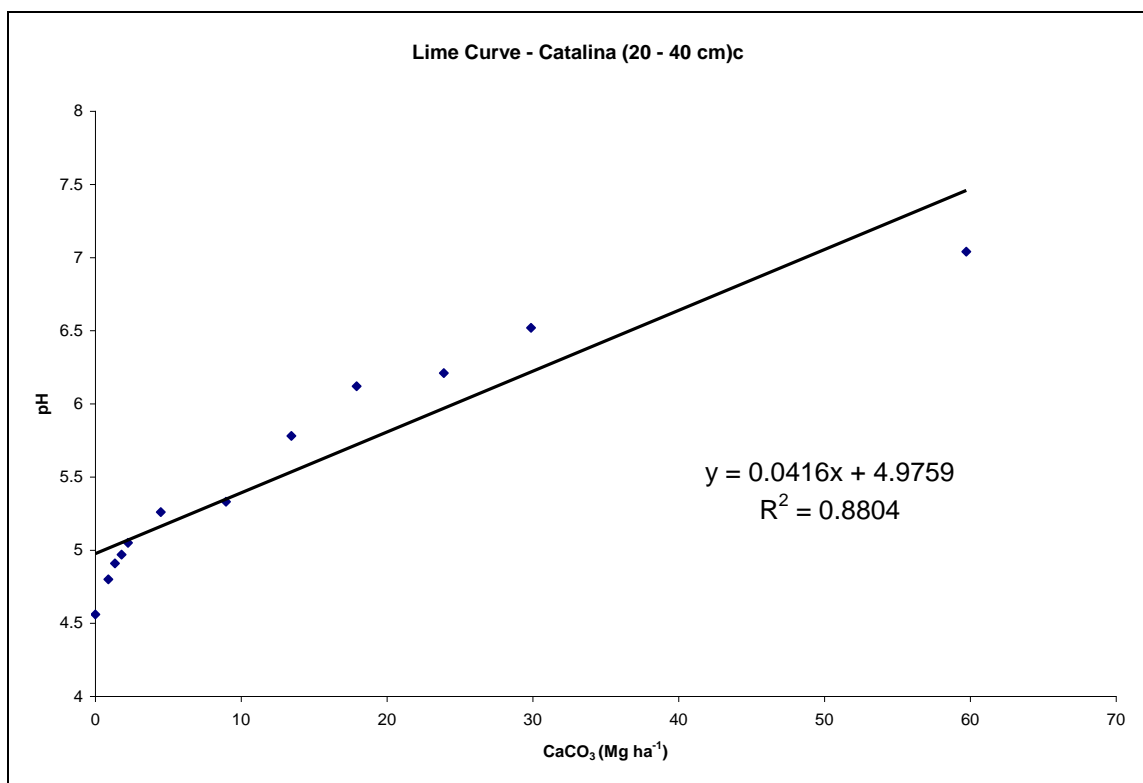




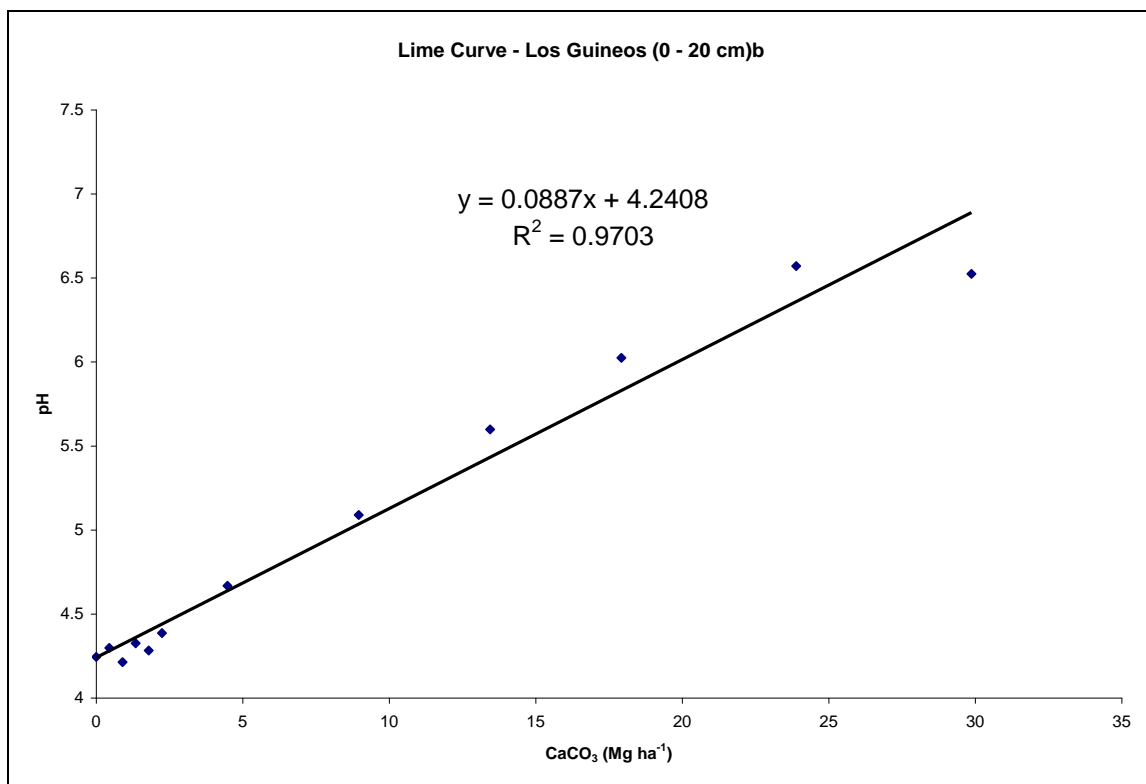
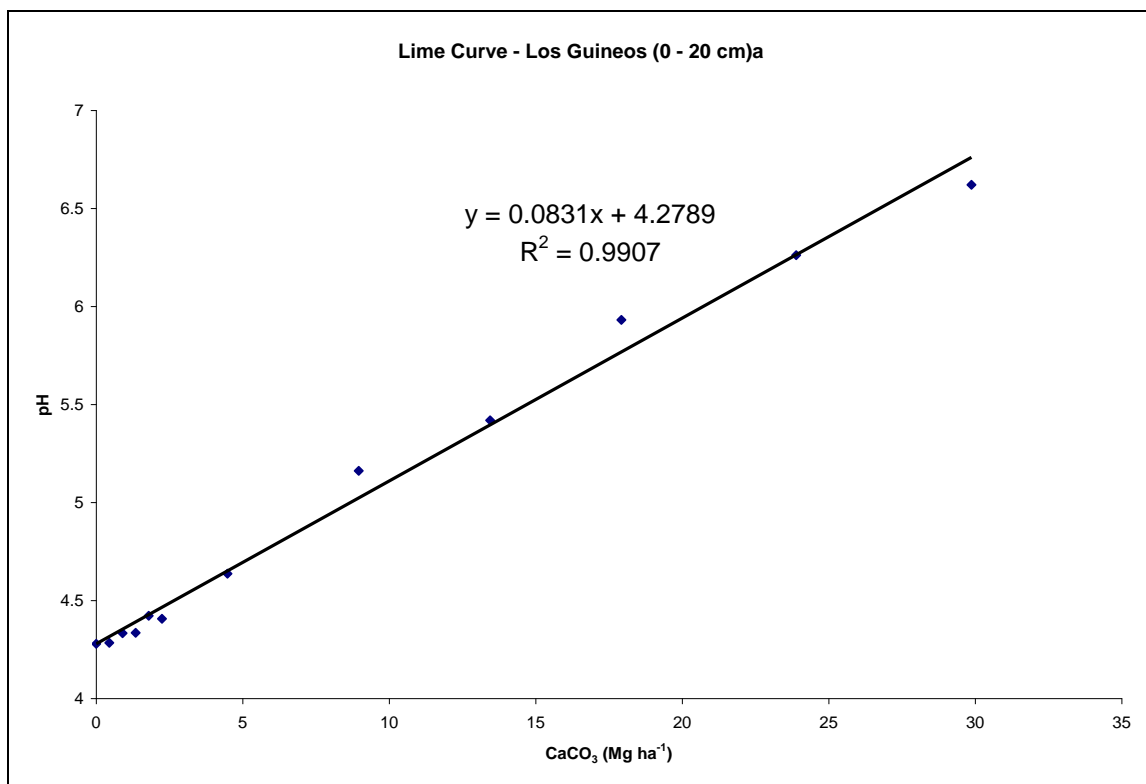


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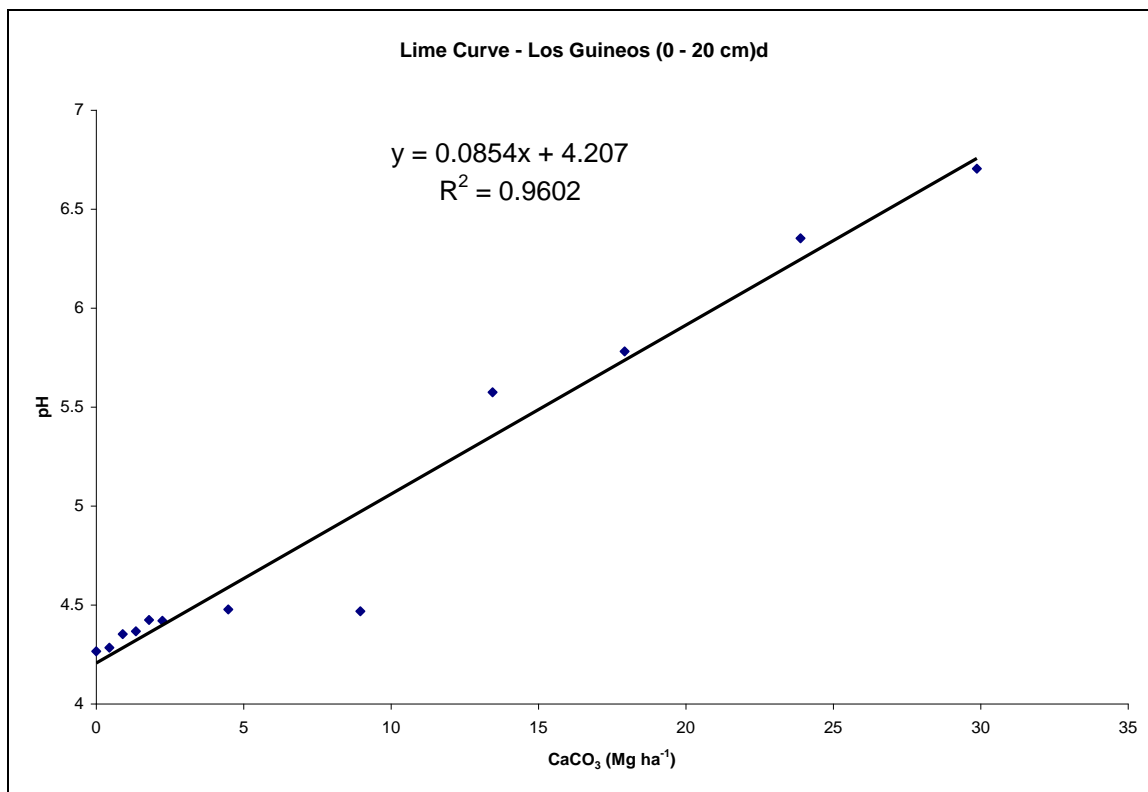
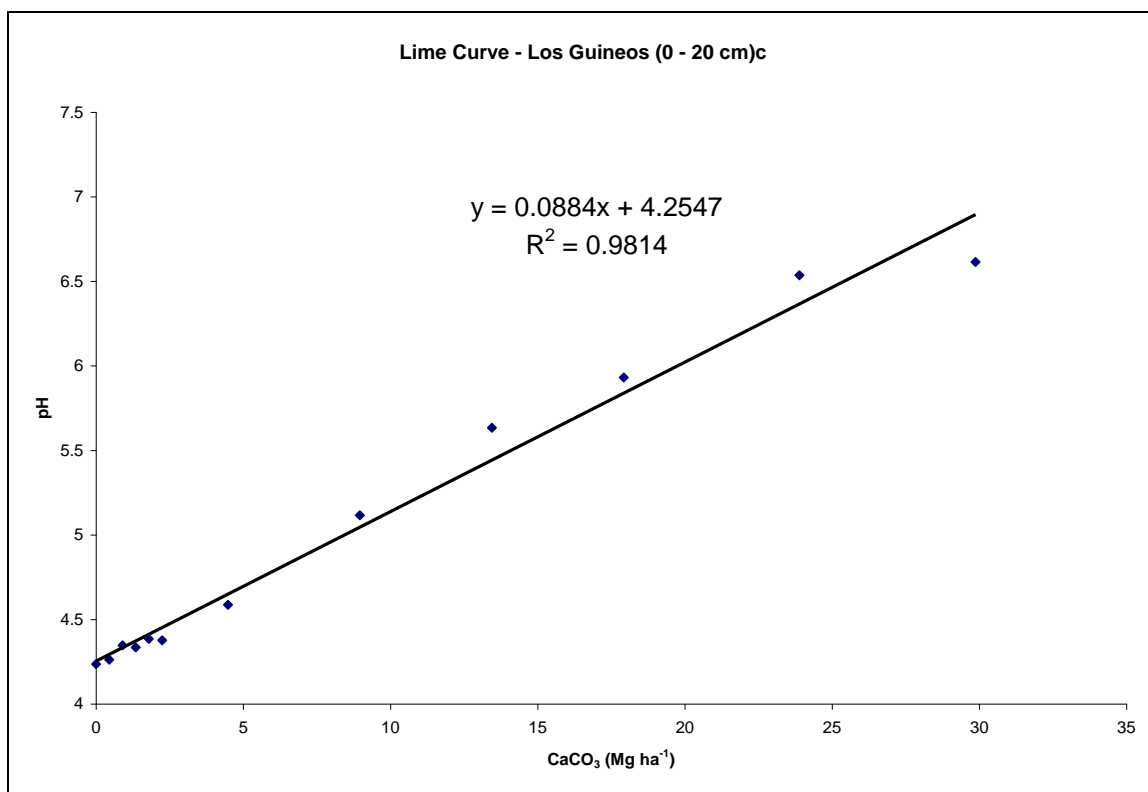


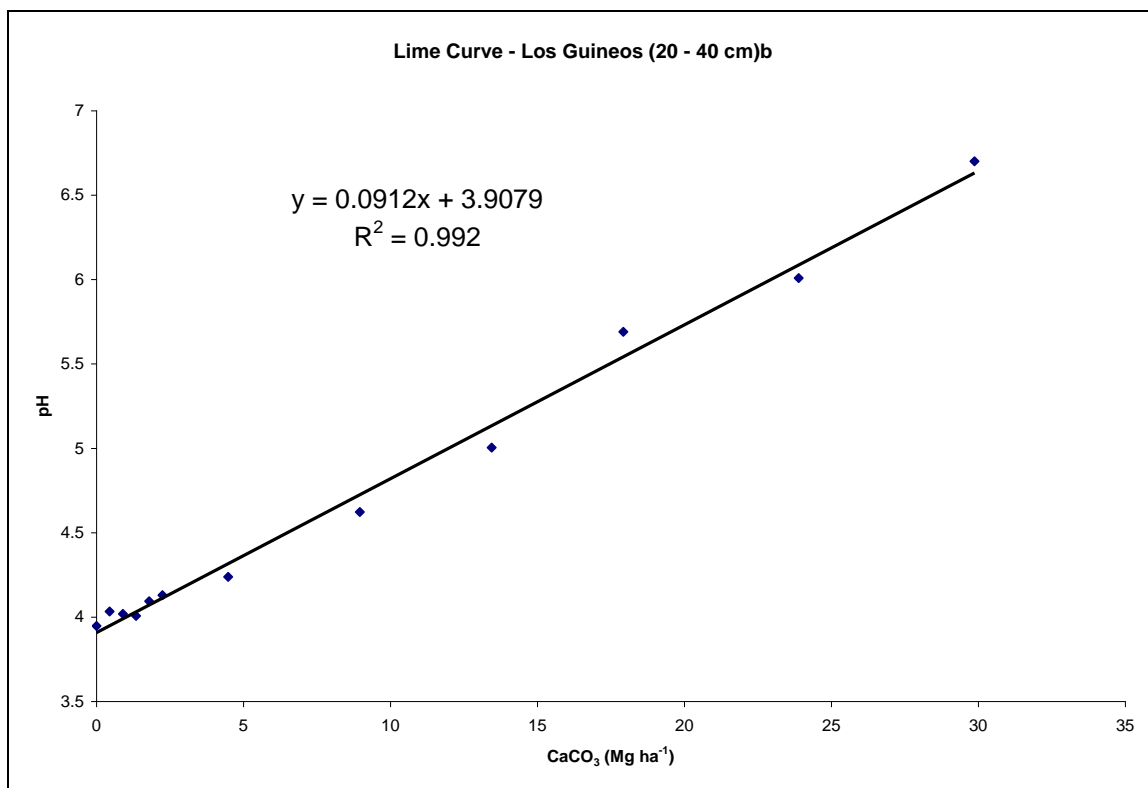
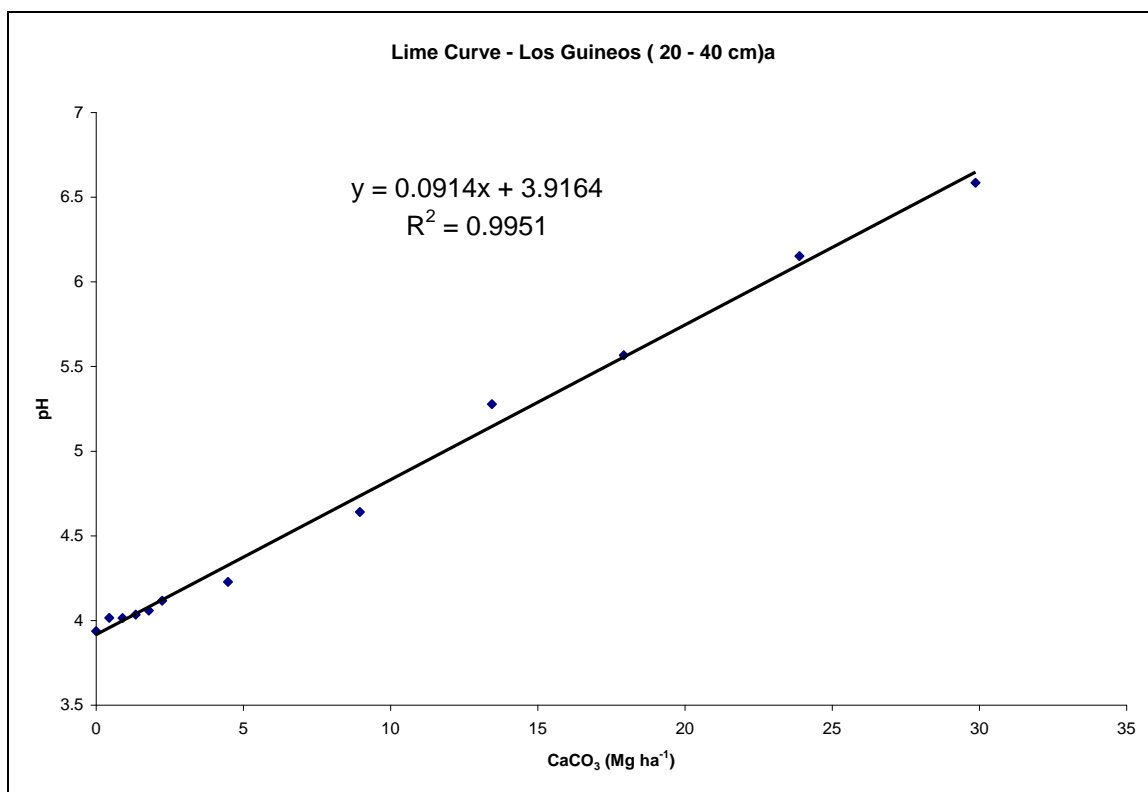


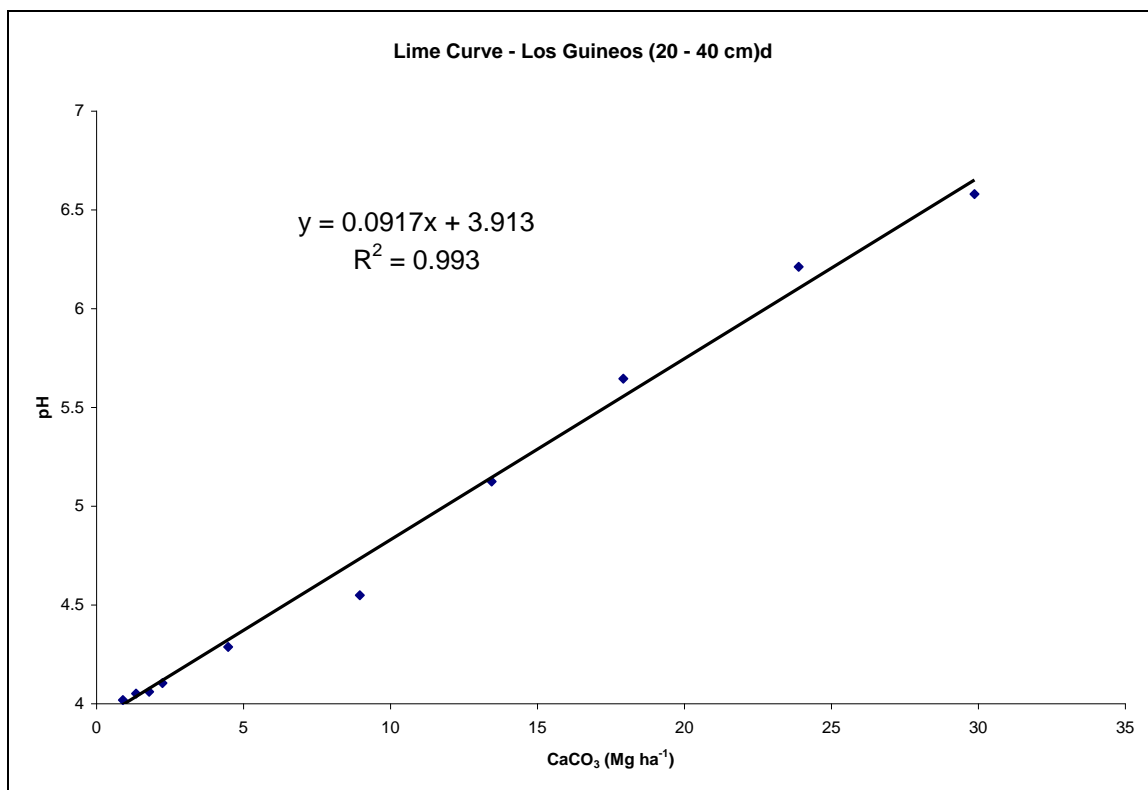
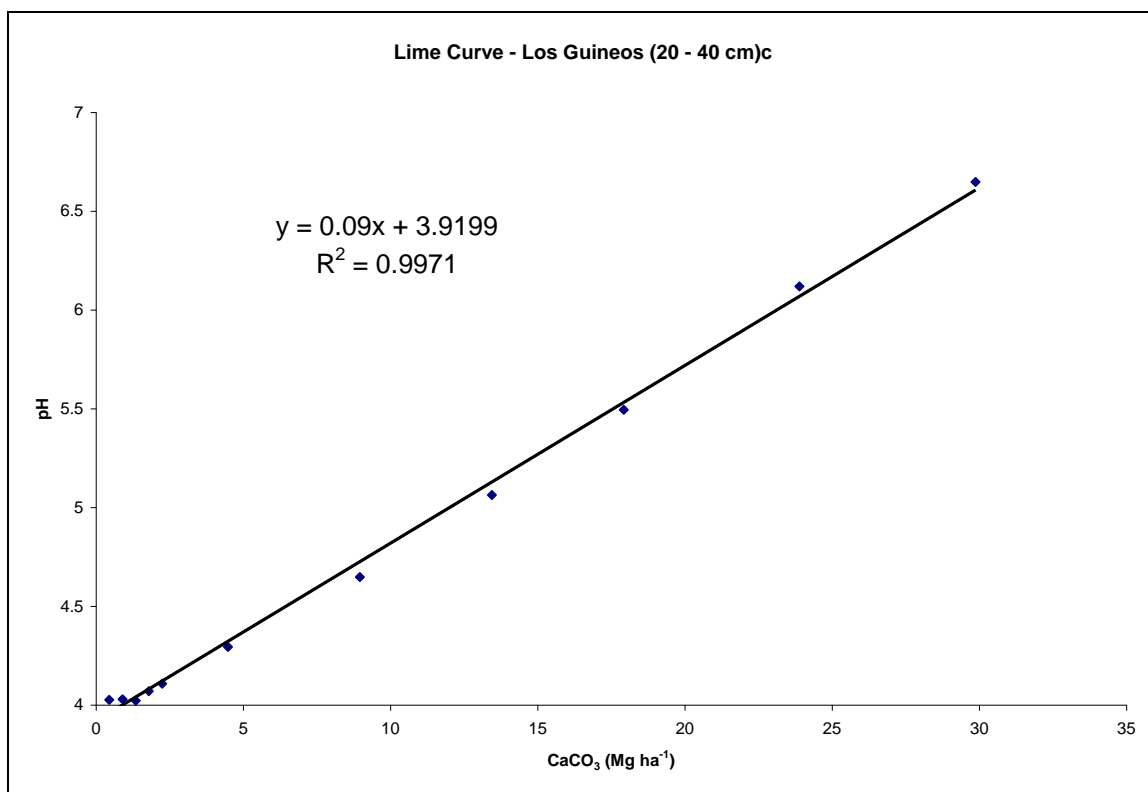
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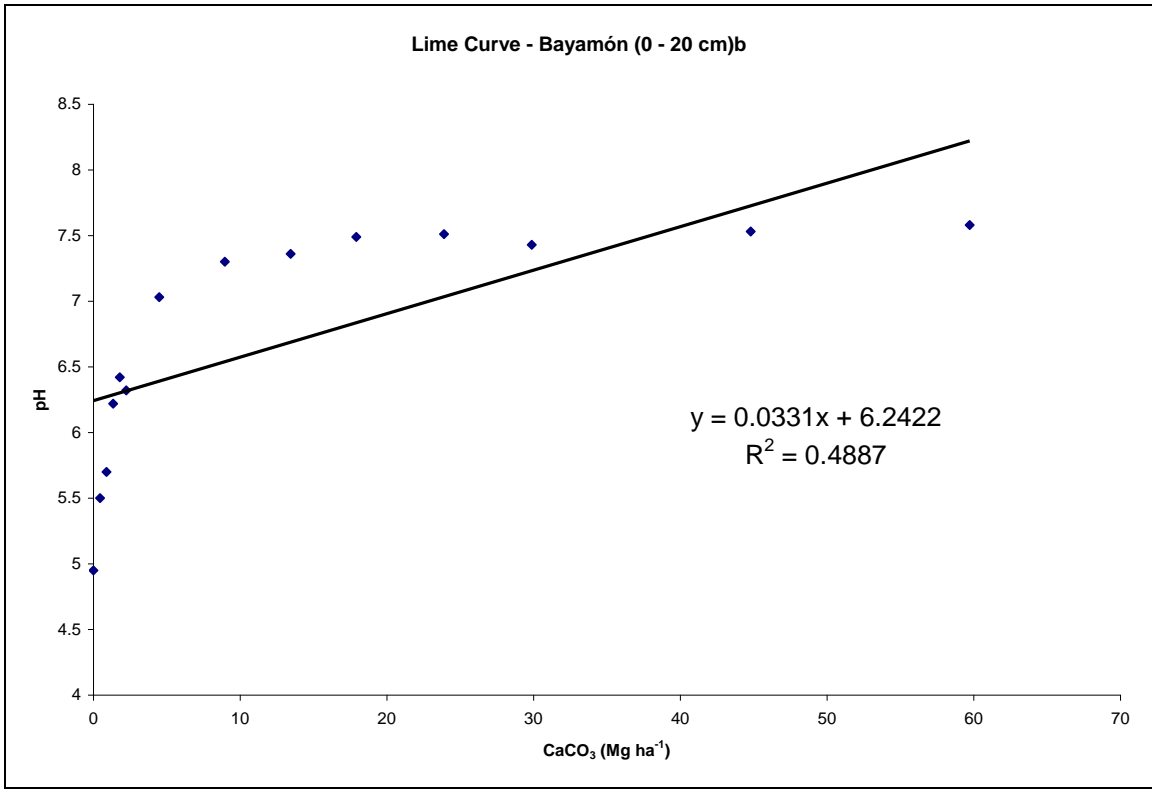
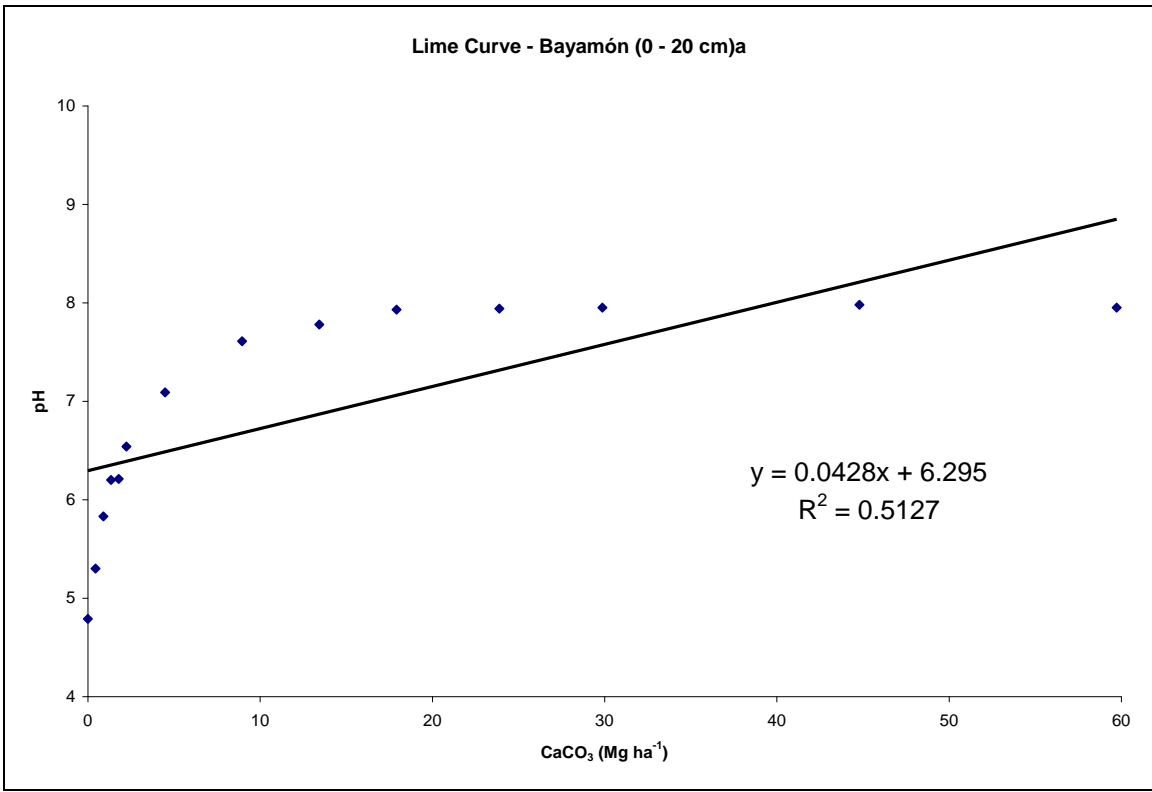


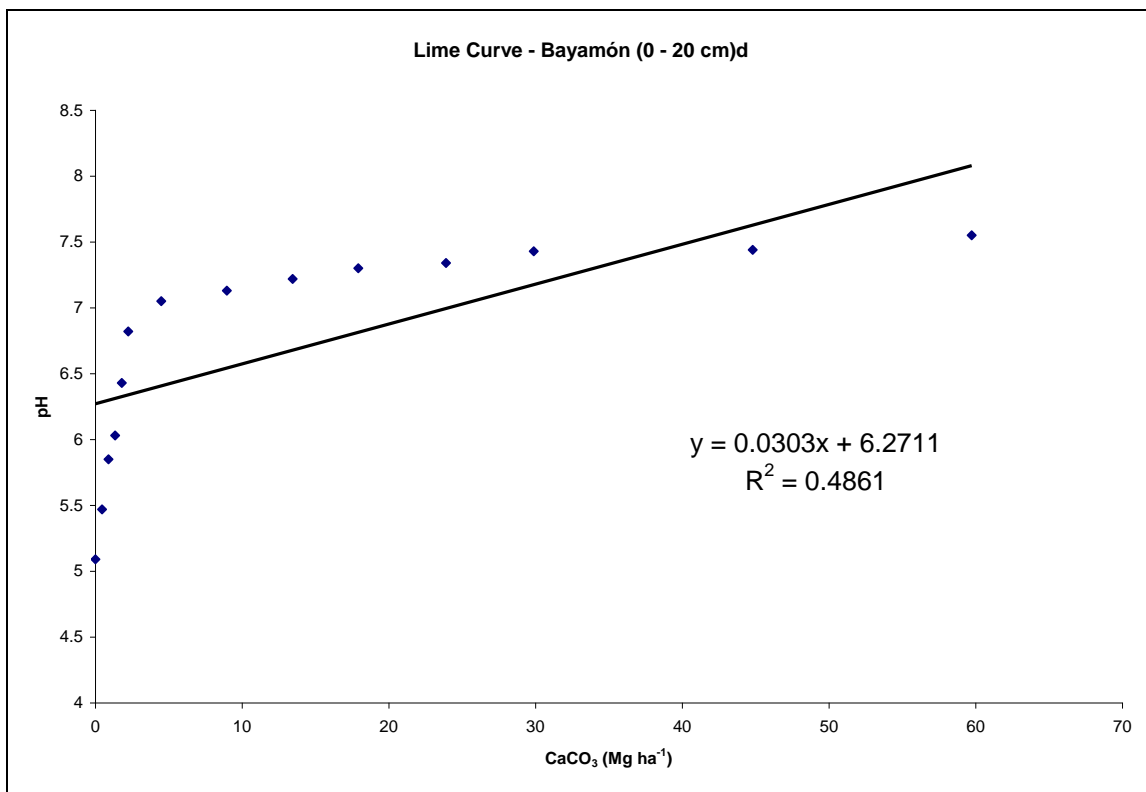
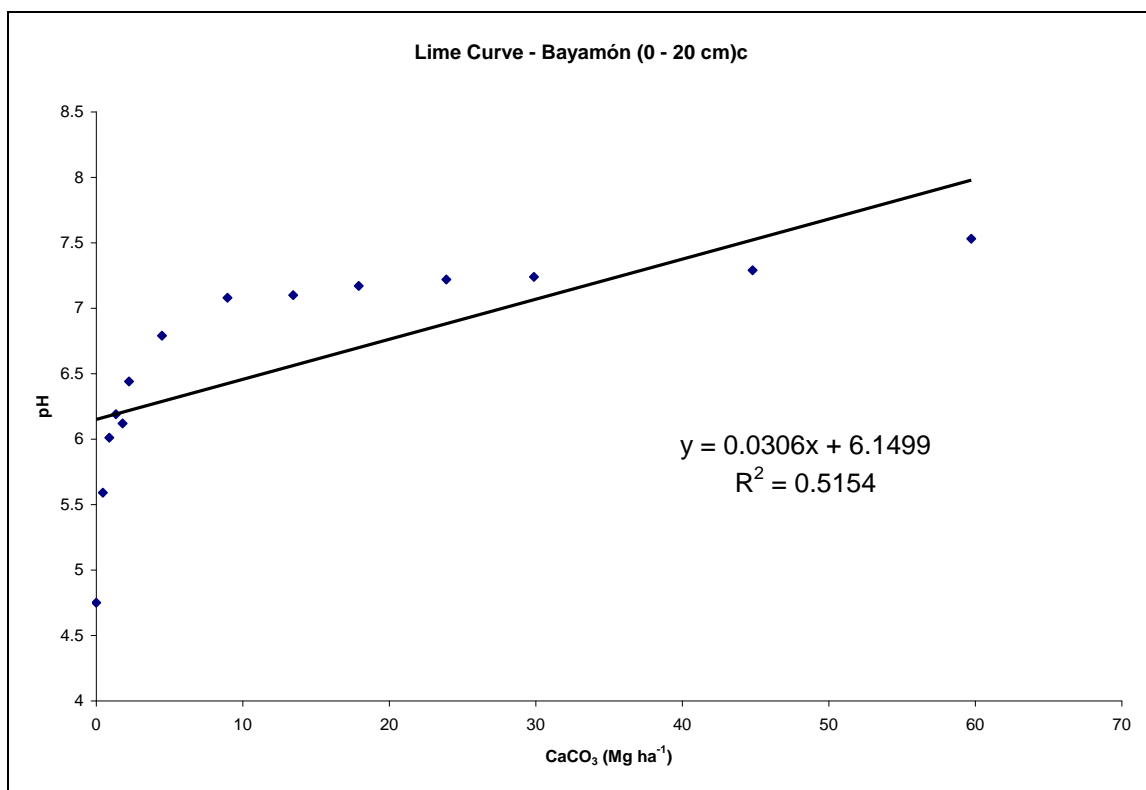


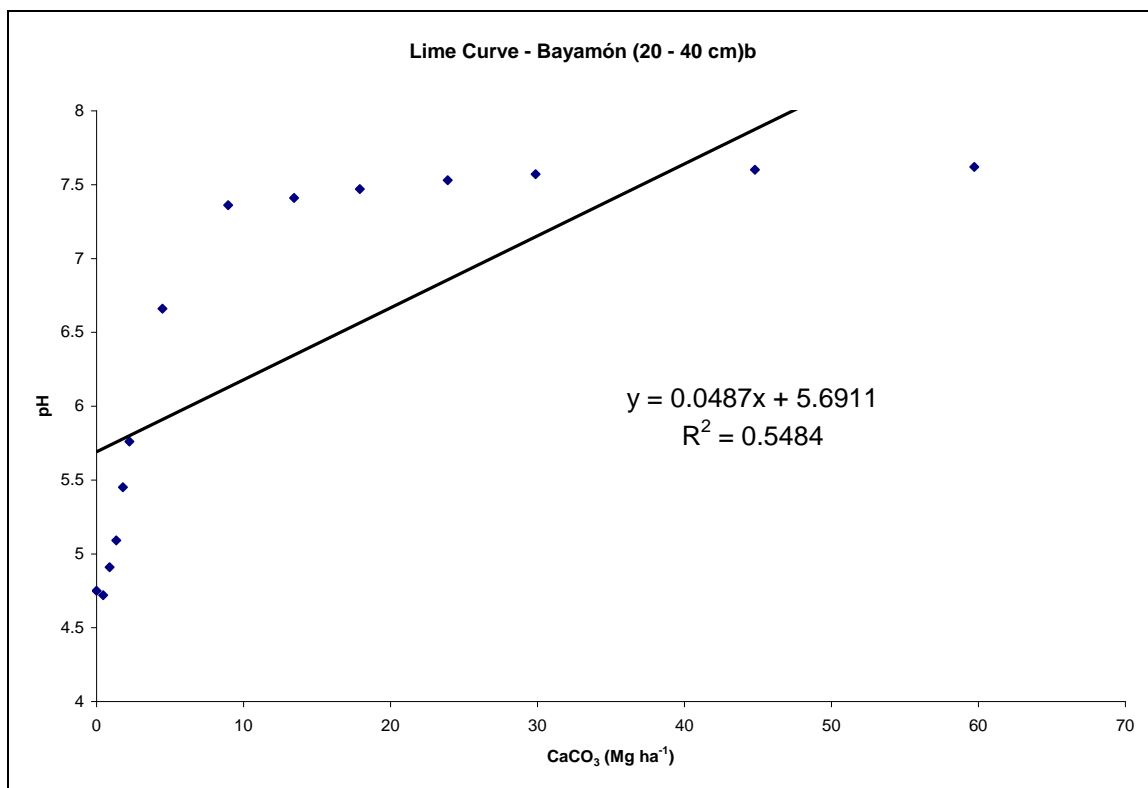
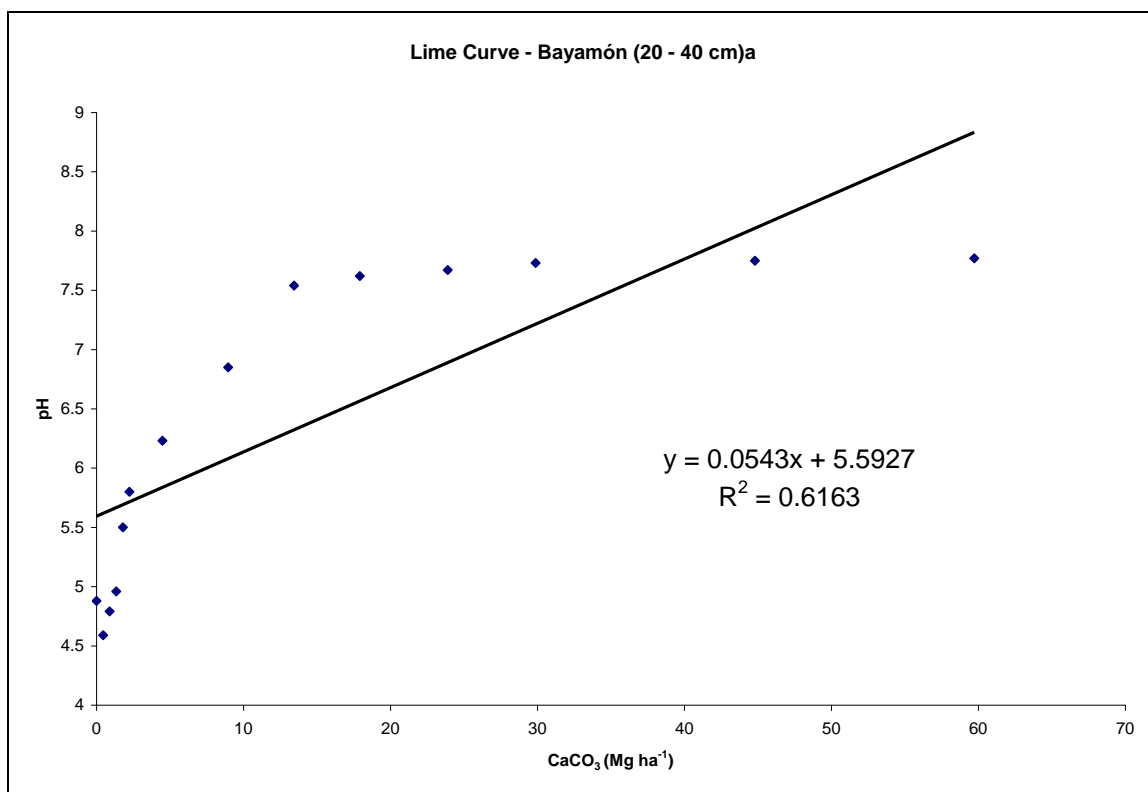


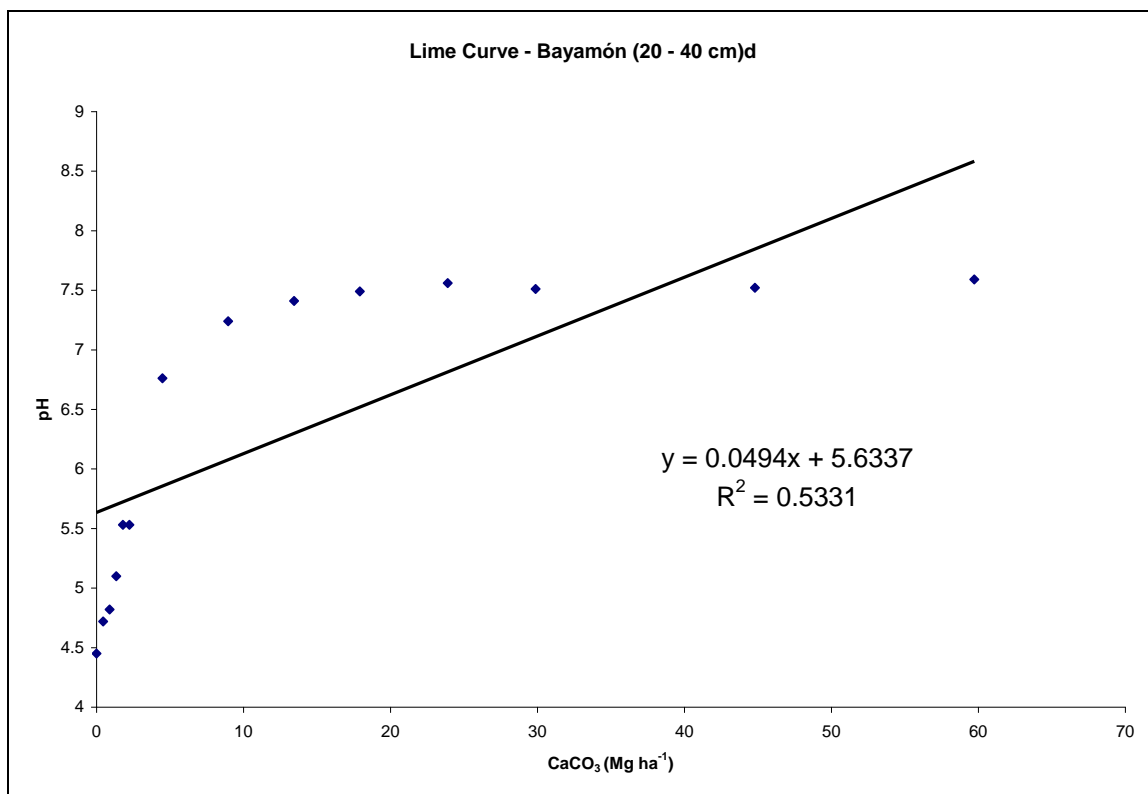
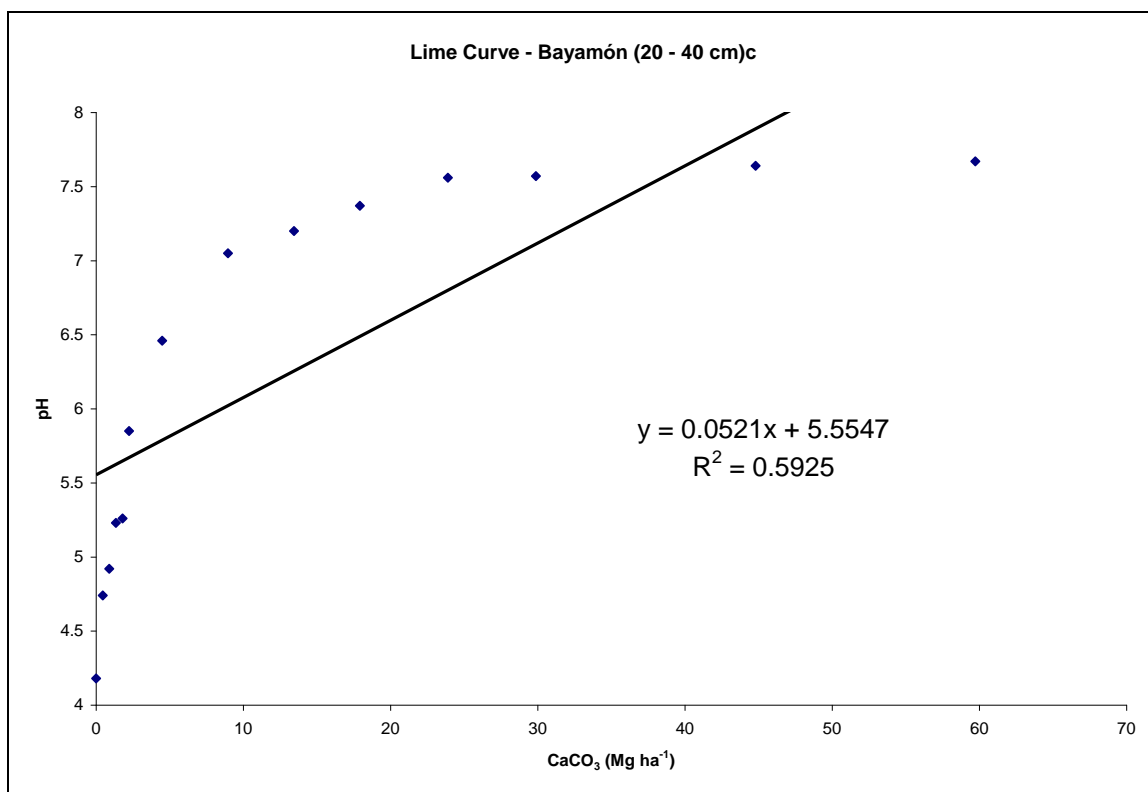


### G. Bayamón Series

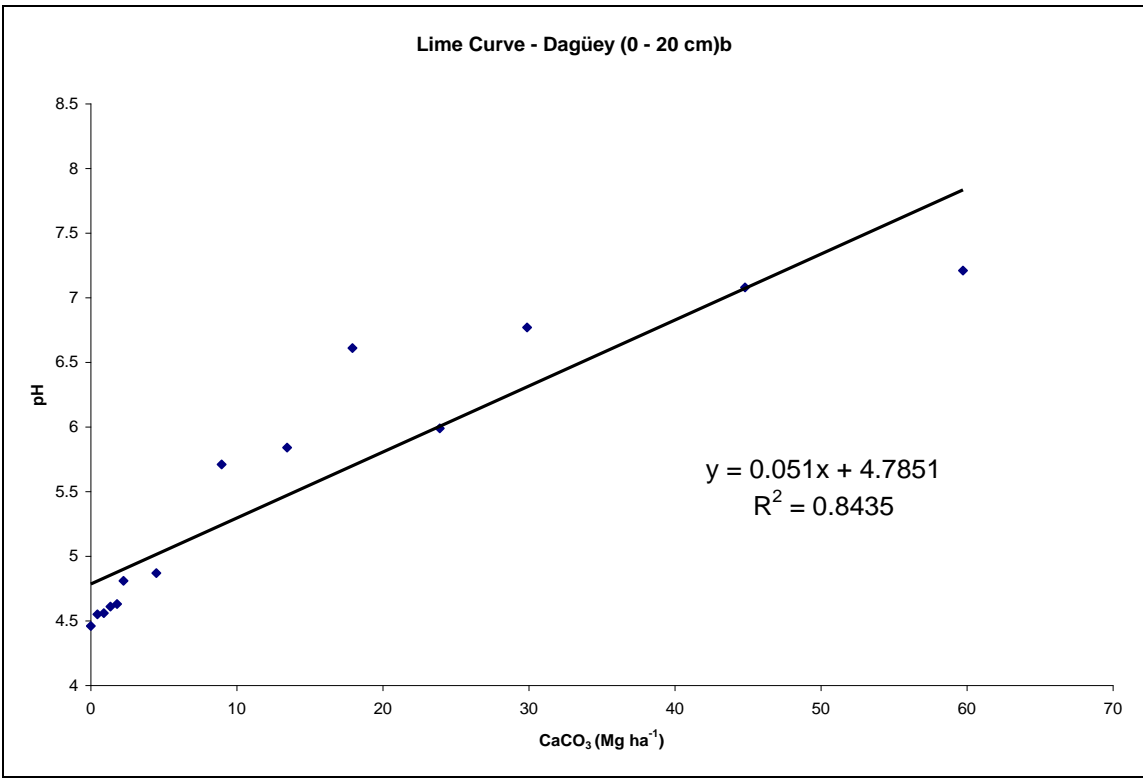
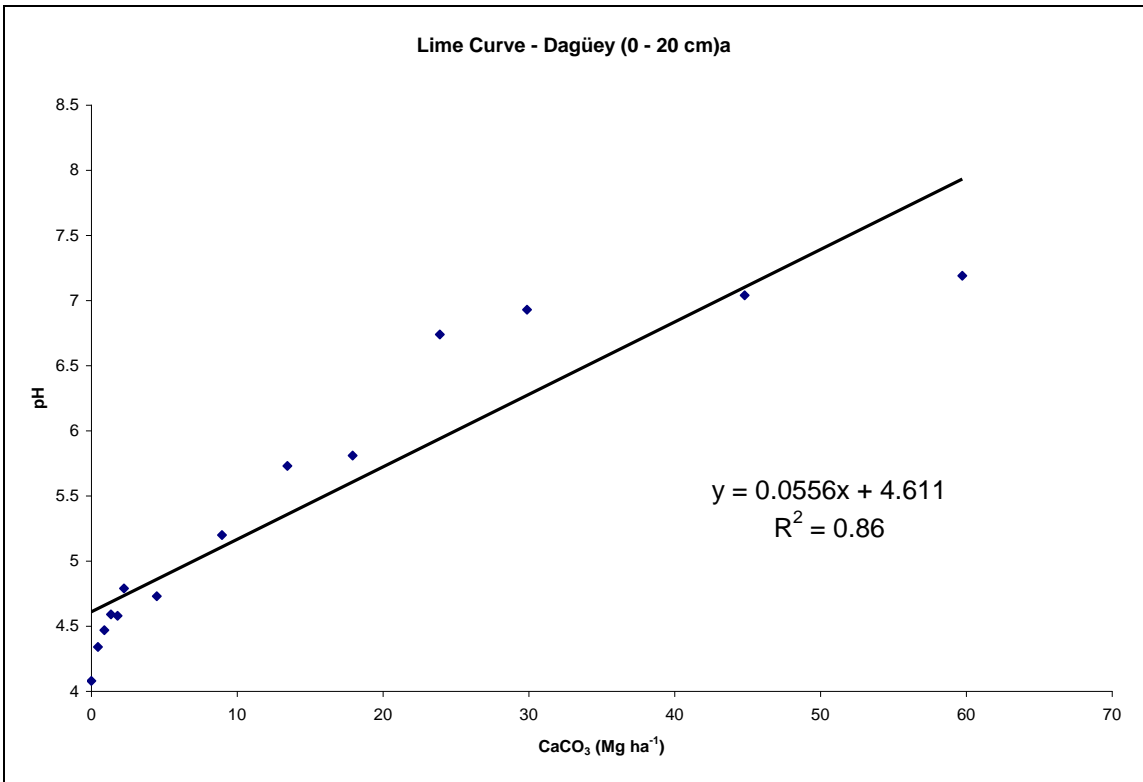




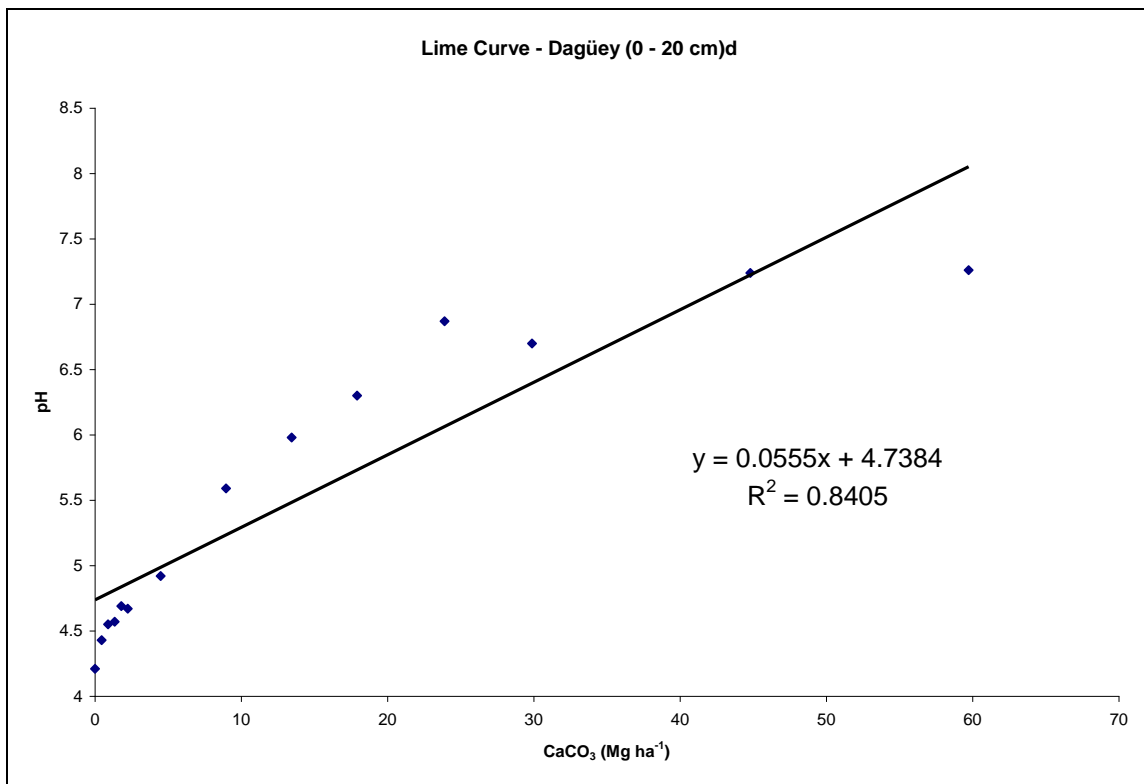
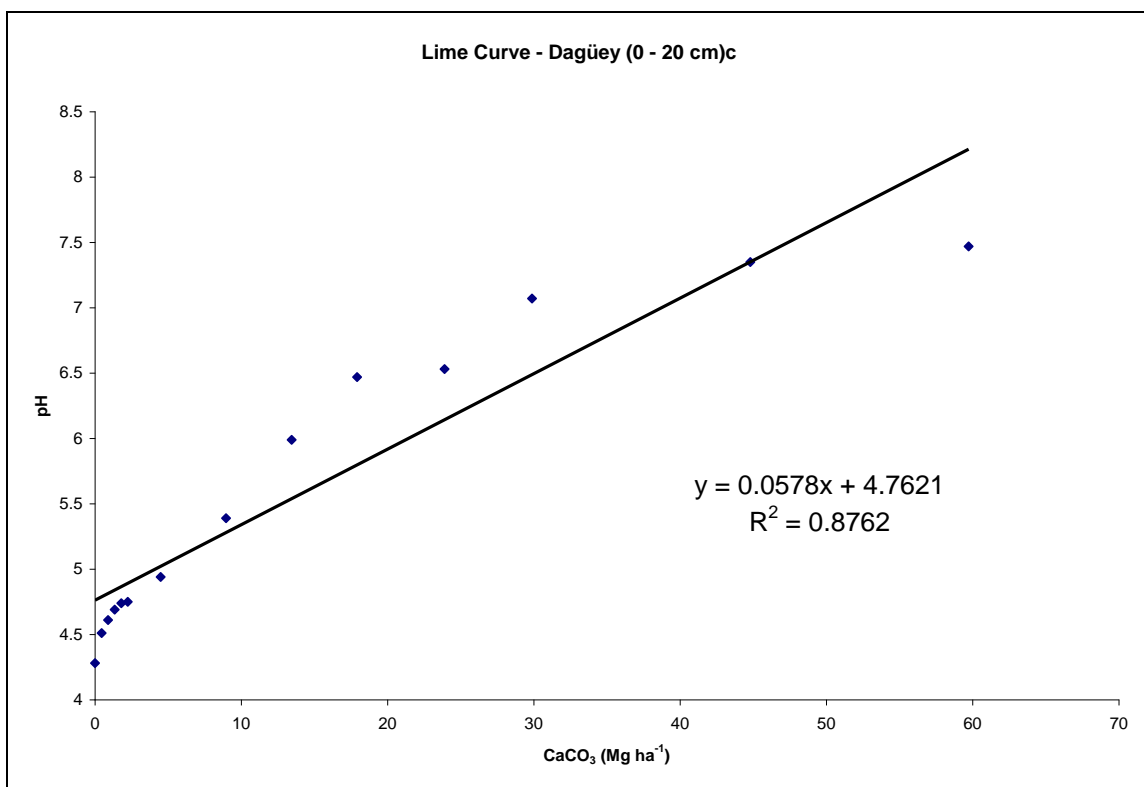


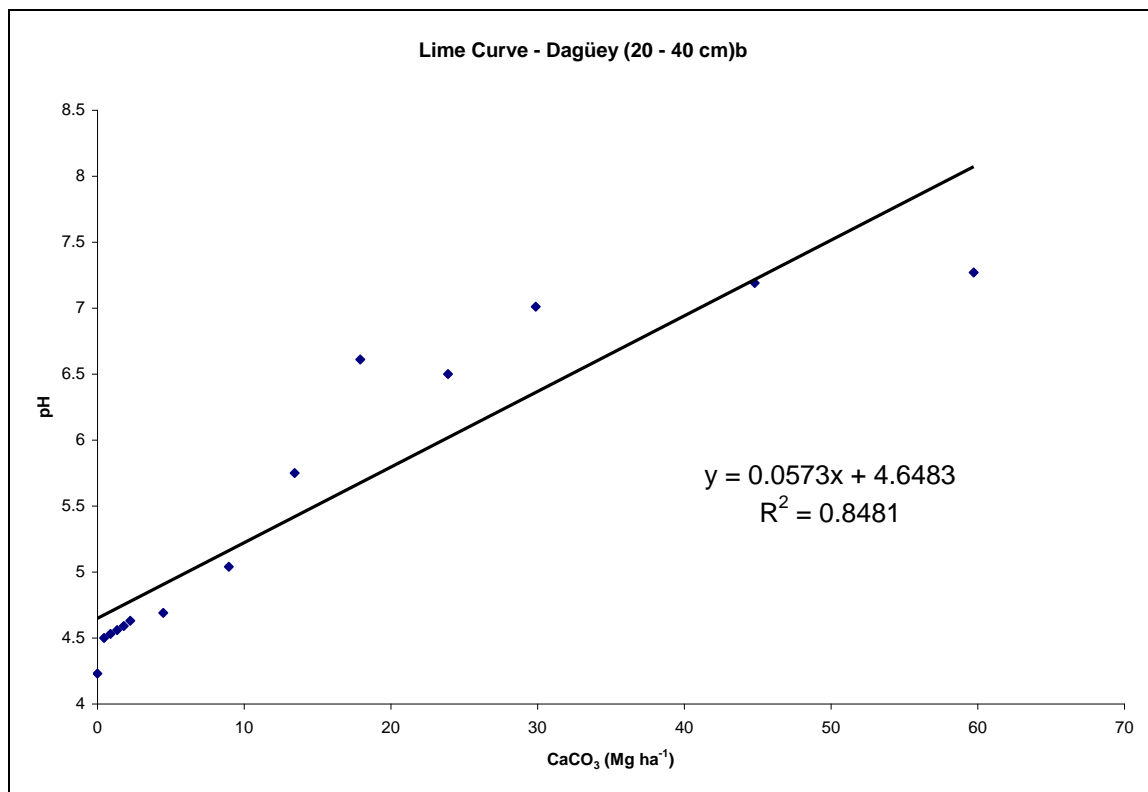
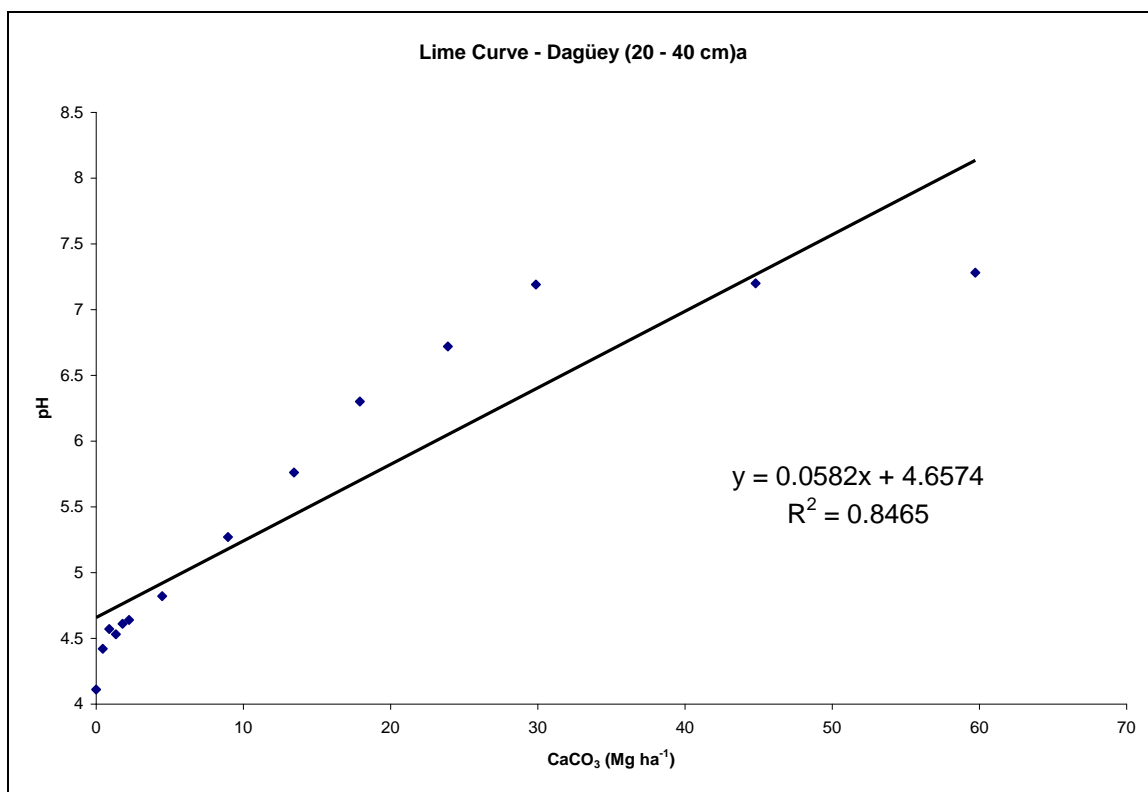


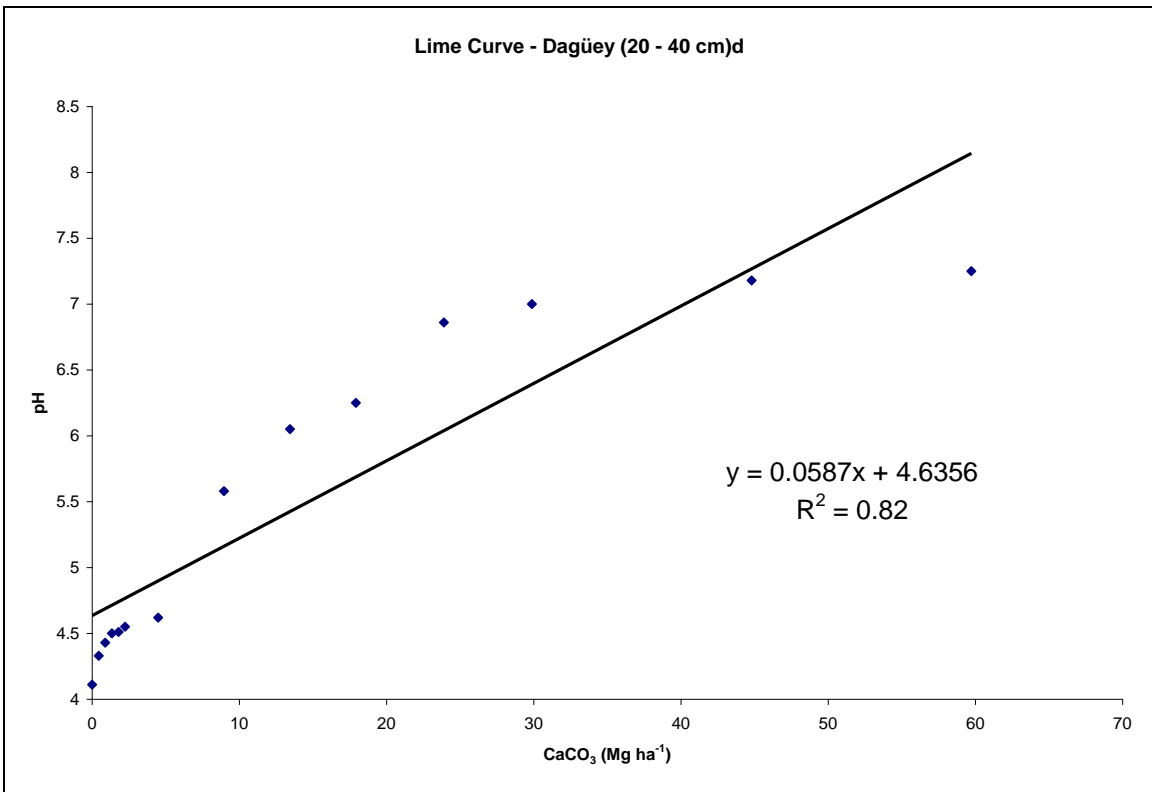
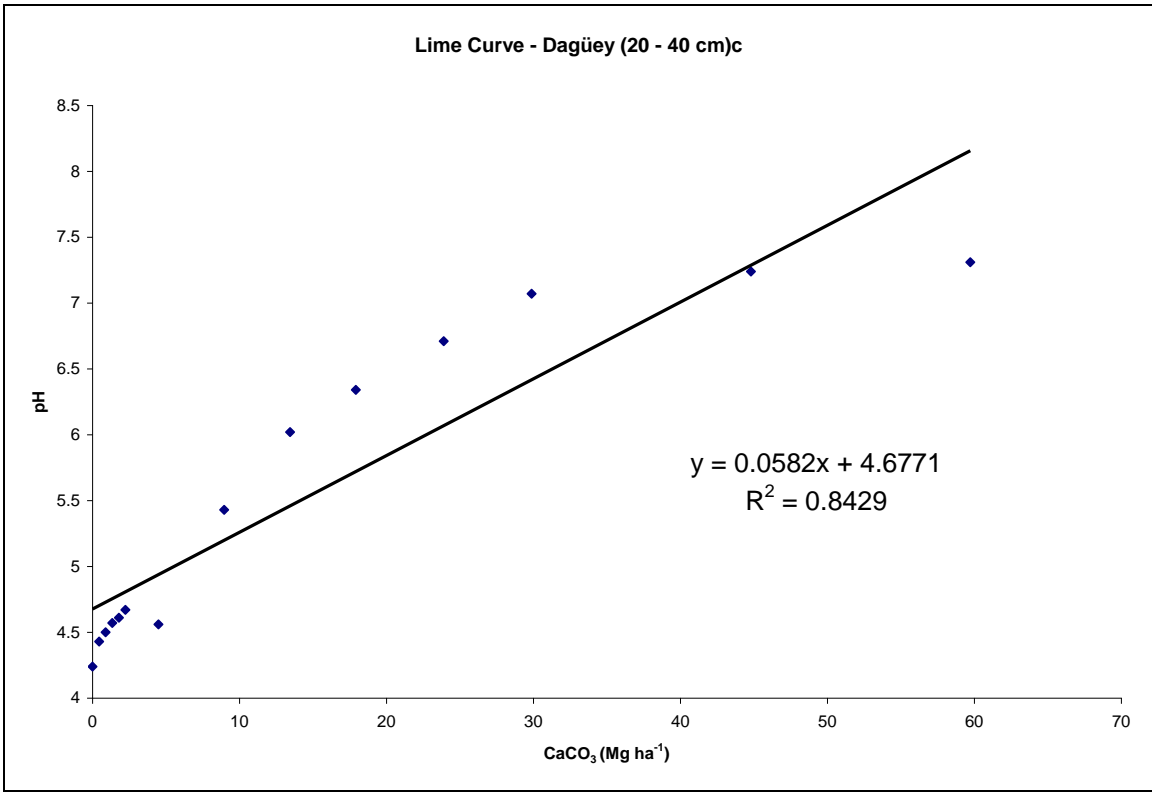
### H. Dagüey Series



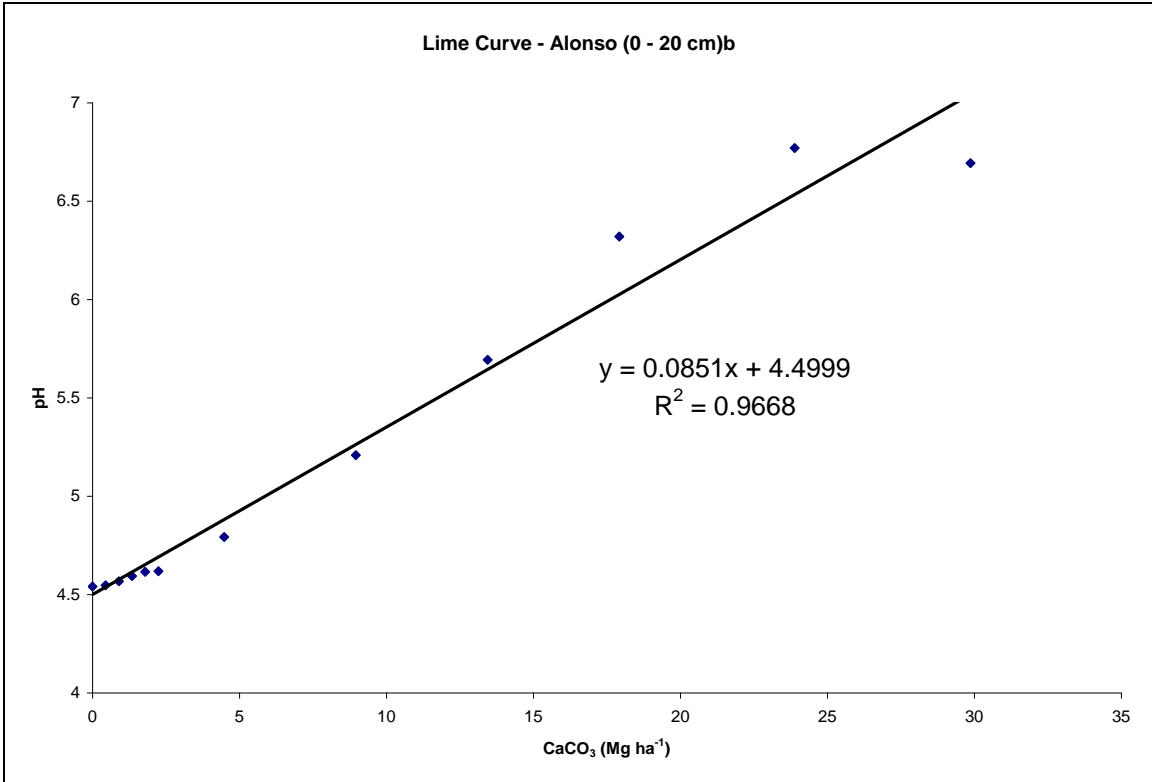
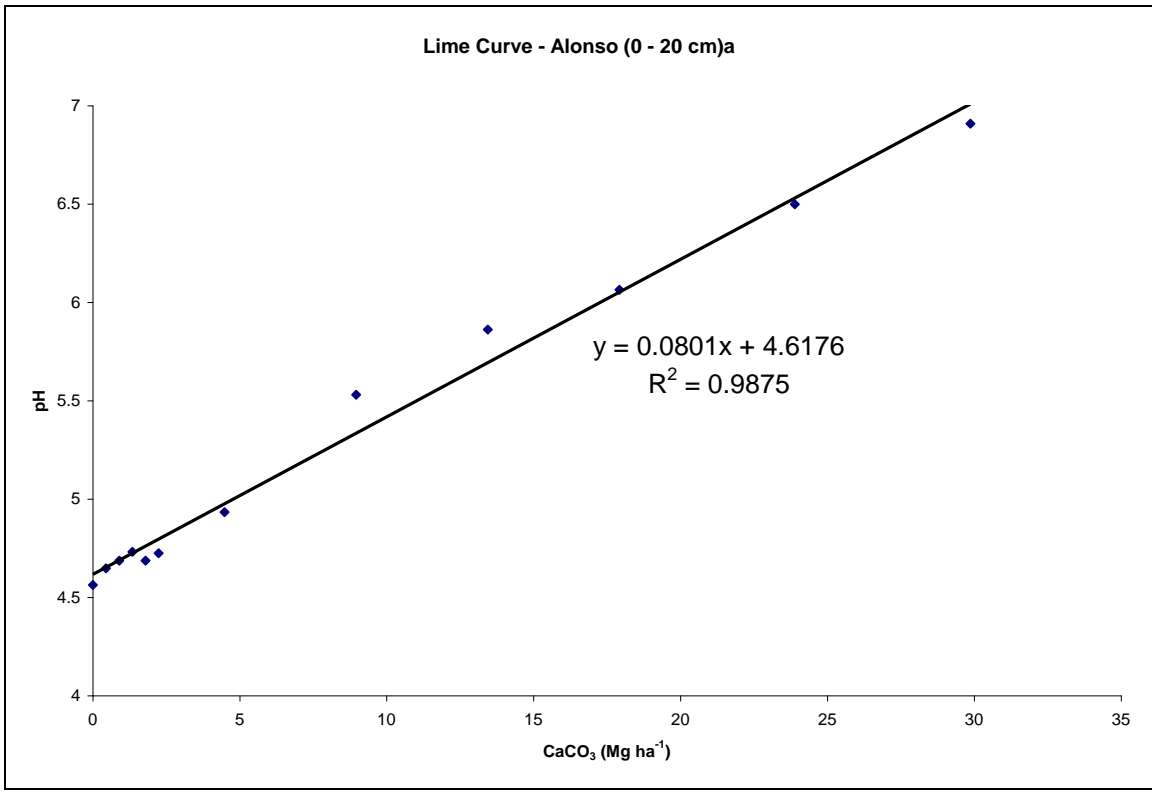


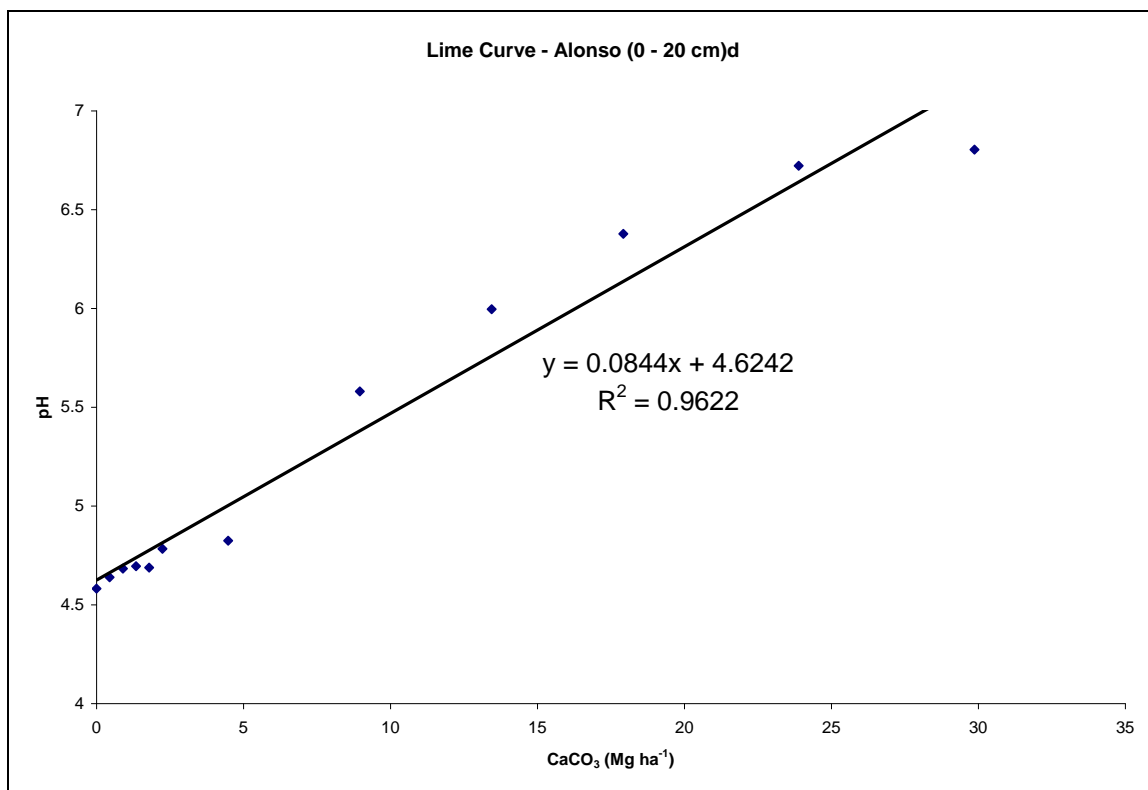
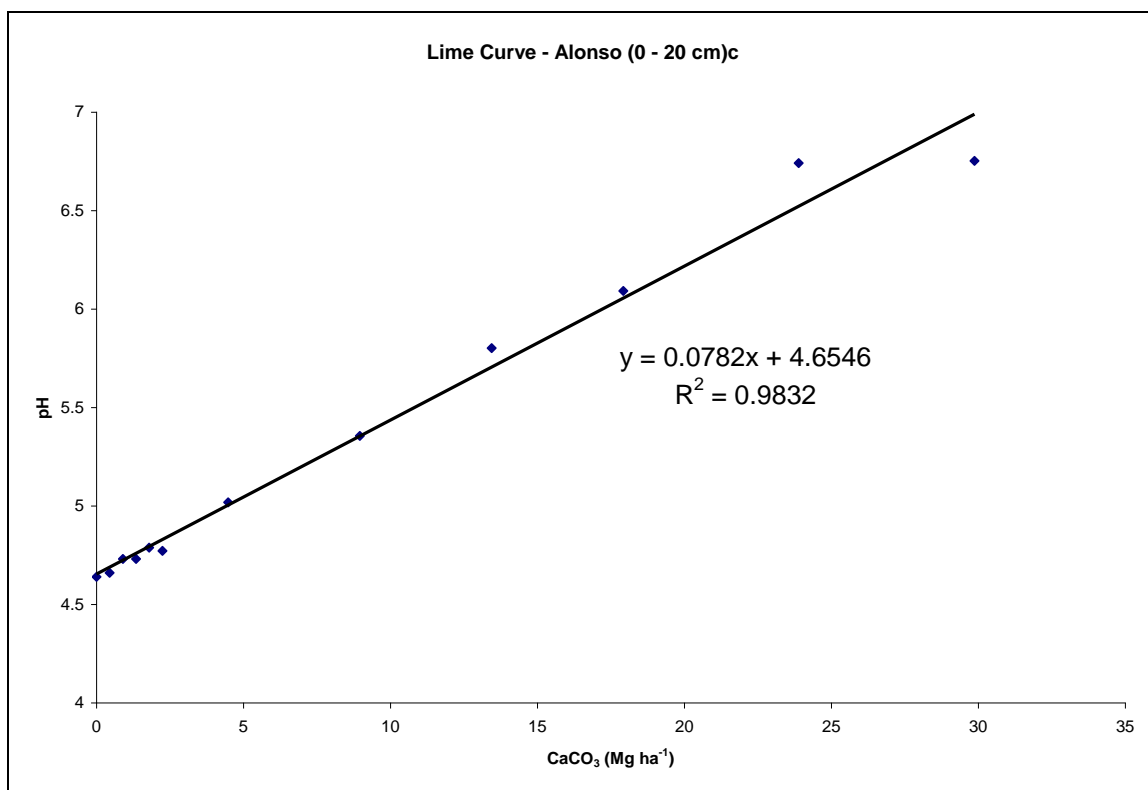


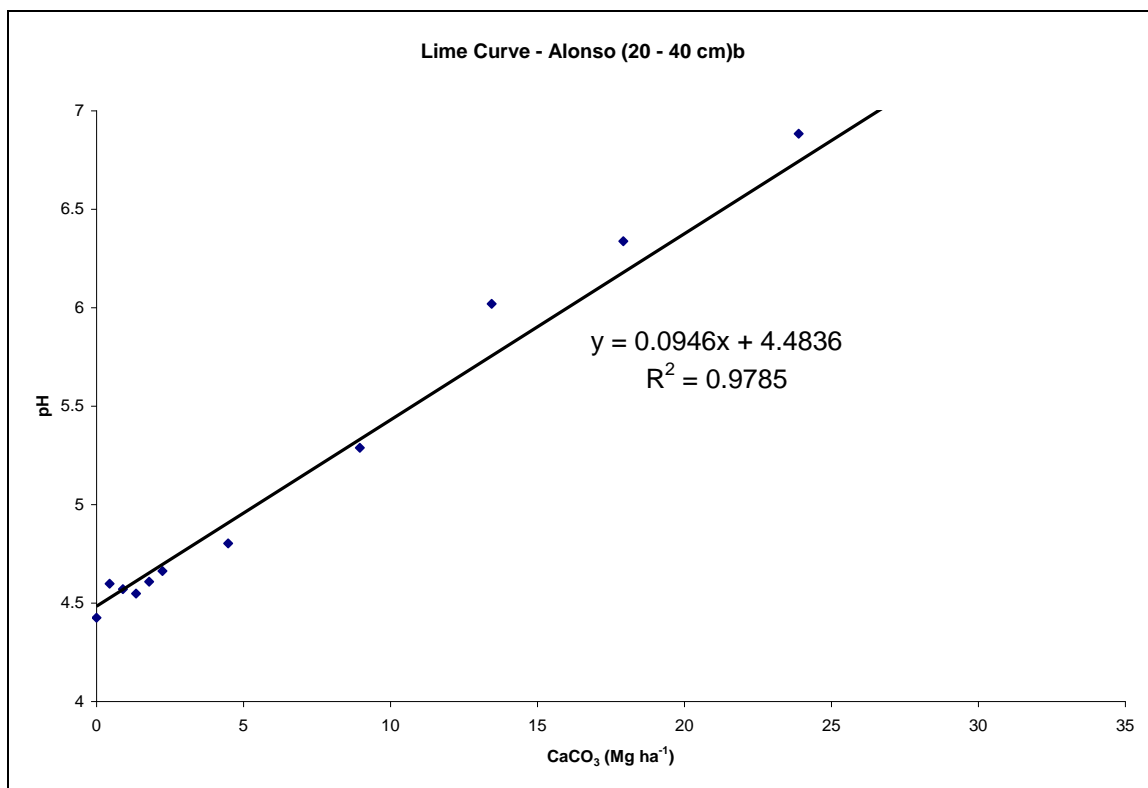
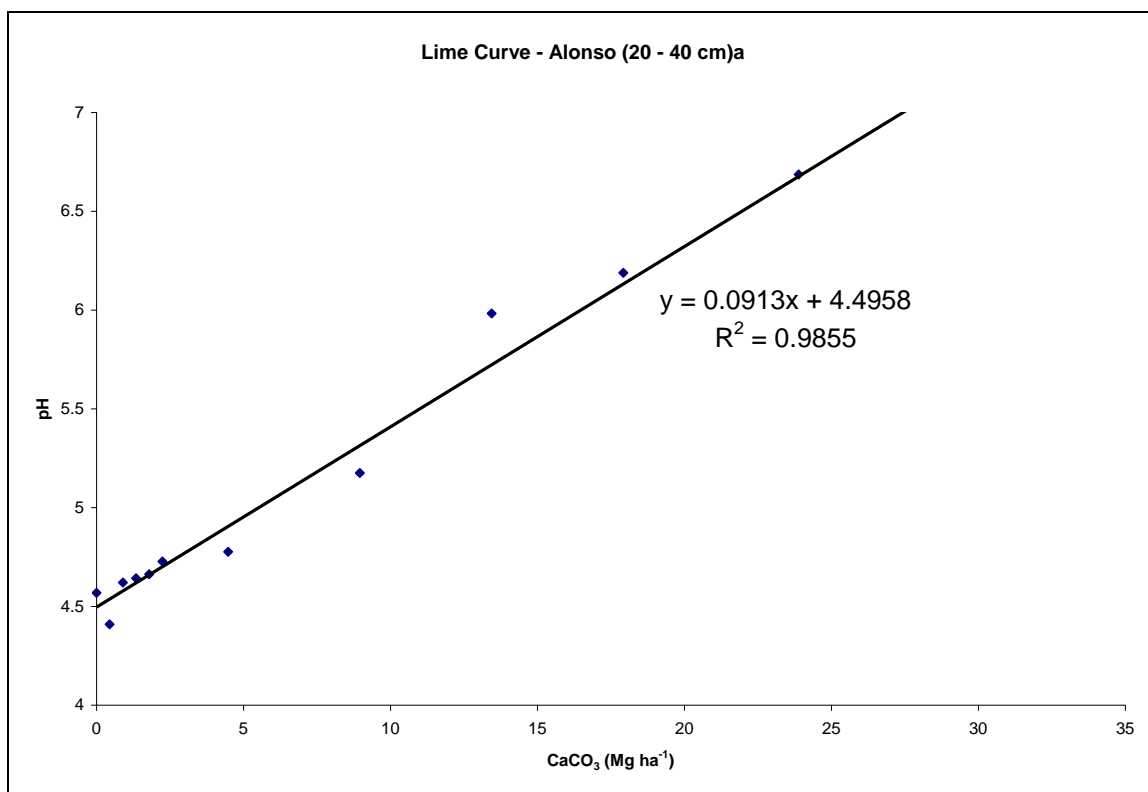


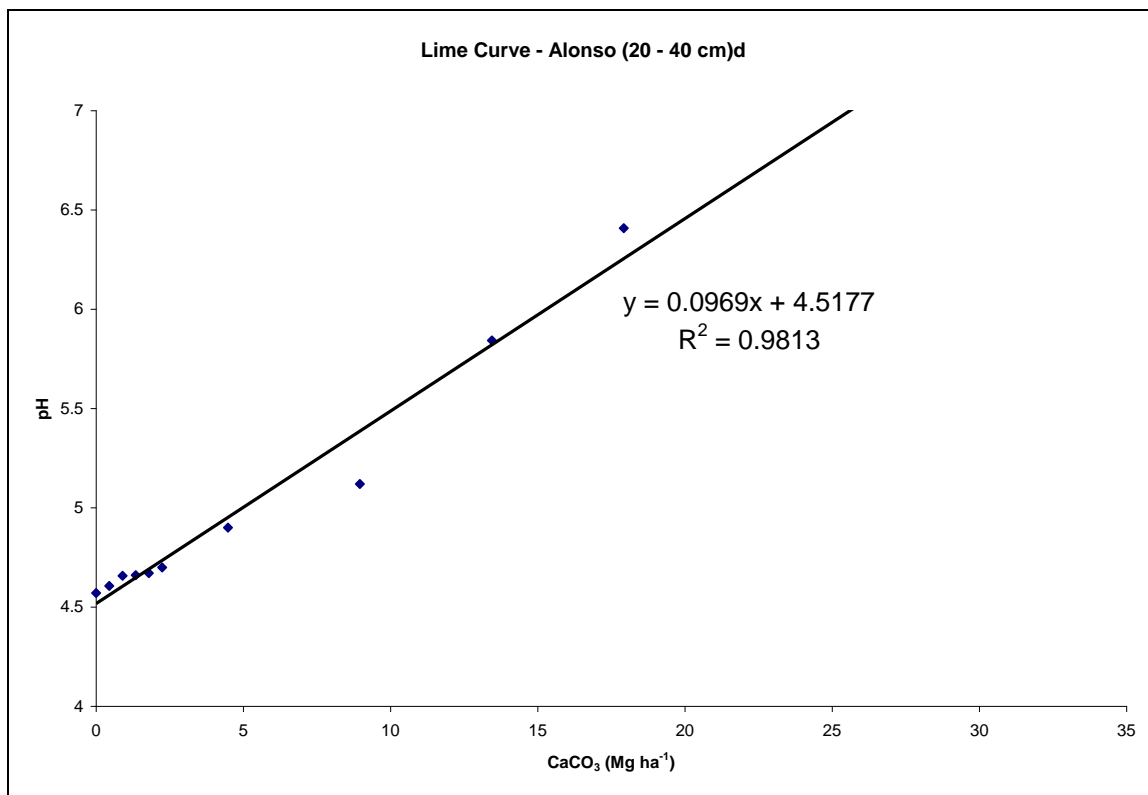
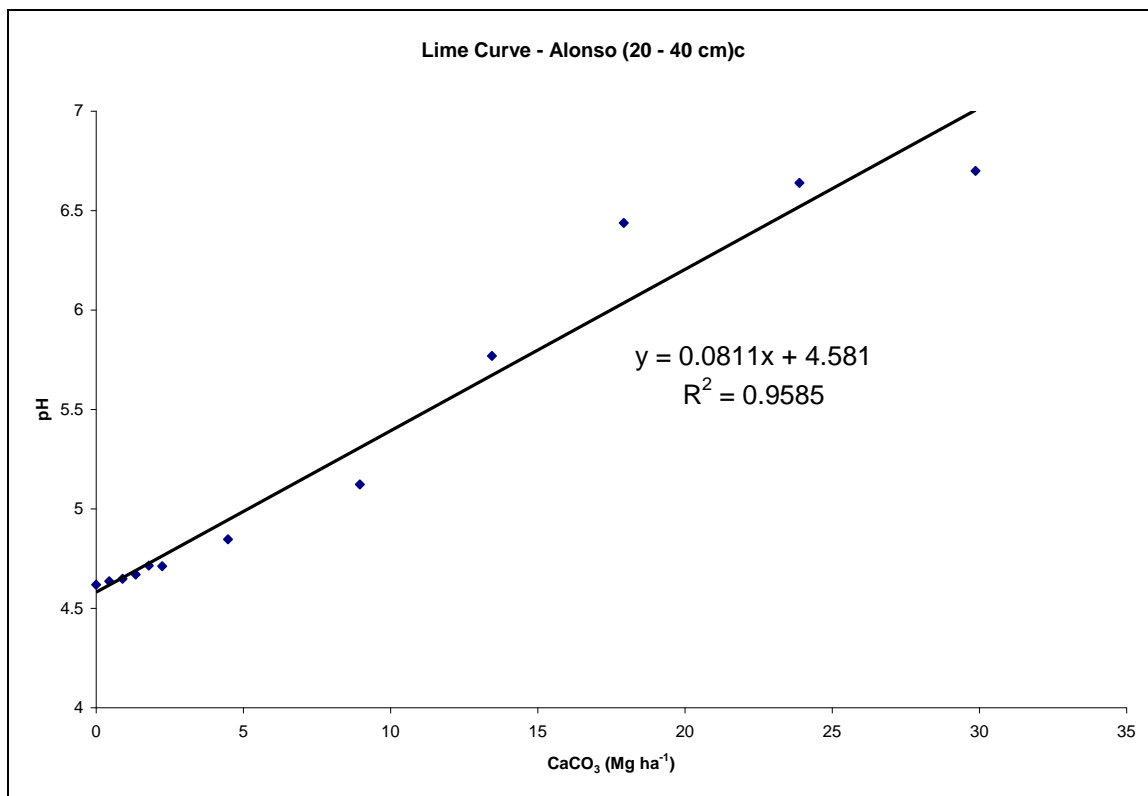


### I. Alonso Series

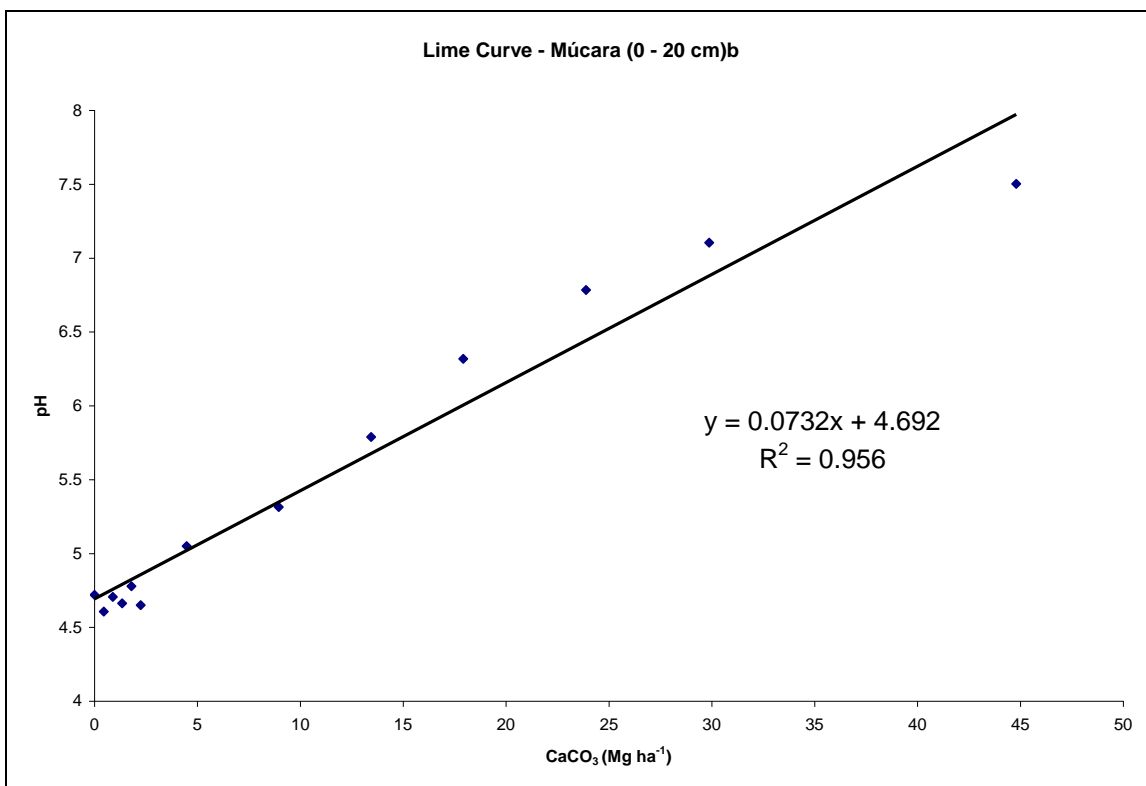
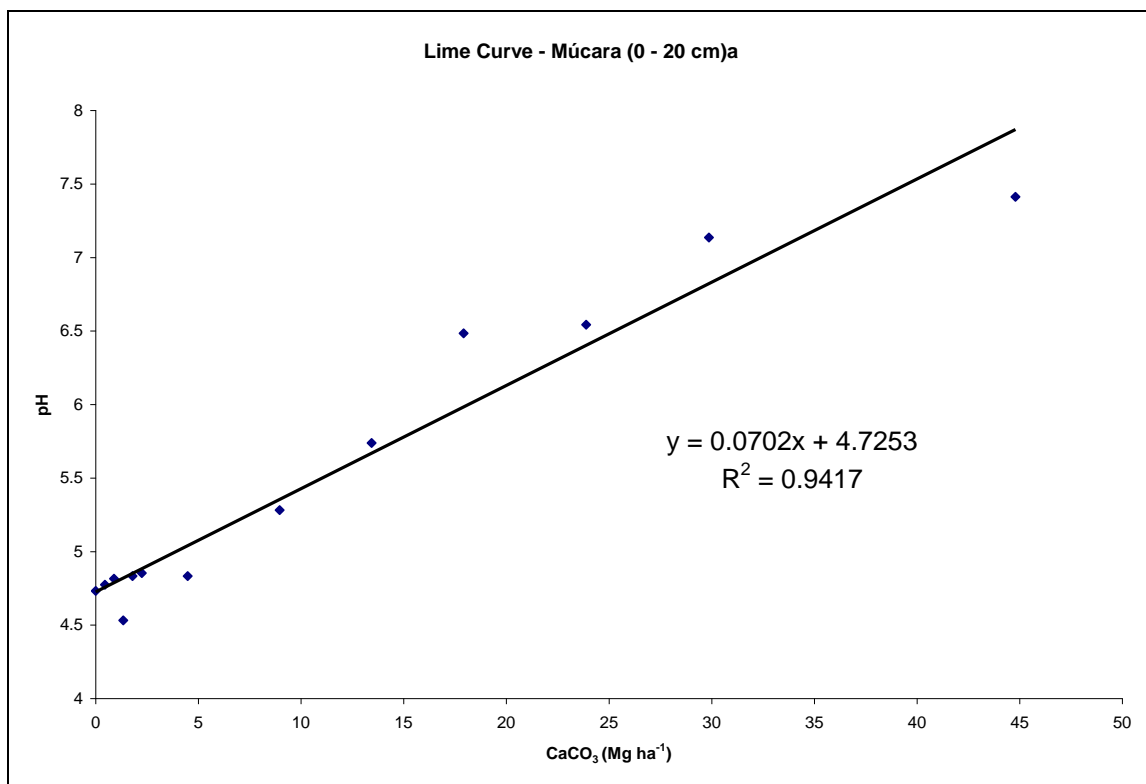




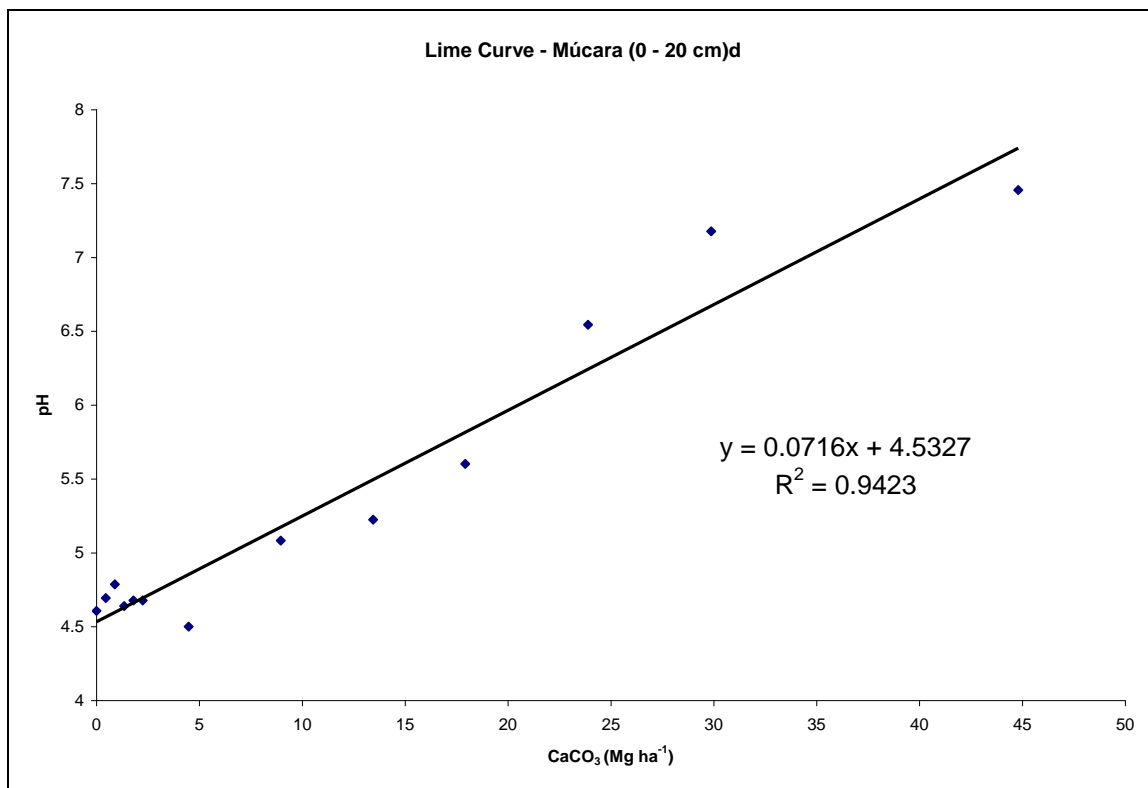
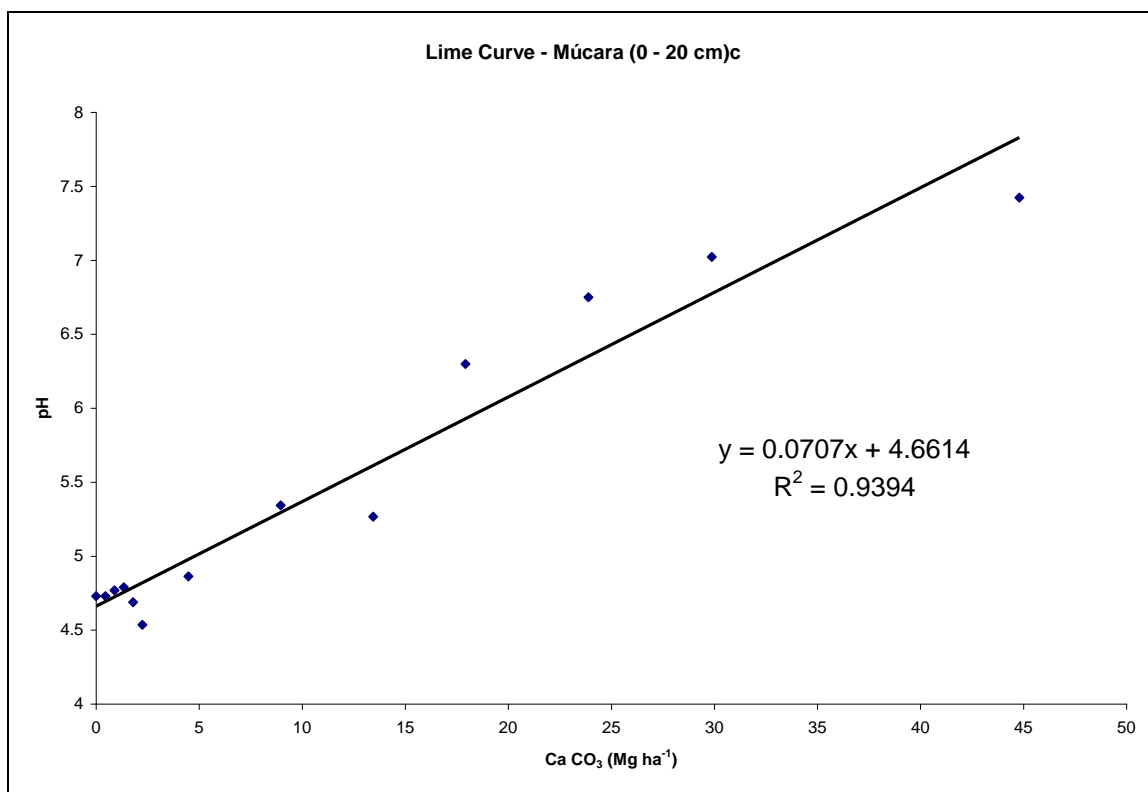


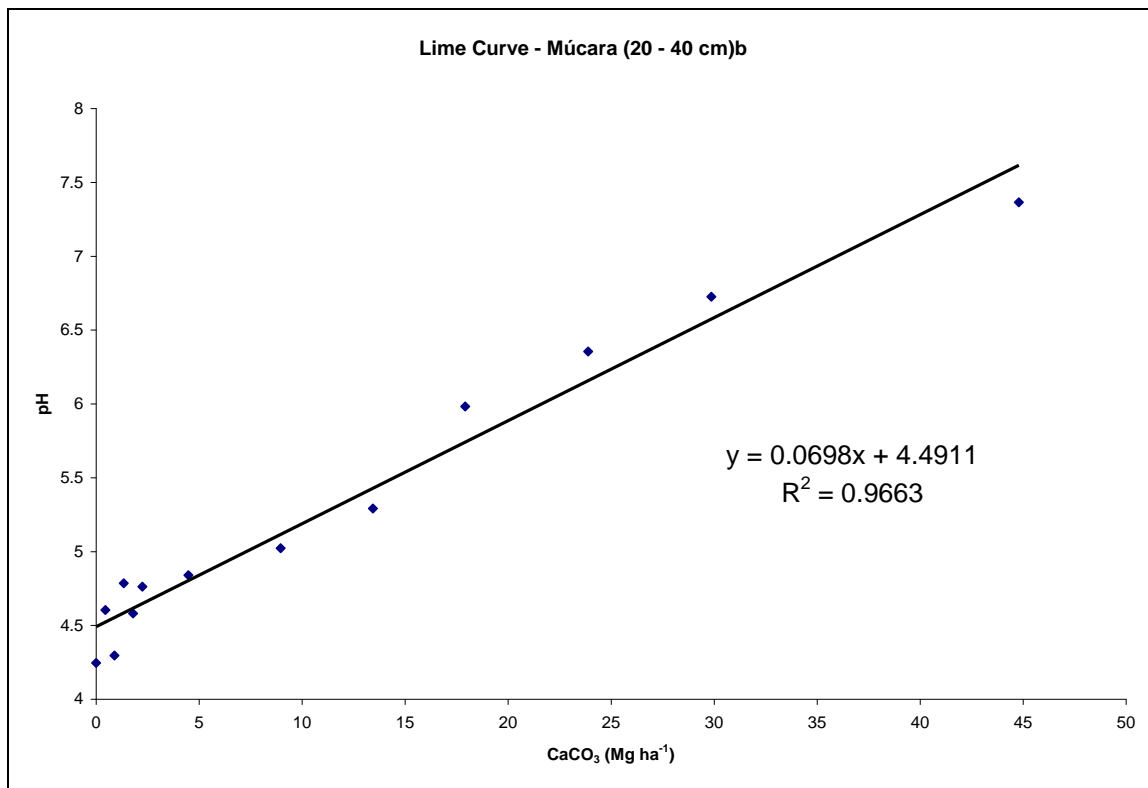
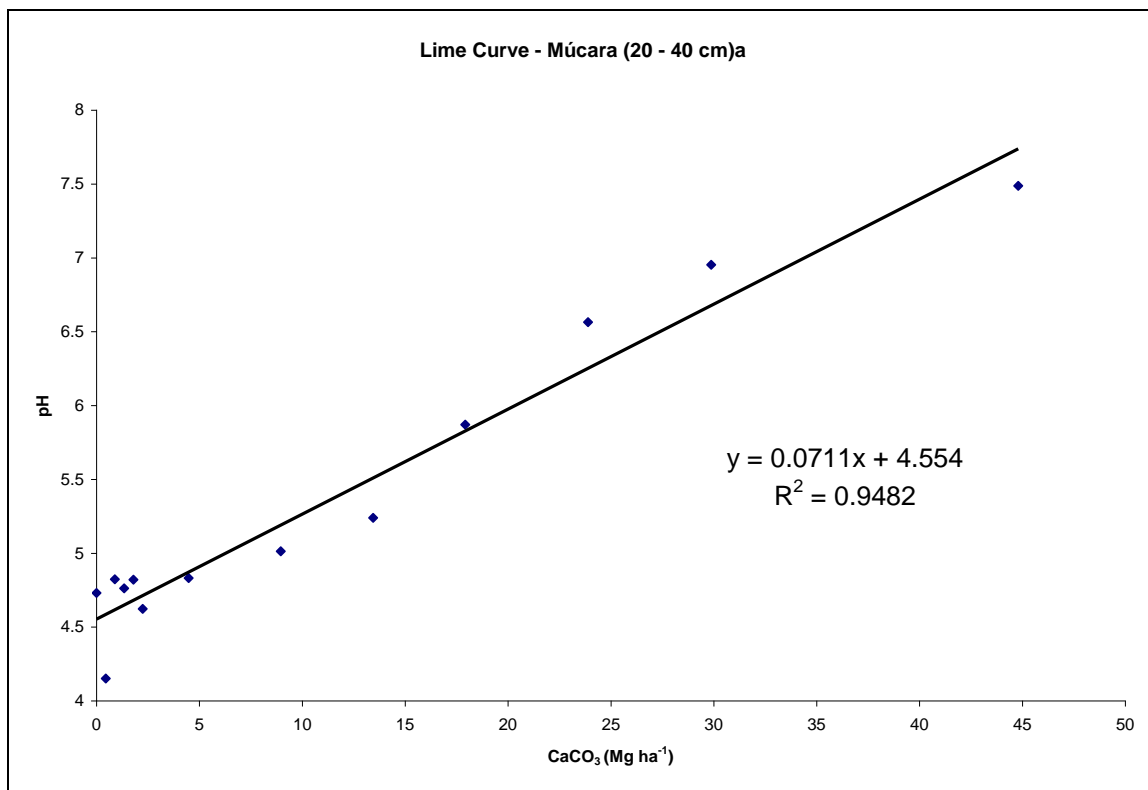


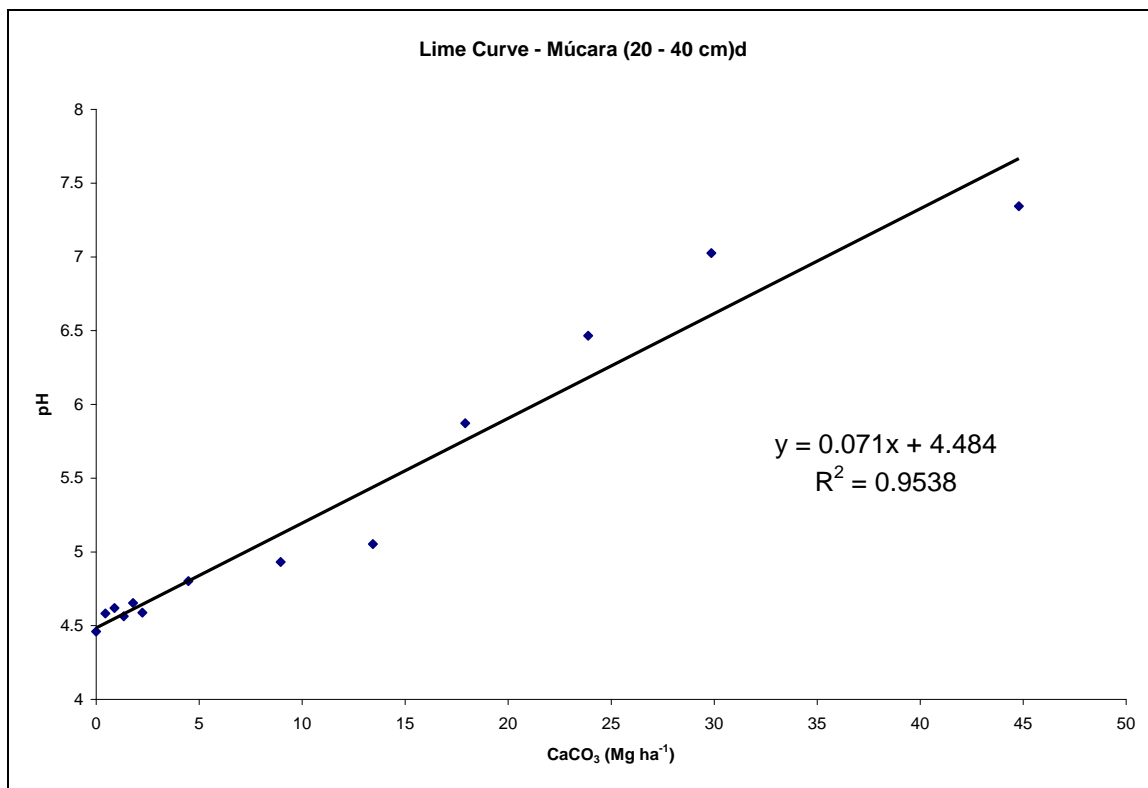
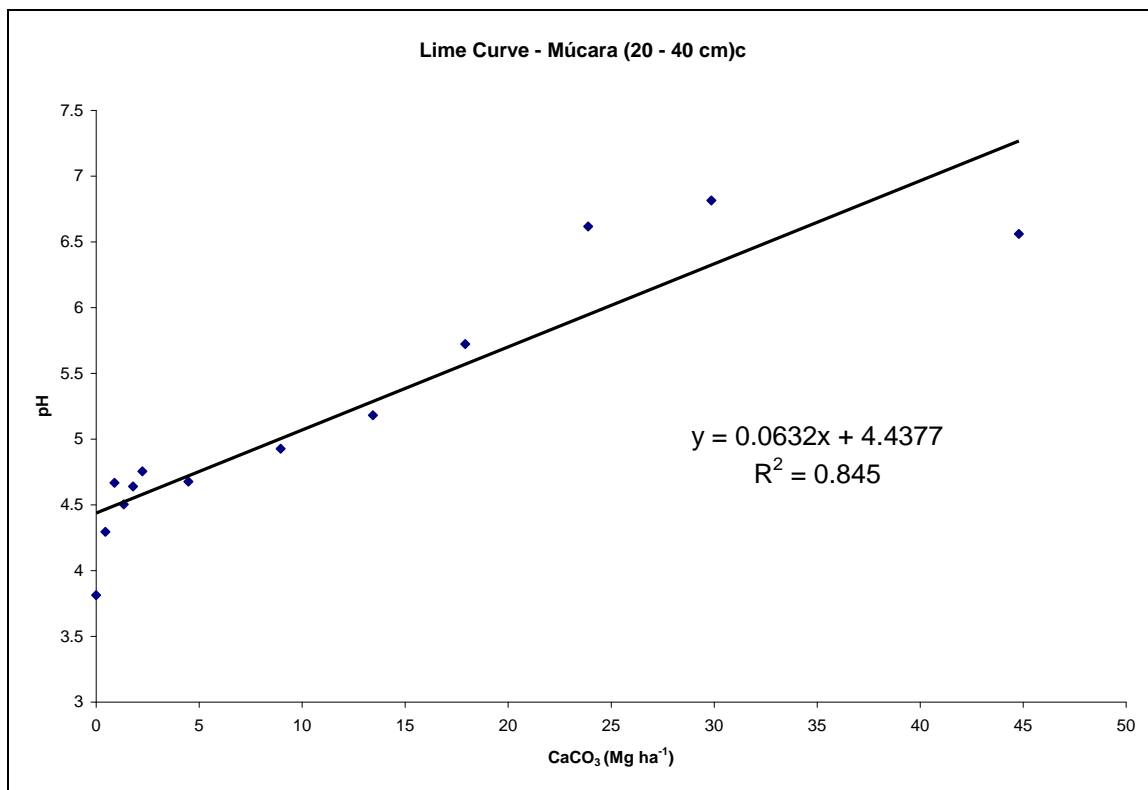
## J. Múcara Series











## II. Locations of the soil series used in this research.

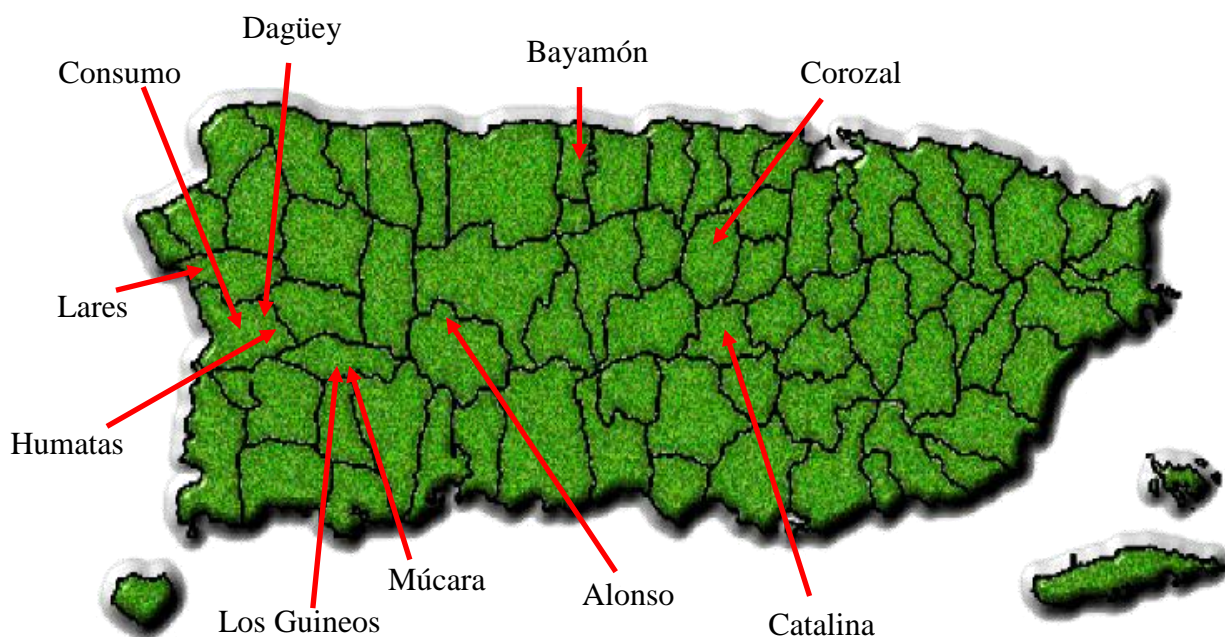


Figure 1. Map of Puerto Rico showing the places where the soils were collected. Consumo, Dagüey and Humatas series were collected in Mayagüez. Lares series was collected in Añasco. Los Guineos and Múcara series were collected in Maricao. Alonso series was collected in Adjuntas. Catalina series was collected in Naranjito. Corozal series was collected in Corozal. Bayamón series was collected in Barceloneta.