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Exchangeable aluminum as a measure of lime requirement of Ultisols and Alfisols in humid tropical Western Ethiopia

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ABSTRACT

Acid soils with pH-H_2O < 5.5 are widely distributed in humid tropical Western Ethiopia. Liming is used to amend soil acidity and exchangeable aluminum (Al_{ex}) toxicity through precipitating Al_{ex} and increasing pH. Liming requirement (LR) for humid tropical Western Ethiopia on the basis of KCl extractable Al_{ex} has not yet been established but there is a strong need for this recommendation as a rapid and reliable method for reclaiming soil acidity. The objectives of this study were to determine LR of Ultisols and Alfisols, establish relationship between LR and Al_{ex}, and further verify the results through a greenhouse pot experiment. Soil samples were collected from Ultisols and Alfisols from 0 to 20 cm depth. Seven samples with Al saturation ranging from 7 to 75% and pH from 4.7 to 5.2 were screened and advanced to a 60-day incubation experiment. The LR was determined from intercepts of regression equations of lime ($CaCO_3$) rate versus Al_{ex}. The LR ranged from 1.72 to 9.24 cmolc $CaCO_3$ kg^{-1} which is equivalent to 1.54 to 11.41 ton $CaCO_3$ ha^{-1}. These LR recommendations contradict with the 3 ton $CaCO_3$ ha^{-1} blanket recommendation developed 35 years ago. The LR and Al_{ex} of experimental soils fit to an inverse quadratic relationship, where the LR (i.e., $CaCO_3$ needed) and Al_{ex} are expressed as cmolc kg^{-1} soil. Aluminum saturation becomes zero at pH 5.1 to 5.2. The linear model of LR is expressed as LR = $1.47 * Al\text{ex}$ (cmolc $CaCO_3$ kg^{-1} soil), ($R^2 = 0.72$), and the quadratic one as LR = $2.56 * Al_{ex} - 0.19 * (Al_{ex})^2$ (cmolc $CaCO_3$ kg^{-1} soil) ($R^2 = 0.90$). The quadratic model fitted well with results of LR of previous studies and predicted properly LR of test soil used for verification. The LR of Ultisols and Alfisols of humid tropical Western Ethiopia can be reliably predicted by use of this quadratic model of LR determination on the basis of exchangeable Al.

Keywords: Aluminum toxicity, laboratory incubation, linear and quadratic models.

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INTRODUCTION

Diverse groups of tropical and subtropical soils are found in humid tropical Western Ethiopia (Henricksen et al., 1984). The soils in the humid tropics and subtropics have undergone natural acidification processes due to intense weathering and leaching under prevailing warm and humid climatic conditions (Blamey and Edwards, 1989; Banguy et al., 2017). Acid deposition and excessive application of NH_4^+ containing fertilizers can also accelerate the rate of acidification of humid tropical and subtropical soils (Alewell, 2003; Bolan and Hedley, 2003). Acid soils as defined by Uexkull and Mutert (1995) have pH-H_2O < 5.5. The soils of humid tropical Western Ethiopia suffer from soil acidity problem and Al toxicity (Mesfin, 2007; Abdenna, 2013; Abdenna et al., 2013). About 41% of Ethiopian soil coverage has a pH < 6.7, among which about 28% has a pH in the range of 5.5 to 6.7, while about 13% (14,954,000 ha) of the soil coverage have pH < 5.5. The soils which have a pH < 5.5

suffer from Al toxicity (Schlede, 1989). Acid tropical soils dominated by (hydroxy)oxides of Al and Fe with Al toxicity are predominantly found in Oromia, Amhara, Southern Nations, Nationalities and People and Bennishangul Gomez Regional States (Henricksen et al., 1984; Schlede, 1989; Tadesse, 1990; Mesfin, 2007; Abdenna et al., 2013; Oromia Land and Environmental Protection Authority, 2014a, b; Oromia Irrigation Development Authority, 2017a, b). Ferralsols, Alisols, Lixisols, Acrisols and Luvisols (WRB, 2014) are the major soils types suffering from acidity-related infertility (Oromia Land and Environmental Protection Authority, 2014a, b; Oromia Irrigation Development Authority, 2017a, b). The soils have low pH, high exchangeable acidity, low concentration of exchangeable bases, and high Al saturation (Al_{sat}) and various nutrient deficiencies.

Liming acid soils is a common method of ameliorating soil acidity and Al toxicity (Uexkull, 1986; Edmeades and Ridley, 2003; Fageria and Baligar, 2008). Liming weathered tropical acid soils is aimed at precipitating Al_{ex}, usually attained at about pH 5.5 (Uexkull, 1986; Espinosa, 1996). This approach of LR recommendation takes into account the Al_{ex} presents in the top soil. Lime requirement for most tropical soils is usually predicted as $\mathrm{CaC0_3\ (ton/ha) = Factor \times me\ Al\ 100g^{-1} soil}$ (Equation 1 in Espinosa, 1996). For soils with low permanent and high variable charges, it is suggested that lime recommendation based on amount of Al_{ex} in topsoil corresponds to 1.5 mili-equivalent (me) of $CaCO_3$ for a me of Al_{ex} for pH range of 4.0 to 5.6 (Kamprath, 1980). The Al_{ex} extractable with *1M* KCl has been in use as a valid criterion for determining LR of soils of tropics and sub tropics. The LR on the basis of Al_{ex} eliminates the need for time consuming neutralization test in laboratory (Blamey and Edwards, 1989). However, the actual value of LR for different soils is determined in accordance with site specificity of soil properties and crop tolerance for Al (Uexkull, 1986; International Soil Fertility Manual, 1995; Espinosa, 1996). The factor in the equation above for tropical soils of Latin America varied from 1.5 to 3 (Espinosa, 1996). According to International Soil Fertility Manual (1995), the factor in Equation 1 of Espinosa (1996) for prediction of LR for tropical soils ranges from 1.5 to 3.3 and lies mostly between 1.5 and 2.0. Crops tolerant to Al can grow and produce a satisfactory yield at moderate to high Al saturation. This further elaborates the need for not precipitating the entire Al on exchange sites and calls for lower amount of LR to reduce Al saturation (Al_{sat}) to the desired level (Espinosa, 1996). Lime requirement on the basis of precipitating Al_{ex} is based on level of Al_{sat} (Blamey and Edwards, 1989).

Liming research in Ethiopia dates back to early 1980's. The attempt was to raise pH of acid soils rich in Al_{ex} to neutrality and improve nutrient availability (Mesfin, 2007). Impressive plant growth and yield response to liming and interaction with nutrients were reported. For example, at Gimbi and Nejo on strongly acid soils lime, P and N fertilizers application increased agronomic yields of many crops (Adugna, 1984). At Chencha liming increased yield of barley (Angaw and Desta, 1988). Finger millet and maize yield increments were reported in Wollega zones with application of 3 tons of calcite with supplementary N and P fertilization (Tadesse, 1990). Wassie and Shiferaw (2011) also reported tuber yield increase of Irish potato to liming acid soils with 3.5 tons per ha^{-1} with 110:40:100 kg N:P:K ha^{-1} compared to sole application of the NPK in Southern Ethiopia. However, liming studies conducted on wheat, soybean and haricot bean did not significantly increase yield (Angaw and Desta, 1988). In various earlier liming studies, 3 tons ha^{-1} of lime was tentatively recommended but it was not translated into action to reclaim soil acidity (Tadesse, 1990; Mesfin, 2007). However, liming acid soils in Ethiopia is a new practice for farming community. It started in 2007 when the Ethiopian government recognized the adverse effect of soil acidity to increase agricultural productivity and developed policy strategy of liming acid soils. Since then liming research has been reemphasized. Plethora of academic research reports have been published (Achalu et al., 2012; Workneh, 2013; Abraha et al., 2013; Mekonin et al., 2014; Asmare et al., 2015; Jafer and Hailu, 2017; Endalkachew et al., 2017; Wassie and Shiferaw, 2011). Although lime research dates back to 1980's, lime application at farm level is fairly a new practice in Ethiopia. The government of Ethiopia started to demonstrate method of lime application, yield increment of agronomic crops, and installation of lime processing plants as of 2007. Farm level lime demonstration on model farmers revealed that an agronomic yield increment of 500% on demonstration plots of some farms were reported (Tekalign, 2015). However, there is no established rapid and reliable method of LR determination to neutralize Al toxicity for acid soil management of humid Western Ethiopian soils. Thus, there is a strong need to establish relationship between a soil-test based rapid method of determining LR that can support the government policy and strategy to reclaim soil acidity and increase productivity. The objectives of this research were to determine LR of Ultisols and Alfisols, and to establish and verify relationship between LR of laboratory experiments with LR determined on the basis of Al_{ex} extractable with *1M* KCl.

MATERIALS AND METHODS

Description of the study site

The study was conducted at Didessa watershed of humid Western Ethiopia (Figure 1). The study region represents the host spot of soils affected with soil acidity and Al toxicity. According to Soil Survey Staff (2014) classification system, Ultisols (Typic Hapludults), Alfisols (Typic Ferrudalfs and Rhodudalfs) and Vertisols (Typic Hapluderts) were the major soil types of the watershed. According to World Reference Base for Soil Resources (WRB, 2014), the soil groups correspond to Alisols (Ferric Rhodic Alisols), Luvisols (Ferric Rhodic Luvisols and Ferric Chromic

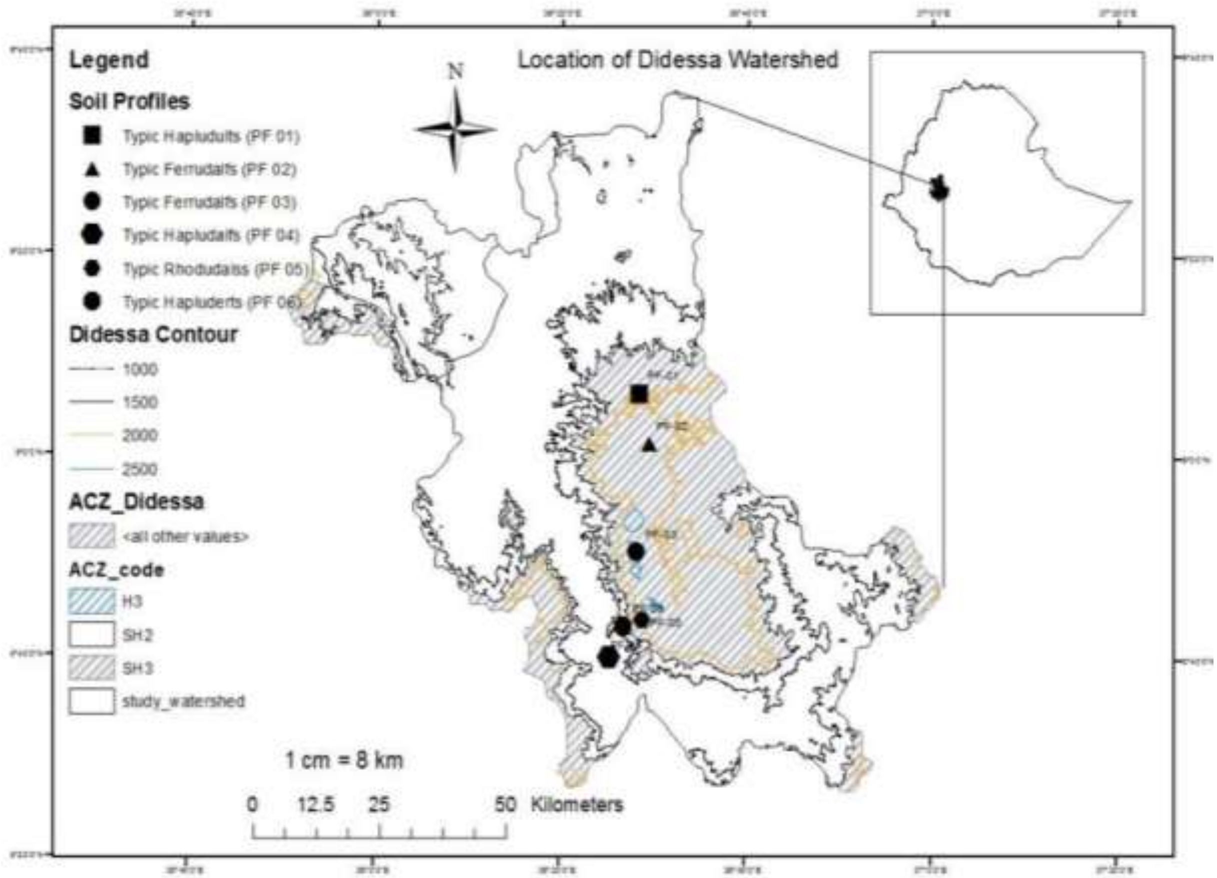

Figure 1. Study location characteristics of Didessa Watershed.

Luvisols), and Vertisols (Calcic Pellic Vertisols). In the present study, however, LR of soils was determined for Ultisols (Typic Hapludults) and Alfisols (Luvisols). Vertisols were not included for LR determination as pH-H_2O was higher than 6.0 and calcareous. The morphological, physical and chemical properties and the classifications of the soils were reported in detail by Abdenna et al. (2018).

According to data from National Metrological Agency, the mean annual long- term rainfall of the watershed ranges from 1400 to 1920 mm with unimodal pattern of distribution. The length of growing period (LGP) varies from 210 to 300 days. Mean long term monthly temperature minima and maxima range from 14 to 19 and 23 to 28°C, respectively. Elevation of the watershed varies between 845 and 2685 m. Three major topographic positions namely lowland, midland and highland with elevation range of 835 to 1500, 500-2000, and 2000-2685 m are found in the study watershed, respectively. Three agro-climatic zones namely warm sub-humid lowland with 180-240 LGP, 20-28°C and 500 to 1300 m, tepid sub-humid midland with 180-240 LGP, 15 to 20°C, 1500 to 2000 m and tepid humid highland with 240 to 300 LGP, 15 to 20°C, 2000 to 2685 masl are found the watershed.

Soil sampling

Soil samples were collected from Ultisols (Typic Hapludults) and Alfisols (Typic Ferrudalfs and Rhodudalfs) (Soil Survey Staff, 2014). Twenty to thirty subsamples were collected following standard soil sampling procedure to the depth of 0 to 20 cm. The subsamples were composited and 2.0 kg composites samples were sampled. Generally thirty three composite soil samples were collected and air dried, sieved through 2 mm. The land use history and land use characteristics of sampling sites are summarized in Table 1.

Analysis of soil physical and chemical properties

Analysis of particle size distribution was done by modified sedimentation hydrometer procedure of Bouyoucos (Kroetsch and Wang, 2006). During particle size analysis, organic carbon (OC) and $CaCO_3$ were removed by treating with H_2O_2 and HCl, respectively. Soil pH was measured in supernatant suspension of soil to liquid ratios of 1:2.5 in H_2O (pH-H_2O) and 1M KCl (pH-KCl) by procedure outlined by Reeuwijk (1992). Soil organic carbon was determined by the Walkley-Black procedure. Exchangeable acidity was extracted by 1M KCl solution and determined titrimetrically (Bertsch and Bloom, 1996) complxed with 1M KF and Al_{ex} was determined colorimetrically by titration with 0.025 M HCl (Reeuwijk, 1992). Extractable acidity (titratable acidity) was determined from soil extract by $BaCl_2$-TEA buffer solution at pH 8.2 (Reeuwijk, 1992). Exchangeable bases (Na, Ca, Mg and K) and CEC were determined in 1M ammonium acetate at pH 7 (Reeuwijk, 1992). The concentration of Na and K were measured by flame photometer while the concentration of Ca and Mg were measured by EDTA colorimeters. The Al_{ex} saturation was calculated as ratio of Al_{ex} to effective CEC multiplied by 100.

Table 1. Description of major land uses characteristics of the soil sampling sites.

Field code	Soil types	Land use history and characteristics
LS-2	Hapludults (Alisols)	Eucalyptus agroforestry of about 10 years of age
LS-3	Hapludults (Alisols)	Continuous cultivation with maize-sorghum-finger millet-noug rotation over the past 40 years
LS-4	Hapludults (Alisols)	Short fallow for 2 to 3 years after continuous cropping to restore soil fertility. During short fallow, the land used as grazing for livestock husbandry
LS-7	Ferrudalfs (Luvisols)	The land had been under small holder traditional agriculture. As the land lost its productivity, it became under Eucalyptus agroforestry since 10 to 15 years. Currently. the land is covered by mature eucalyptus agroforestry
LS-14	Ferrudalfs (Luvisols)	The land is under continuous crop cultivation with tef-millet-noug in rotation and then short fallowing for 2-3 years during which the land is used as grazing land for livestock
LS-16	Ferrudalfs (Luvisols)	Short fallow for 2 to 3 years after tef-millet-noug crop rotation. The land currently used as grazing land for livestock husbandry
LS-17	Ferrudalfs (Luvisols)	Communal grazing land for about 8 years. The land were under cropping land before conversion to grazing land
Ver-01	Hapludults (Alisols)	The land was under cultivation for long period and follow for three consecutive years

Lime requirement determination

Seven composite soil samples were screened from the thirty-three soil samples on the basis of soil pH, exchangeable acidity, titratable acidity and OC. The soils were advanced for the lime incubation experiments. The arrangement of lime treatments were estimated from Al_{ex} of the soils (Table 2). One hundred grams of soils were weighed and added into 250 ml capacity glass funnels and watered to field capacity and incubated for 60 days in chamber at 20°C in laboratory. High grade of $CaCO_3$ was used as liming material to neutralize exchangeable and titratable Al of soils during incubation experiment. The soils were watered weekly to maintain optimum soil moisture in the incubation chamber. At 60 days of incubation, the glass funnels were removed from the chamber and soils were air dried. The air dried lime treated soils were analyzed for pH-H_2O, Al_{ex} and H, and the results were reported on dry weight basis.

Greenhouse experiment

Composite soil sample (Ver-01) was used for the greenhouse pot experiment. This soil was collected from fallow land at Guto Gida district of Didessa watershed of humid Western Ethiopia, dried on canvas, crushed and passed through a 5 mm sieve. The chemical and physical property of this soil is indicated in Table 3. The greenhouse pot experiment was conducted at Holeta Agricultural Research Center. Very fine powder (<0.1 mm diameter) dolomitic limestone ($Ca*Mg\ (CO_3)_2$) was used as liming material. The dolomitic liming material contained 88% calcium carbonate and 3.53% magnesium carbonate with total calcium and magnesium content of about purity of 91.5%. The lime treatments were arranged as percentage of equivalent amount of Al_{ex} of soils used for greenhouse pot experiment. The lime treatments were arranged on the basis of Al_{ex} as 0.0, 50, 100, 150, 200, 250 and 300% of the lime requirement estimated from equivalent amount of cmolc Al kg^{-1}. These correspond with 0.0, 4.87, 9.71, 14.57, 19.43, 24.28, and 29.13 t ha^{-1} of calcium carbonate equivalents (CCE) and soil bulk density 1447 kg m^{-3} and 0.15 cm topsoil layer, respectively.

Five kg of soil was added into plastic pot with three replications and seven rates of lime treatments were added to the soils and well homogenized on canvas. The pots were watered to field capacity and set aside for sixteen days in greenhouse. The pots were watered every other day. The incubated soils treated with different lime rates were planted on seventeenth day with open pollinated maize variety (Hora) as test crop in each pot according to recommended agronomic practices. Equivalent amount of field recommendation of nitrogen, phosphorus and sulfur containing inorganic fertilizers were applied at planting, urea and di-ammonium phosphate were additionally applied when the test crop reached knee height. Six seeds per pot were planted and thinned to four plants per pot after germination. The thinned plants were incorporated into soils of their respective pots to avoid absorbed nutrient loss. A completely randomized design (CRD) with three replications was used and soil moisture level was maintained at approximately 75 to 100% field capacity during the growth period using tap water at three days intervals.

Data recording

Plant height of test crop was measured using metering tape starting from the base of maize plants to the tip of fully developed leaves. The plants were harvested at 60 days after planting when significant biomass and maximum root development were achieved. The roots and soils were separated from each other by immersing the roots and the rhizosphere soil into bucket of water and through carefully loosening the soil in the bucket. The roots separated from soil masses were washed out by applying a jet of water from tap water. The fresh weight of plants per pot was determined using a digital balance. The root length was also measured using

Table 2. Physical and chemical properties of the study soils.

Soil properties	Measurements	Soil codes							Ver-01
		LS-2	LS-3	LS-4	LS-7	LS-14	LS-16	LS-17	
Texture	Sand	57	53	47	53	43	37	53	30
	Silt	23	27	27	25	25	37	29	35
	Clay	20	20	26	22	32	26	18	35
	Class	SL	SL	SL	SCL	CL	L	SL	CL
Bulk density	gcm^{-3}	1.12	1.08	1.07	1.12	1.26	1.19	1.24	1.47
pH	H_2O	4.8	5	4.9	4.7	5.0	4.9	5.2	4.8
	KCl	3.6	3.9	3.7	3.6	3.6	3.67	3.9	4.1
CEC	Cmolc kg^{-1}	39	37	36	24	34	32	35	31
Exchange acidity	Cmolc kg^{-1}	8.2	1.4	2.2	9.3	4.5	2.6	1.5	10
Exchangeable Al	Cmolc kg^{-1}	8	1.4	2.2	8.8	4.4	2.53	1.23	8.2
Exchangeable H	Cmolc kg^{-1}	0.20	trace	trace	0.57	0.09	0.08	0.28	-
Titratable e acidity	Cmolc kg^{-1}	41.6	32.9	33.3	40.6	27.2	23.7	28.9	-
Exchangeable Ca	Cmolc kg^{-1}	1.39	8.00	6.28	1.35	5.10	7.29	8.14	11.9
Exchangeable Mg	Cmolc kg^{-1}	1.39	2.66	3.77	1.35	3.81	3.61	9.50	2.85
Exchangeable Na	Cmolc kg^{-1}	0.10	0.10	0.12	0.13	0.10	0.11	0.10	0.09
Exchangeable K	Cmolc kg^{-1}	0.18	2.28	1.20	0.21	0.67	0.90	1.17	0.15
Sum of bases	cmolc kg-1	3.06	13.04	11.37	3.04	9.68	11.9	18.9	14.3
PBS	%	27.2	90.30	83.8	26.4	68.4	77.4	92.6	46.0
PAS	%	72.8	9.70	16.2	75.4	31.7	19.1	7.40	54.0
OC	%	6.40	4.80	5.20	5.70	4.00	4.60	6.20	2.48
Olsen P	ppm	2.30	6.00	2.30	2.30	2.30	2.30	2.50	8.73

PBS = Percent exchangeable base Saturation; PAS = Percent exchangeable acid Saturation, SOC = soil organic carbon.

Table 3. Lime treatments on the basis of equivalent amount of exchangeable Al for different soils.

Field code	Titratable acidity	Al_{ex}	Amount of $CaCO_3$ (mg per kg)				
	Cmolc kg^{-1}		0% cmolc Al_{ex}	50% cmolc Al_{ex}	100%cmolc Al_{ex}	150%cmolc Al_{ex}	200%cmolc Al_{ex}
LS-2	41.59	8.20	0	205	410	615	820
LS-3	32.96	1.39	0	35	70	104	139
LS-4	33.32	2.18	0	55	109	164	218
LS-7	40.58	8.75	0	219	438	656	875
LS-14	27.16	4.43	0	111	222	332	443
LS-16	23.73	2.53	0	63	127	190	253
LS-17	28.92	1.23	0	31	62	92	123

measuring tape, the total dry shoot and root biomass was determined after drying all the harvests at 60°C for 48 h.

Statistical analysis

Statistical analyses of the data were determined using SPSS software version 20.5. Statistical significance level was determined at 0.01 and 0.05 (risk level, p value). Linear and quadratic curve fittings through regression analysis were done to develop regression equations that describe the lime rate and Alex to determine the optimum lime rate for laboratory incubation and greenhouse verification experiments. Correlation analysis was carried out to determine association between soil parameters and amount of optimum lime required to neutralize exchangeable acidity. Analysis of variance and mean separation were carried out to identify the statistical significance of the effect of lime rate on maize biomass, root length and height grown in greenhouse pot experiment.

RESULTS AND DISCUSSION

Physical and chemical properties of soils

Table 3 indicates the physical and chemical properties of the study soils. Textural classes ranged from sandy loam to sandy clay loam. The soil pH-H2O ranged from 4.7 to 5.2 and pH-KCl ranged from 3.6 to 3.9. According to Robarge (2008) pH scale, the study soils are extremely acidic in reaction. The CEC of soils ranged from 24 to 39 cmolc kg-1soil which corresponds to medium to high status (Landon, 1991). The exchangeable acidity varied from 1.4 to 10 cmolc kg^{-1} soil, and Alex ranged from 1.23 to 8.2 cmolc kg^{-1}. The exchangeable H accounted for tiny fraction of exchangeable acidity. Titratable acidity ranged from 23.7 to 41.6 cmolc kg^{-1}. Percentage Alsat ranged from 7.4 to 72.8%. The study soils had medium to high SOC that ranged from 4.0 to 6.4%. The Olsen P content of soils ranged from 2.3 to 6 mg kg^{-1} soil which indicates the soils are deficient in available P (Jones, 2003).

Lime requirements

Table 4 indicates the soil chemical properties after sixty days of laboratory incubation. Liming acid soils increased soil pH, exchangeable Ca and base saturation, and decreased Al_{ex} with progressive increment of lime rates. During 60 days of incubation, the Al_{ex} in the plots that received zero calcium carbonate as treatments decreased 18 to 37%. This might be due continuous watering of the plots with ground water containing basic cations as well as basic cation released from mineralization of organic matter that precipitated the Alex from colloidal sites. The calcium ions from dissolution of lime have replaced Al ions from exchange site resulting in Al precipitation in the form of gibbsite. Caires et al. (2007) and Fageria and Baligar (2008) also reported increased soil pH and exchangeable Ca, and decreased Alex with increasing rate of liming in the form of calcium carbonate. The relationships between LR and Al_{ex} are indicated in Table 5. The Al_{ex} decreased with increased pH and Al_{ex} fully precipitated at pH of 5.1 to 5.2.

Incremental addition of lime rate increased exchangeable Ca and ECEC. The relationships between LR and Al_{ex} for individual experimental soils are quadratic. The optimum LR for precipitating Al_{ex} was represented by y-intercept of regression curves (Table 6).

The relationship between optimum LR determined from incubation experiments and Al_{ex} of soils could be described either with a linear or quadratic regression equations (Figure 2). The equations are as follows:

$$\text{LR (cmolc } CaCO_3\text{) / kg soil} = 1.4689 \times \text{cmolc } Al_{ex} \text{ per kg soil} \quad (1)$$

$$\text{LR (cmolc } CaCO_3\text{)/kg soil} = [(2.5554 \times \text{cmolc } Al_{ex} \text{ per kg soil}) - 0.1921^* (\text{cmolc } Al_{ex})^2)] \quad (2)$$

Comparison of both models based on R^2 indicated that the quadratic relationship ($R^2 = 0.90$) is better than the linear one ($R^2 = 0.72$). However, comparison of the model outputs with actual experimental results of LR determined from incubation experiment revealed that both models are fairly good in predicting LR of Ultisols and Alfisols having varying levels of Al_{ex} (Figure 3).

The linear model slightly underestimates LR of soils with Al_{ex} less than 7 cmolc kg^{-1} soil while the quadratic model consistently estimates LR of soils with Al_{ex}. Expressing the outcome in a more practical way, LR of any soil having certain amount of Al_{ex} can be calculated with the linear model as follows:

$$\text{LR (ton } CaCO_3\text{)/ha)} = 0.5 \times 1.47 \times \text{Al (cmolc/kg)} \times \text{soil mass (ton/ha)}$$

And with the quadratic model as follows:

$$\text{LR (ton } CaCO_3\text{/ha)} = 0.5 \times [(2.5554 \times \text{Al}) - 0.1921 \times (\text{Al})^2] \text{ cmolc/kg} \times \text{soil mass (ton/ha)}$$

The choice of the model depends on the accuracy of the model (R^2). The constant (0.5) is the unit conversion factor from cmolc to g of $CaCO_3$. The soil mass ha^{-1} can be calculated as ρb*h*10, where ρb = bulk density (g cm^3); h=rooting depth (0.15 m); Al_{ex} = exchangeable Al (cmolc kg^{-1}); 10 is unit conversion from quintal to ton. For example, according to the linear model, precipitating 8.19 cmolc Al_{ex} kg^{-1} for the soil Ver-01 to the 0.15 m rooting depth and bulk density of 1.447 g cm^{-3}, 1.6 ton $CaCO_3$ ha^{-1} $cmolc^{-1}$ Al is required and 13.1 tons $CaCO_3$ ha^{-1} required to precipitate 8.19 cmolc Al kg^{-1} soil within one hectare to the depth of 0.15 m. Based on the quadratic model, 8.73 tons of $CaCO_3$ ha^{-1} is required to precipitate the same amount of Al_{ex}. As indicated in Figure 3, the quadratic model slightly underestimates LR while the linear model overestimates LR of soils for Al_{ex} exceeding 5.5 cmolc Al kg^{-1} soil.

Comparison of lime requirement of the previous lime recommendation with model outputs

The current model output was compared with four previous academic studies conducted in Ethiopia (Achalu et al., 2012; Mekonin et al., 2013; Hirpha, 2013). The studies were carried out in pot experiments with soils from humid tropical Western and Northwestern Ethiopia. The LR for each of the study soils on the basis of Al_{ex} were recalculated using the linear equation (Equation 1) and quadratic equation (Equation 2). The comparison of the present model outputs and the previous studies are indicated in Table 7 and Figure 4. Comparison of the model outputs with the previous optimum lime rate recommended to precipitate Al_{ex} from liming rate trials revealed results of the similar magnitude. The previous studies were conducted on acid soils with varying Al_{ex} ranging from 1.2 to 5.56 cmolc kg^{-1}. The LR recommendations were directly proportional with Al_{ex}. The LR recommendations ranged from 2.2 to 7.0 ton ha^{-1}.

Table 4. The effect of lime application on soil reaction and exchangeable bases and Al_{ex}.

Soil code	$CaCO_3$	pH	Ex.Al	∆Ex. Al	∑ Bases	ECEC	PBS	PAS
	cmolc kg^{-1} soil	H_2O	Cmolckg^{-1}	%	cmolc kg^{-1} soil		%	
LS-2	0.0	4.2	6.7	18	1.67	8.37	20	80
	4.1	4.8	2.8	66	5.67	8.47	67	33
	10.4	5.1	0.0	100	7.67	7.67	100	0
	20.8	5.6	0.0	100	17.67	17.67	100	0
	31.4	6.7	0.0	100	20.67	20.67	100	0
LS-3	0.0	4.9	1.1	21	9.04	10.14	89	11
	3.3	5.1	0.7	50	10.04	10.74	93	7
	8.4	5.1	0.1	93	11.04	11.14	99	1
	16.7	5.2	0.0	100	11.04	11.04	100	0
	25.0	5.4	0.0	100	14.04	14.04	100	0
LS-4	0.0	4.8	1.7	22	9.09	10.79	84	16
	4.1	5.0	0.3	86	10.09	10.39	97	3
	10.2	5.5	0.0	100	13.09	13.09	100	0
	20.4	5.9	0.0	100	20.09	20.09	100	0
	30.5	6.3	0.0	100	22.09	22.09	100	0
LS-7	0.0	4.5	5.5	37	1.69	7.19	24	76
	2.7	5.1	3.5	60	4.69	8.19	57	43
	6.8	5.2	0.3	97	8.69	8.99	97	3
	13.6	6.0	0.0	100	14.69	14.69	100	0
	20.4	6.4	0.0	100	21.69	21.69	100	0
LS-14	0.0	5.0	3.1	30	7.58	10.68	71	29
	2.4	5.1	1.4	68	14.58	15.98	91	9
	5.9	5.3	0.0	100	15.58	15.58	100	0
	11.9	5.5	0.0	100	16.58	16.58	100	0
	17.9	6.3	0.0	100	20.58	20.58	100	0
LS-16	0.0	5.0	0.8	68	7.62	8.42	90	10
	0.4	5.1	0.2	92	10.62	10.82	98	2
	1.7	5.2	0.0	100	16.62	16.62	100	0
	3.5	5.9	0.0	100	17.62	17.62	100	0
	6.6	6.9	0.0	100	19.62	19.62	100	0
LS-17	0.0	5.1	0.8	35	13.77	14.57	95	5
	1.4	5.0	0.2	84	17.77	17.97	99	1
	3.0	5.2	0.0	100	19.77	19.77	100	0
	7.2	5.6	0.0	100	22.77	22.77	100	0
	14.6	6.3	0.0	100	24.77	24.77	100	0

*data is not available for accuracy reason.

Comparison of these results with both linear and quadratic model outputs obtained by substituting Al_{ex} into these models show that the quadratic model yields results that are closer to the experimental results of the original reports. Thus, the current model outputs of LR for quadratic equation fit well with results of previous studies while the linear model outputs was not consistent. The quadratic model can thus be used to determine LR of soils with Al_{ex} and the linear model is less accurate. Thus with the use of these equations to determine optimum LR site specific lime rate trials can be avoided while the results can be obtained using a rapid KCl extraction to

Table 5. Regression equations of lime requirements as the function of cmolc Al kg^{-1} soil by curve fitting.

Soil code	Regression equations	R^2	LR, Cmolc $CaCO_3$ per kg soil
LS-2	$LR = 0.1152*(Al_{ex})^2 - 2.1513*Al_{ex} + 9.24$	1.0	9.24
LS-3	$LR = -4.6877*(Al_{ex})^2 - 15.119*Al_{ex} + 11.137$	0.97	*
LS-4	$LR = -0.4202*(Al_{ex})^2 - 2.0739*Al_{ex} + 4.74$	1.0	4.74
LS-7	$LR = -0.0116*(Al_{ex})^2 - 1.209*Al_{ex} + 7.1622$	1.0	7.16
LS-14	$LR = 0.3003*(Al_{ex})^2 - 2.7634*Al_{ex} + 5.68$	1.0	5.68
LS-16	$LR = 7.7375*(Al_{ex})^2 - 8.3375*Al_{ex} + 1.718$	1.0	1.72
LS-17	$LR = 5.8625*(Al_{ex})^2 - 8.2625*Al_{ex} + 2.858$	1.0	2.86

Where Al_{ex} = exchangeable Al; LR = Lime Requirement as y-intercepts of regression equations),*= unrealistic value.

Table 6. Optimum LR ($CaCO_3$ kg^{-1}) of experimental soils as intercept of curve fitting.

Codes	Soil types	ton ha^{-1}
LS-2	Hapludults	11.41
LS-3	Hapludults	*
LS-4	Hapludults	7.61
LS-7	Ferrudalfs	6.77
LS-14	Ferrudalfs	5.37
LS-16	Ferrudalfs	1.54
LS-17	Ferrudalfs	2.66

*unrealistic value.

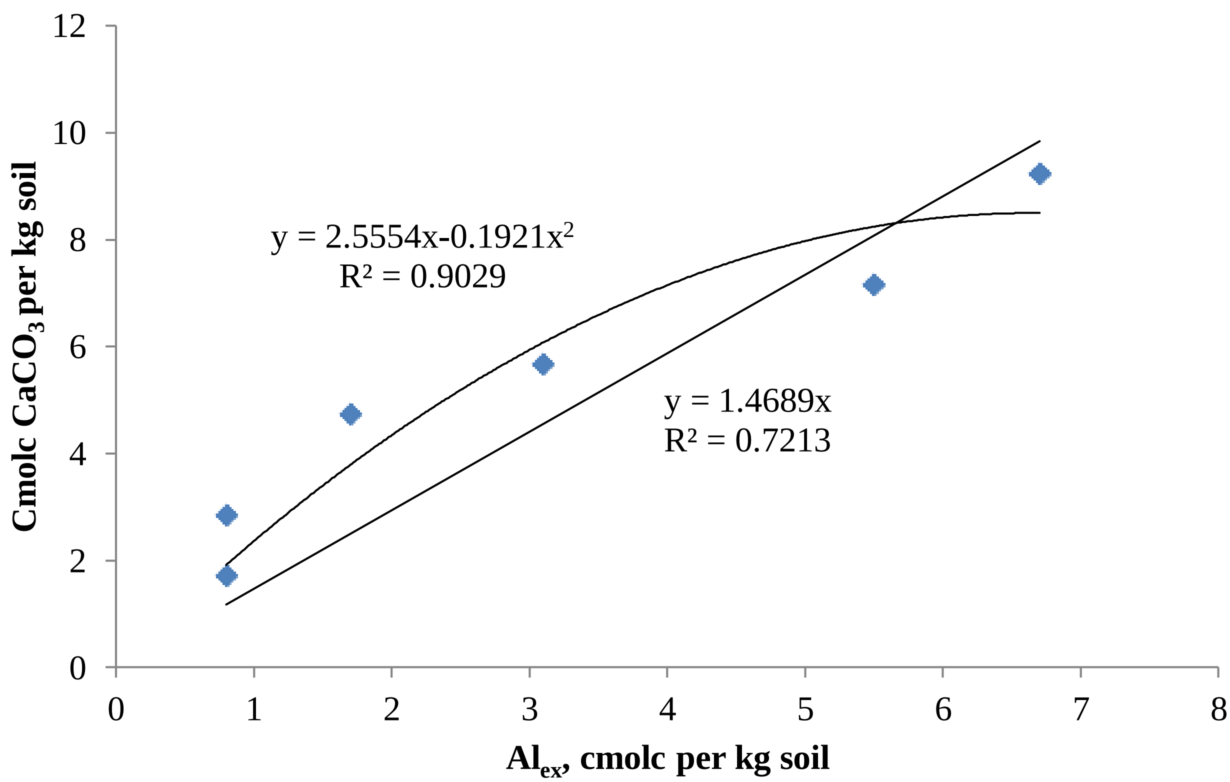

Figure 2. Relationships between lime requirement (cmolc $CaCO_3$) of experimental soils and Alex (cmolc kg^{-1} soil).

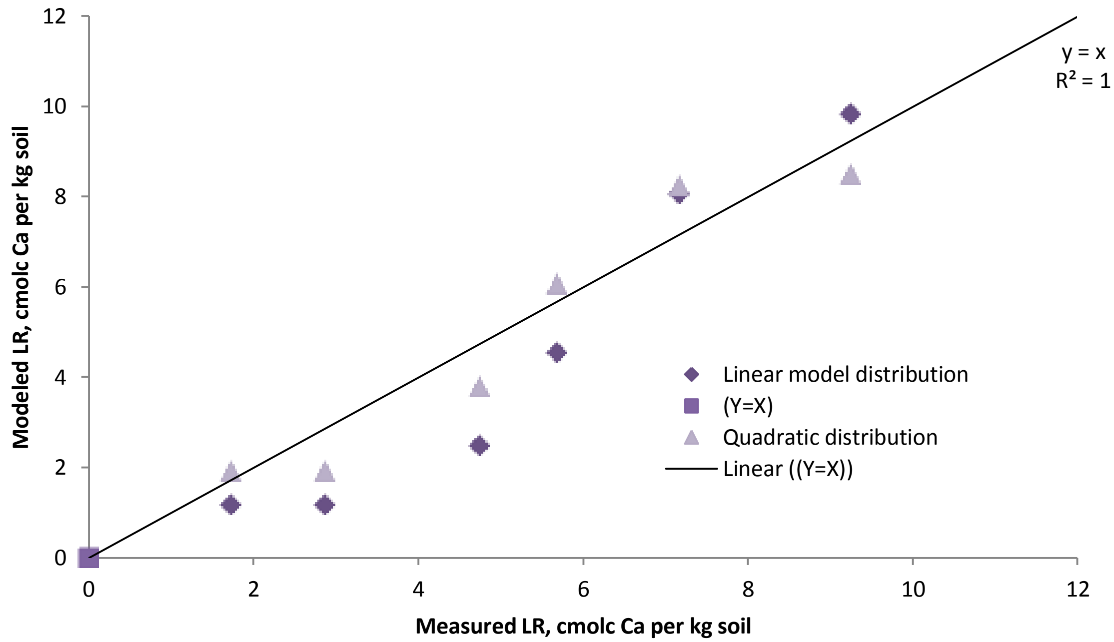

Figure 3. Comparisons experimental LR and model out puts on 1:1 line.

Table 7. Comparison of previous study results and recalculated LR using current model outputs.

References	Alsat	LR (authors)	LR (Linear model)	LR (Quadratic model)
	%		ton $CaCO_3$ ha^{-1}	
Chimdi et al. (2013)	NR	7.0	4.94	6.59
Legese et al. (2013)	45.9	4.4	4.15	5.35
Asrat et al. (2014)	11.2	2.2	1.91	2.79
Asmare et al. (2015)	NR	3.5	2.39	3.4

NR = Not reported.

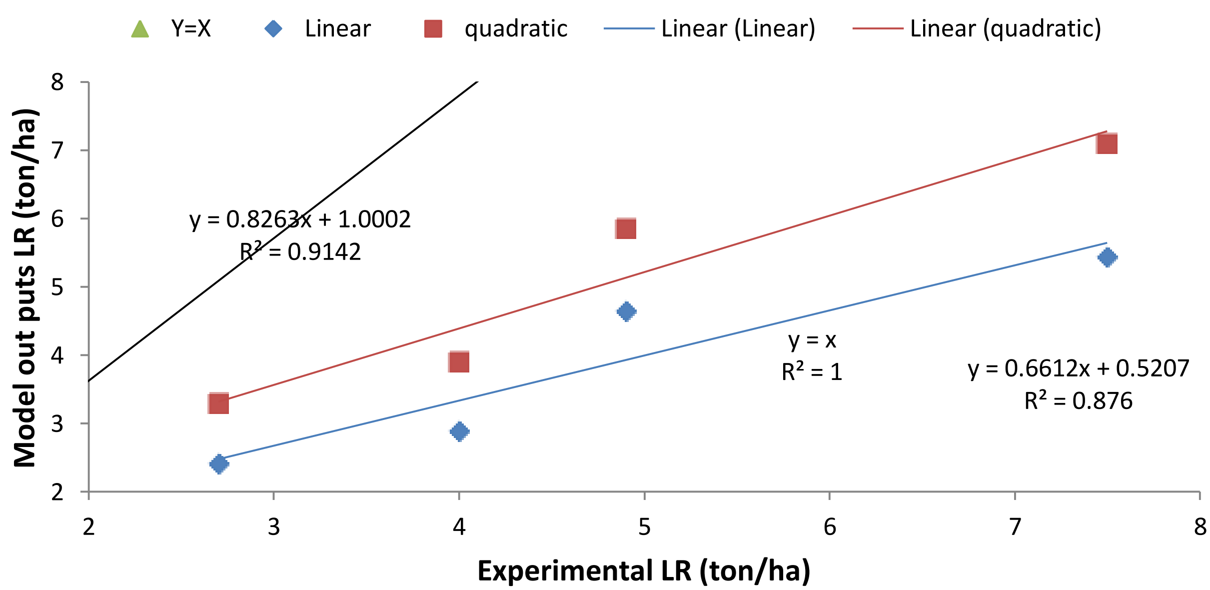

Figure 4. Comparison of recalculated quadratic and linear model outputs with LR of previous studies.

determine Al_{ex}.

Verification of LR models in the greenhouse pot experiment using maize as test crop

Table 8 indicates the effect of lime treatments on maize biomass, height and root length. The overall growth performance of test crop in greenhouse pot experiment is indicated in Figure 5. The highest maize biomass yield was obtained from pot that received 4.48 g equivalent to 9.93 ton CCE ha^{-1} (treatment 3). The highest plant height was obtained from pot that received 6.71 g equivalent to 14.87 ton CCE ha^{-1} (treatment 4) and the highest root length measured from pot that received 2.24 g equivalent to 4.96 ton CCE ha^{-1}, although this is not statistically significantly different from treatment 3 and 4. The results revealed that moderate amount of lime rates increase biomass, height and root length. Maize plants grown in pot treated with zero lime rates were toppled down between 3 to 4 weeks after plant emergence because of root damaged by Al_{ex} and dried out immediately. Liming above 14.87 ton ha^{-1}, significantly depressed biomass, maize height and root length. The yield depression due to lime rate above 14.87 ton ha^{-1} might be due to deficiency of phosphate caused by over liming (Haynes, 1982). Moreover, as soil pH increase above 6.0 in tropical soils, molybdenum becomes toxic while copper, boron and manganese become deficient, and further deterioration of soil physical structures (Robert, 2007). In general, the maize growth performance due to lime treatments was not so vigorous. This is due to the fact that the soil used for pot experiment was impoverished of essential nutrients. After initial yield increment, similar decline in yield of soybeans, common beans, corns, cotton and corn were also reported by Fageria and Baligar (2008).

Table 8. Effect of lime treatment on maize height, root length and biomass (g) per pot (test crop).

Treatment #	Lime rate, Ca*Mg $(CO_3)_2$		Mean biomass, g	Root length, cm	Plant height, cm
	g kg^{-1}	ton ha^{-1}			
1	0.0	0.0	1.92[a]	ND	44[a]
2	2.24	4.96	14.4[ab]	33[a]	77[b]
3	4.48	9.93	33.6[c]	40[b]	73[b]
4	6.71	14.87	21.9[bc]	67[b]	71[b]
5	8.95	19.83	14.5[ab]	38[a]	56[a]
6	11.19	24.79	16.6[b]	45[ab]	53[a]
7	13.43	29.75	14.7[ab]	43[ab]	47[a]

Means in a column followed the same letter are not statistically significant at the risk of 5%.

The greenhouse pot experiment confirmed that optimum LR for the test soil and the test crop is in the range of 9.93 to 14.89 ton CCE ha^{-1}. This range corresponds to outputs obtained from the quadratic model. The linear model has overestimated the biological (physiological) optimum LR of the soil and test crop. The optimum LR that gave the highest maize biomass coincides with LR determined from quadratic model. Liming the soils with the factors greater than 1.47 × cmolc Al kg^{-1} depressed growth of maize grown as a test crop. Application of [(2.5554 × cmolc Al kg^{-1}) - (0.1921 × cmolc Al^2 kg^{-1}) CCE kg^{-1} soil] has provided comparable result with the greenhouse experimental result. This result confirmed that the newly developed quadratic model effectively measures LR of other soils requiring treatment of Al toxicity problem.

The factor determined for LR determination in the current study is not comparable with lime recommendation of 1.5cmol $CaCO_3$ kg^{-1} or 1.65 tons of $CaCO_3$ suggested for humid tropical soils (FAO, 1984). It is also lower than the LR for Latin American soils that ranged from 1.5 to 3 cmolc CaCO3 to neutralize every cmolc of Al kg^{-1} soil (Espinosa, 1996). The current LR recommendation also contradicted the 3 ton $CaCO_3$ ha^{-1} blanket recommendation developed 35 year ago for management of acid soils of Ethiopia (Mesfin, 2007). To ameliorate Al toxicity for soil characterized by low to high SOC (2.5 to 6.4%), pH of 4.7 to 5.2, Al_{sat} of 7.5 to 75.4%, 18 to 35% of clay, the use of quadratic model for the determination of LR is recommended for humid Western Ethiopian Alfisols and Ultisols.

CONCLUSIONS AND RECOMMENDATIONS

1. The Al_{ex} in the present soils ranged from 1.23 to 8.2 cmolc kg^{-1} soil.
2. There was a quadratic inverse relationship between lime application rates and Al_{ex} of the experimental soils and the optimum LR to precipitate Al_{ex} ranged from 1.54 to 11.41 ton ha^{-1}.
3. The current LR recommendation contradicted with the 3 ton $CaCO_3$ ha^{-1} blanket recommendation developed 35 year ago.

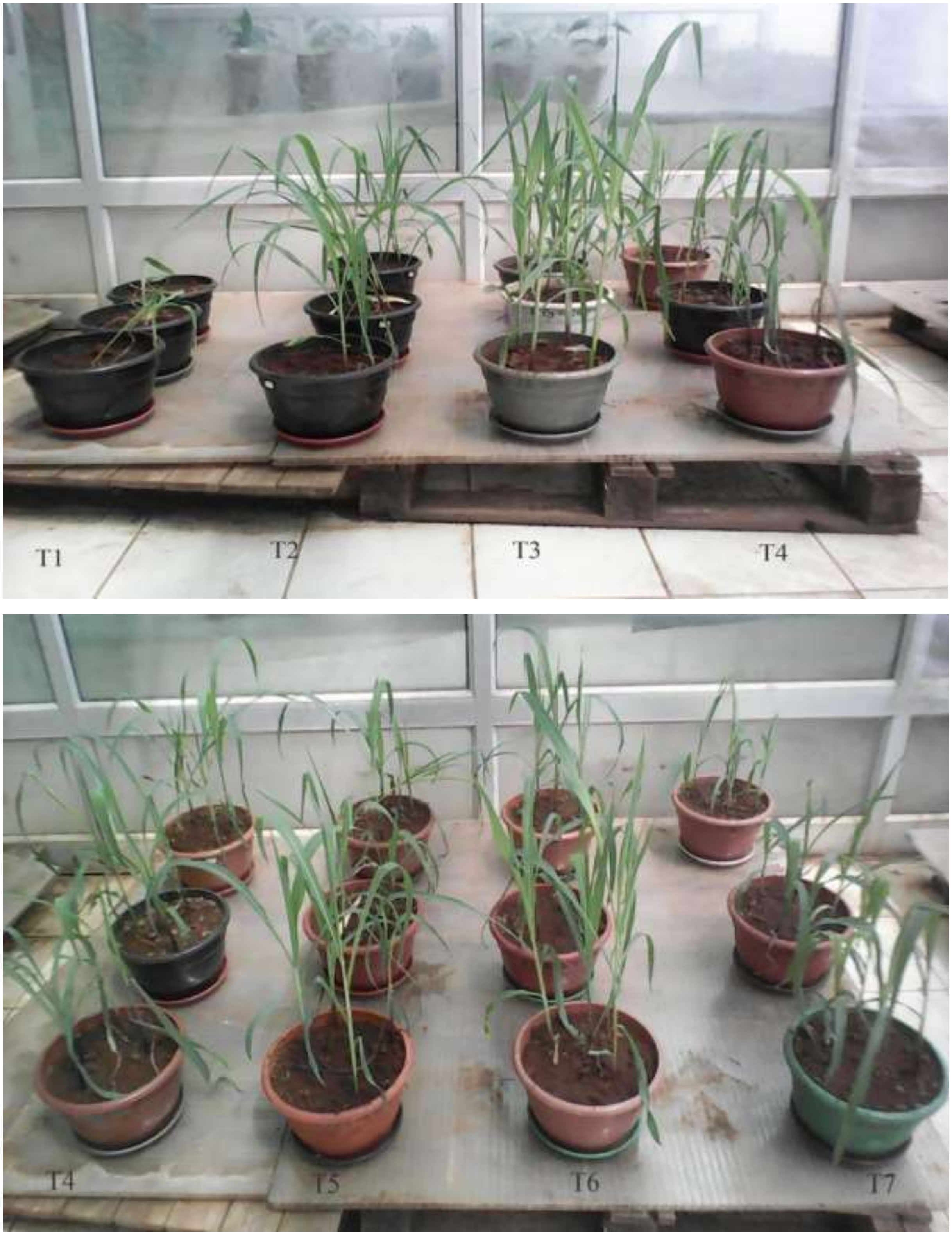

Figure 5. Growth of maize in acidic soils treated with seven rates of lime in humid Western Ethiopia.

4. Curve fitting of optimum LR determined from laboratory incubation experiments versus Al_{ex} of the experimental soils demonstrated that the relationship fits better with a quadratic relationship (LR, cmolc $CaCO_3$ per kg soil =

2.56*Al - 0.19*Al^2 cmolc/kg soil, R^2 = 0.90) than the linear relationship (LR, cmolc $CaCO_3$ per kg soil =1.47*Al cmolc/kg soil, R^2 = 0.72).

5. Testing of model outputs by comparing with results of four previous LR studies revealed that the relationship of optimum LR and Al_{ex} fitted well to the quadratic relationship.

6. Testing of the outputs obtained from the linear and quadratic LR models in a greenhouse pot experiment with maize as test crop also confirmed that the relationship between optimum LR and Al_{ex} is more of quadratic nature.

7. The linear model is inconsistent while the quadratic model well fitted to the test soil under greenhouse experiment. Moreover, results of previous optimum LR requirement determined both in field and greenhouse experiments fitted well for quadratic model.

8. The optimum LR of acidic Ultisols and Alfisols of humid tropical Western Ethiopia can be reliably determined as LR (cmolc $CaCO_3$ kg^{-1}) = 2.56*Al - 0.19*Al^2 (cmolc/kg soil, R^2 = 0.90) or LR (ton $CaCO_3$ ha^{-1}) = 0.5*(2.56*Al - 0.19*Al^2 (cmolc/kg)* soil mass (ton ha^{-1}) using the quadratic model of LR determination. The greenhouse pot experiment confirmed that optimum LR for the test soil and the test crop is in the range of 9.93 to 14.89 ton CCE ha^{-1}.

9. The use of this approach can replace lime incubation experiments in laboratory. In a developing country like Ethiopia where laboratory and reagents are expensive and scarcely available, small holder farmers can easily afford the price for testing the Al_{ex} using 1M KCl extraction method.

10. This determination method for optimum LR is worthy to be further verified at multi-field trial to broaden its geographic applicability. Moreover, it deserves to be disseminated to development workers and farming community in acid affected regions of humid tropical Western Ethiopia.

Competing interests: The authors declare that they have no competing interests.

Availability of data and materials: Not applicable.

Ethics approval and consent to participate: The manuscript does not contain data or information from any person or individual apart from field and laboratory investigation. All data and information are generated and synthesized by first author and approved by the co-authors.

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ABBREVIATIONS

$Al(OH)_3$ = Gibbsite; Al = Aluminum; Alex = Exchangeable Aluminum; Alsat = Aluminum saturation; $BaCl_2$-TEA = Barium Chloride Tri-Ethanol Amine; PBS = Base Saturation; Ca = Calcium; $CaCO_3$ = Calcium Carbonate; $CaMg(CaCO_3)$ = Dolomitic Limestone; CCE = Calcium Carbonate Equivalent; CEC = Cation Exchange Capacity; Cmolc = Centi-Mole Charge; CRD = Completely Randomized Design; ECEC = Effective Cation Exchange Capacity; EDTA = Ethylene Di-Amine Tetra Acetic Acid; Ex. Ca = Exchangeable Ca; Ex. H = Exchangeable H; Fe = Iron; H = Hydrogen; H_2O = water; HCl = Hydrochloric Acid; K = Potassium; KCl = Potassium Chloride; KF = Potassium Florid; LGP = Length of Growing Period; LR = Lime Requirement; M = meter; MASL = Meter Above Sea Level; Mg = Magnesium; Mn = Manganese; N = Nitrogen; Na = Sodium; OC = Organic Carbon; P = Phosphorus; PAS = Percent Acid Saturation; PAS = Percent Acid Saturation; PBS = Percent Base Saturation; PH=Power of Hydrogen; PH = Power of Hydrogen; SPSS = Statistical Packages for Social Sciences; Σ Bases = Summation of Exchangeable Bases.

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