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Lime requirements for bean production on two contrasting soils of Lake Victoria Crescent agro-ecological zone

P. Kyomuhendo[1]*, M. M. Tenywa[1], O. Semalulu[2], A. Lenssen[3], R. Yost[4], R. Mazur[3] and S. Kyebogola[1]

[1]College of Agricultural and Environmental Sciences, Makerere University, Kampala 7062, Uganda,
[2]National Agricultural Research Laboratories (NARL) Kawanda, Kampala 7065, Uganda.
[3]Iowa State University, Ames, Iowa 50011-1070, United States.
[4]Tropical Plant and Soil Sciences, University of Hawai`i at Manoa Honolulu, Hawai`i.

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In East Africa, research has indicated that N, P and soil acidity are the major production constraints to common bean production. The optimum pH for bean production in tropical soils ranges from 5.8 to 6.5. But in Uganda, 23% of beans are grown in soils with pH below 5.0. Research conducted on common bean production is mainly about the major nutrients and information about lime requirements to address soil acidity in different soils is patchy. A study was carried out to determine the lime requirements for *Phaseolus vulgaris* L. production in Cambisols and Umbrisols and this was based on their low soil pH and Ca levels. The lime requirement was determined using titration method and titration curves for each soil type established by titrating 30 g soil in 60 mL 0.01 *M* $CaCl_2$ (1:2) with 3 mL 0.022 *M*$Ca(OH)_2$ per addition. Results indicate that to raise pH from 5.02 to 6.5, the Cambisol ("Limyufumyufu") requires 6.1 tonnes of $Ca(OH)_2$ per hectare, while the Umbrisol("Luyinjayinja") requires 5.4 tonnes of $Ca(OH)_2$ per hectare to raise pH from 5.26 to 6.5. There is need to address soil acidity in Cambisol and Umbrisol through liming using the lime requirement equations determined in this study. In order to provide growers and farmers with more options for such acid soils,however, plant breeding programs should select or develop germplasm tolerant to Al toxicity and/ or low soil available phosphorus as well.

Key words: *Phaseolus vulgaris* L., titration, Al toxicity, Cambisol, Umbrisol.

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) isestimated to be the second most important source of dietary protein and the third most important source of calories (FAOSTAT, 2012). Common bean is considered a low status food,

*Corresponding author. E-mail: prossykyomuhendo@gmail.com.

often referred to as “meat of the poor” (Katungi, 2009) with the annual per capita consumption being higher among low-income people who cannot afford animal protein (Beebe et al*.,* 2013).

Uganda’s bean production is common in the central, eastern and western regions (Sibikoet al*.,* 2013). In the Lake Victoria Crescent agroecological zone, beans are mainly grown on three soil types locally classified as: ‘Liddugavu’’ (Phaoezem, Hapludoll), ‘‘Limyufumyufu’’ (Cambisol, Kandiudalf) and ‘Luyinjayinja’’ (Umbrisol, Hapludoll) (Tenywaet al., 2014). The latter two soils are locally known as having the “lunnyo” condition, which according to local, indigenous knowledge suggests multiple factors limit bean (*P. vulgaris*, L.) production (Fungo et al., 2010).

Smallholder farmers encounter multiple constraints such as pests and diseases (Beebe et al*.,* 2013), low labour productivity and unreliable climatic conditions (Birachi et al*.*, 2012). Soil related constraints account for about 30% of the widely acknowledged ‘yield gap’ (Folmer et al*.,* 1998; Kapkiyai et al*.,* 1999) that threatens food security.

Among soil related constraints, low extractable phosphorus, nitrogen, and high soil acidity associated with aluminium and manganese toxicity (Lunze et al*.,* 2012) are the major soil fertility problems associated with the “lunnyo” soils. Soil pH strongly influences the availability of nutrients in the soil, the activities of soil microorganisms, plant growth and yield (Anderson et al*.,* 2013). The optimum pH for bean production in tropical soils ranges from 5.8 to 6.5 (Edmeades et al*.,* 2012). However, most of the soils in Sub Saharan Africa are acidic and possess high phosphorus-fixing capacities (Nziguheba, 2007).

The major options for improving soil fertility include use of wood ash, crop residues and manures, but they vary widely in quantity and quality (Ebanyat, 2009). Inorganic fertilizers are highly nutrient concentrated, but at times they give no yield response when applied where soil acidity is severe (Fageria and Baligar, 2008).The lime requirement to address soil acidity in different soils is not known. Therefore, this study was conducted to determine the lime requirements for bean production in the extensive local soils “Limyufumyufu” and “Luyinjayinja”.

MATERIALS AND METHODS

Study soil collection and preparation

The two soils known to have the “lunnyo” condition were collected from farmers’ fields in two representative communities (Mukungwe and Lwankoni) in Masaka district located in Central Uganda at 31.7361°E latitude and 0.34111°S longitude). These soils were selected for study based on a series of farmer meetings from three communities, which indicated that these two soils are important, farmer-recognized soil series for common bean production. In addition, the farmers indicated that bean production on the two soils was problematic and therefore were considered to have the “lunnyo” condition or characteristic. Soil analysis results (Table 1). indicate that, indeed, the two soils are low in soil pH and the Limyufumyufu is low in soil Ca. KCl-extractable Al, a measure of level of toxic aluminium, was high in the Limyufumyufu suggesting another probable reason that Al-sensitive bean (*P. vulgaris*, L.) was known by farmers to grow poorly in this soil. The two soil types(Limyufumyufu and Luyinjayinja) classified in the FAO Mapping Legend as Cambisol and Umbrisol, respectively). They are classified in the US Soil Taxonomy as “TypicKandiudalfs” and “TypicHapludolls”, which, for the former suggests highly weathered and the latter, less weathered status, respectively.Soil samples were obtained in a zig-zag pattern at ten locations within each field, from a depth of 0 to 15 cm.

A composite sample of about 25 kg soil was obtained from an area of approximately 50 m x 100 m for each soil. Soil was takenfor laboratory analyses. Soil samples were air dried in a dust free area, and crushed with a mortar and pestle to pass a 2-mm sieve.

Laboratory analyses for soil samples

Total soil organic carbon was determined by dry combustion method using total organic carbon analyzer(American Society for Testing and Materials, 1994).Extractable P was determined using the Olsen method (Kuo, 1996). Exchangeable K^+, and Na^+ were determined using a flamephotometer, while Ca^{2+} and Mg^{2+} were determined using an atomic absorbance spectrometer. The exchangeable cations were extracted from the samples by shaking for 16 to 24 h with 100 ml 2 MNaClfor 0.5 to 2.5 cmol/kg of exchangeable cations (Clark, 1965). Soil pH was measured in a 1:2.5 soil to water ratio using a pH electrode. The Kjeldahl method was used to determine total N (Bremner, 1965). Micronutrients were extracted in the Mehlich 3 extractant solution (Mehlich, 1984). The micronutrients Cu, Mn and Zn were measured by atomic absorption, while boron was measured using a colorimetric method (Berger and Truog 1939).Soil texture was determined using the hydrometer method (Bouyoucos, 1936).

Titration method of determining the lime requirement in the laboratory

The lime requirementwas determined in the laboratory at Makerere University using titration method as follows:The pH meter was calibrated with standard pH 4.00 and 7.00 buffers before each titration, soil pH measurements and titrations were performed in a soil/0.01 M $CaCl_2$ (1:2) suspension while being stirred. Titration curves for each soil type were established by titrating 30 g soil in 60 mL 0.01 M $CaCl_2$ (1:2) with 3 mL 0.022 M $Ca(OH)_2$ per addition (Kisselet al*.,* 2010; Barouchas et al*.,* 2013). The time interval to achieve an ion-exchange balance between 0.022 M $Ca(OH)_2$ additions was 30 min based on the research results of Liu et al*.* (2004) and Weaver et al*.* (2004). The soil suspension was stirred continuously by a magnetic stirrer during titration and the pH was measured at the end of each time interval. Increments (3-mL aliquots) of 0.022 M $Ca(OH)_2$ were added until the pH reached 6.5. All determinations were performed in triplicate. After each measurement, the electrodeswere rinsed with distilled water to avoid cross contamination from sample to sample. For the evaluation of the Al^{3+} in the extracts of the 1 mol L^{-1}KCl solution, 1:10 (v/v) soil/solution ratio (McLean, 1965), Titrimetric method(standard method), according to the routine methodology adapted from McLean (1965) was used. Primarily, the exchangeable acidity (Al^{3+} + H^+ tit) is determined by titration of 25 mL KCl extract with 0.025 mol L^{-1}NaOH, using 1 g L^{-1} phenolphthalein as an indicator (titration from colorless to pink). Then, the concentrationof $Al^{3+}$was obtained by back-titration of the same KCl extract, previously used, after the acidification with a drop of HCl and addition of 40 g L^{-1}NaF, with 0.025 mol L^{-1}HCl (titration from pink to colorless).

Table 1. Initial physico-chemical properties of the two selected soils used in the LRS.

Soil measurement	Units	Limyufumyufu	Luyinjayinja
pH (H_2O)		5.02	5.26
pH ($CaCl_2$)		3.52	4.56
OM	%	2.35	2.26
K	cmol/kg	1.5	1.5
Ca	cmol/kg	4.8	7.5
Mg	cmol/kg	4.2	8.9
Na	cmol/kg	1.48	1.06
Mn	mg/kg	153	110
Fe	mg/kg	149	151
EC(S)	uS/cm	43	20
Al	mg/kg	1410	1250
C.E.C	cmol/kg	12.3	8.13
Exch.Al	cmol/kg	1.2	0.8
Sand	%	52	51
Silt	%	36	35
Clay	%	14	12
Textural Class	USDA	SCL	SCL

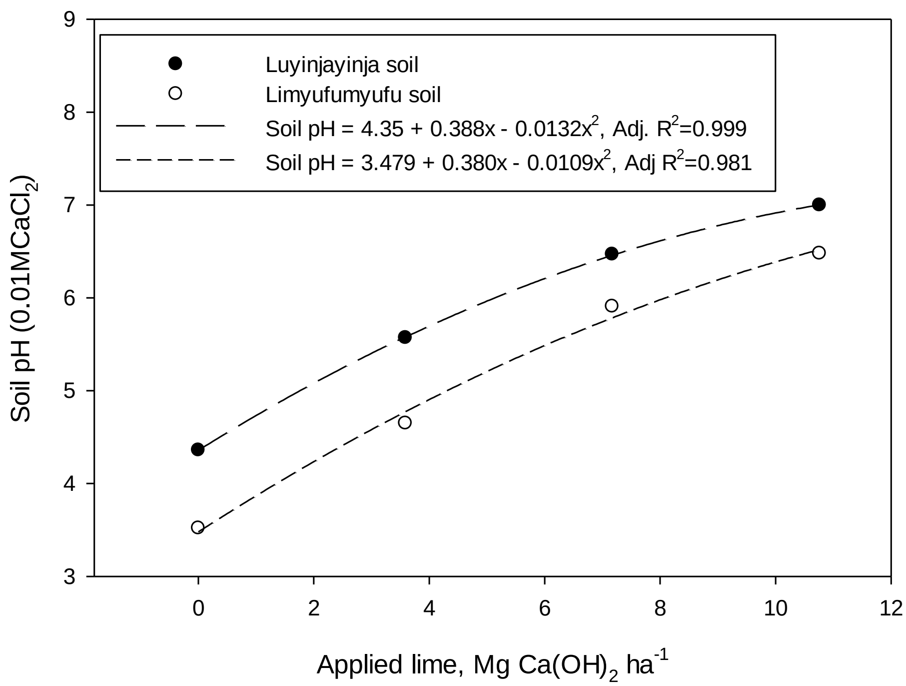

Figure 1. Soil pH (0.01M $CaCl_2$) resulting from additions of $Ca(OH)_2$.

Statistical analysis

Determining the pH resulting from lime ($Ca(OH)_2$) application

The first step in the incubation procedure was to determine the soil pH that resulted from the increasing amounts of added $Ca(OH)_2$. This was determined by plotting the pH resulting from the application of $Ca(OH)_2$ in the $CaCl_2$ suspension on the y-axis and the amounts of added $Ca(OH)_2$ on the x-axis (Figure 1).

Determining the amount of $Ca(OH)_2$ needed to attain a specified soil pH

The incubation data were then re-plotted as the amount of $Ca(OH)_2$ on the y-axis and the soil pH on the x-axis to properly predict the

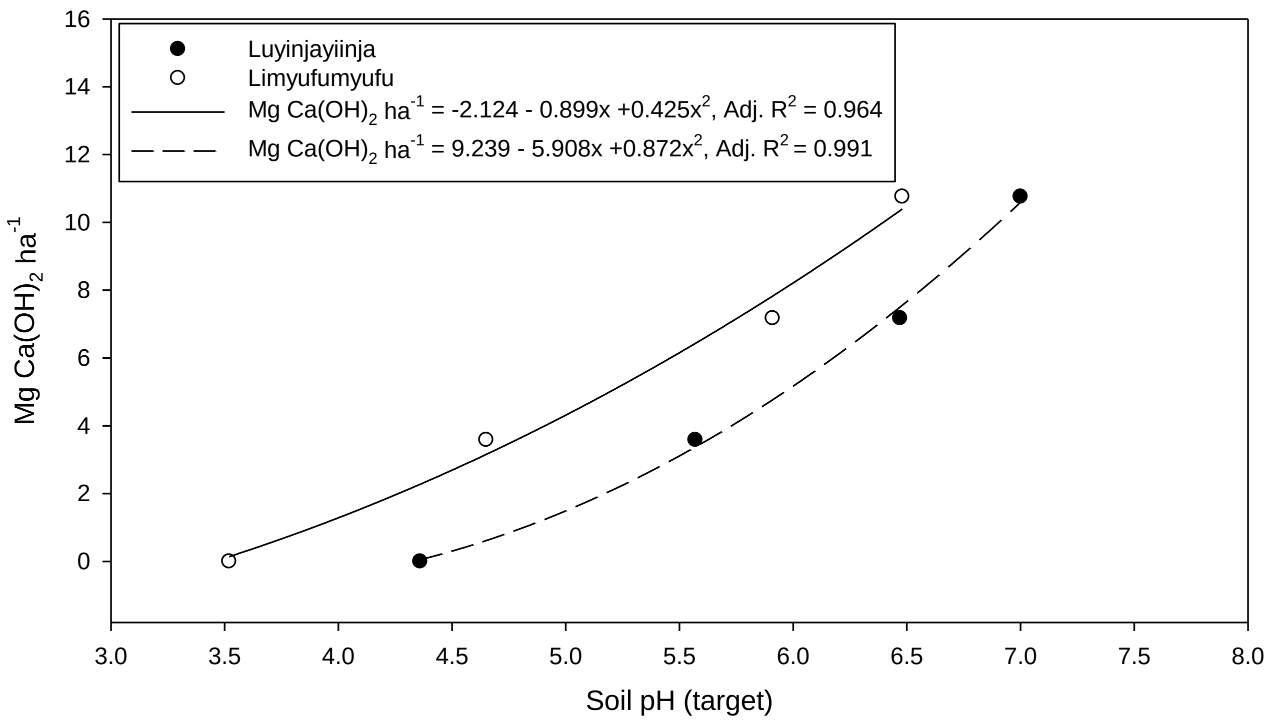

Figure 2. Estimated lime ($Ca(OH)_2$ requirements needed to attain specified soil pH levels.

Table 2. Lime requirements estimated for two soils for various target soil pH's depending on the intended crop.

Soil	Target soil pH (water)				
	Original water pH	**5.0**	**5.5**	**6.0**	**6.5**
Luyinjayinja	5.26	-	0.83	2.89	5.39
Limyufumyufu	5.02	0	1.77	3.83	6.11
Luyinjayinja	Liu (2005) single	-	0.71	2.19	3.68
Limyufumyufu	Liu (2005) single	-	1.42	2.90	4.39

amounts of $Ca(OH)_2$ needed to attain a specific soil pH (in $CaCl_2$) suspension. This step is sometimes called a "Calibration" and differs from simply re-arranging the regression equation from the plot of soil pH on the y-axis and the amounts of $Ca(OH)_2$ on the x-axis as described above. This "calibration" step is needed because a regression equation cannot be simply re-arranged as if it were a standard algebraic equation. For example, one cannot simply re-arrange a regression equation in the above paragraph to predict the amounts of $Ca(OH)_2$ needed for a specific soil pH. After plotting the amounts of $Ca(OH)_2$ on the y-axis and soil pH on the x-axis, a regression equation was fitted to the data to enable the prediction of the amounts of $Ca(OH)_2$ needed to attain a specified soil pH (Figure 2). The estimate of lime requirement is then the difference in the amounts of $Ca(OH)_2$ between the two predictions and is given in Table 2. This replotting and fitting a regression equation to the data is required because a regression equation is a prediction of the dependent variable assuming no errors in the predictor variable (Gelman and Hill, 2009).Various target soil pH values were then selected as possible target values (5.0, 5.5, 6.0, and 6.5, Edmeades et al., 2012). The corresponding amounts of $Ca(OH)_2$ required based on the laboratory incubations for the two soils were then tabulated (Table 2) based on target crop pH requirements after the time allocated for the neutralization reaction to occur.

RESULTS AND DISCUSSION

Soil pH increase with applied $Ca(OH)_2$

The change in soil pH that occurred with lime application is shown in Figure 1. The amount of $Ca(OH)_2$ needed to increase soil pH increases in a nonlinear manner as shown by the quadratic curves that were fit to the data.This nonlinear response to lime applications probably reflects the presence of additional buffering compounds on the soil surfaces that result in smaller increases in pH as higher pH's are obtained. This is not unusual in highly buffered variable charge soils in which the CEC increases as soil pH increases (Uehara and Gilman, 1981).

In order to obtain estimates of lime requirement to attain various target soil pH's, the data shown in Figure 1 are replotted in order to obtain regression estimates of the amount of lime needed to attain various target pH's. We note that it is not valid to take the regression equations fit in Figure 1 and re-arrange them to estimate lime requirement. This occurs because regression equations are fit on the assumptions that there are no errors in the predictor variable and thus regression equations are not the same as a typical algebraic equation with which re-arrangement is valid. Figure 2 shows the replotted data and again illustrate that as the target soil pH increases the amount of lime needed further increases, resulting in the curvilinear relationship between lime applied and the resultant soil pH. It is important to note that this highly buffered behavior of the Ugandan soils differs from the soils in the Liu et al.(2004, 2005) and the Barouchas (2013) papers where the increase in soil pH was linear for the lower levels of applied lime. Consequently, the recommendation of Liu(2005) to use a one-point incubation curve to determine lime requirement does not hold for these two Ugandan soils. Consequently, these data suggest that a lime incubation curve needs to be determined for each of these soil groups, which then can be used to estimate lime requirements to attain various target pH's depending on the desired crop. This is illustrated in Table 2.

For comparison, we have also calculated the lime requirement using Liu et al. (2005)'s recommendation single lime addition method (Table 2) rows 3 and 4. As expected, the lime requirement estimates from single addition underestimate the lime requirement obtained from an incubation curve that spans the range of soil pH 5.0 to 6.5.

Estimates of lime requirement

The practical determination of lime requirements for these soils is not concluded with these estimates; rather, it is only the beginning of practical estimates. These are only estimates of lime requirement based on controlled laboratory conditions. Practical estimates need field verification under realistic conditions of use of a locally available liming material, whose chemical quality relative to the 100% Calcium Carbonate Equivalency of $Ca(OH)_2$ must be determined. In addition, the physical quality of the agricultural limestone must also be determined, since lime that does not pass a 0.15-mm sieve lower possibility of dissolving and thus of lower effectiveness. In addition to these variables that strongly affect lime reactivity, the soil and crop management practices such as amounts and form of nitrogen also strongly affect soil pH in practical situations. Examples abound of the strongly acidifying effects of ammoniacal fertilizers on lowering soil pH (Chao et al*.,*2014). Other factors will affect how frequently soil pH should be monitored. As suggested above, if the lime contains some larger particles these will require a longer time to react, thus affecting the effective residual effectiveness of the limestone. Consequently, soil pH should be monitored over time to ensure crop growth is not limited.

Physico-chemical properties of the two soils used in the LRS

The two soil types were sandy clay loam textural class and they were quite acidic. The Limyufumyufu had a pH of 5.02 while the Luyinjayinjainitial pH was 5.26 (Table 1). Considering the critical levels of K, Mg and Ca (1.15, 3.12 and 0.68 $cmol_c$/kg, respectively), these nutrients were above the critical levels as indicated in Table 1. The Limyufumyufu soil had 33.9% higher Cation Exchange Capacity (CEC) compared to Luyinjayinja. The Cambisol had a much higher exchangeable Aluminium content, which may have resulted in sharply reduced bean growth.

Physico-chemical properties of the selected soils used in the LRS

The initial pH of the two soil types was below the critical level for bean growth which ranges from 5.8 to 6.5 (Table 1) (Edmeades et al*.,* 2012). The availability of phosphorus is also influenced by the pH, which is readily available at a pH (H_2O) of 6 to 7 (Plessis et al*.,* 2002). This is inagreement with the nutrient omission study results, which indicate that phosphorus is the most limiting nutrient in the three soils where beans are mainly grown in Lake Victoria Crescent (Kyomuhendo et al*.,* 2018).

Soil pH in 0.01 $MCaCl_2$ were depressed at all levels of $Ca(OH)_2$ addition in all soils, a common effect due to displacement of Al^{3+} and H^+ from increased soil solution of Ca^{2+}, and due to elimination of the junction potential effect (Bloom, 2000). Fageria andBaligar (2008) noted that Effective Cation Exchange Capacity (ECEC) is an important parameter for predicting fertility behavior of agricultural soils, and in their study, ECEC increased significantly ($P < 0.01$) with increasing pH in aquadratic, nonlinear response.

At low pH values, Al^{3+} is the predominant exchangeable cation on clay minerals. As the pH is raised, the Al^{3+} hydrolyzes, freeing the exchange sites for Ca^{2+}, and results in an increase in the ECEC (Kisinyo et al*.,* 2013). This may be one of the reasons the Limyufumyufu soil requires more lime to achieve suitable pH levels for *P. vulgaris* bean.

Titration curves for the two soil types used in the lime requirement study (LRS)

Cambisol had a higher lime requirement than Umbrisol

(Figure 1). This can be attributed to the differences in the initial pH where Cambisol was more acidic than Umbrisol (Table 1). According to Edmeades et al*.* (2012), the initial pH of the soil is the major factor determining the quantity of lime required to raise pH either to 5.8 or 6.5, a range of pH for bean production.

The higher lime requirement for Cambisol than Umbrisol can be attributed to differences in terms of exchangeable cations where by Ca^{2+}, Mg^{2+}, and K^{+} contents were lower in Cambisol than Umbrisol (Table 1). This is in agreement with results by Fageria and Baligar (2008) who reported that soils with high fertility in terms of exchangeable Ca^{2+}, Mg^{2+}, and K^{+} require less lime than do those with lower soil fertility. When Ca^{2+}, Mg^{2+}, and K^{+} contents are higher, a lower lime rate is required, because of higher levels of these basic cations in the soil, meaning relatively higher base saturation and higher pH than with lower levels of these cations (Fageria and Baligar, 2008).

Anderson et al*.* (2013) reported that in soils with a negligible orno exchangeable A1, the pH did not change by liming meaning that most of the base added had been consumed by deprotonation of hydroxyl groups of organic matter and on clay mineral surfaces (Guadalix and Pardo, 1994).

Conclusions

As indicated above, these laboratory incubations are only relatively quick estimates of lime requirement. Clearly, longer term studies with locally available liming materials that typically vary in Calcium Carbonate Effectiveness (%CCE) and also vary in particle size analysis need to be conducted. Furthermore, local crop management practices such as rates and types of nitrogen fertilizers need to be assessed in field studies.

Nonetheless, these results suggest that major growth limitations due to soil acidity merit further study and field testing in order to more fully utilize such acid soils with food production potential.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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