Granular and powdered lime improves soil properties and maize *(zea mays* l.) performance in humic nitisols of Central Highlands in Kenya

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ABSTRACT

Aims

Soil acidity is a major constraint to crop production on highly weathered tropical soils characterized by high Aluminum (Al) toxicity, low cation exchange capacity, and low phosphorus (P) availability to plants. The objective of this study was to evaluate the effects of two powdered limes (calcium oxide, calcium carbonate), granulated lime (CaO.MgO), and their combinations with mineral fertilizer on soil chemical properties (soil pH, organic carbon, exchangeable acidity, total N, available P and exchangeable bases (Mg^{2+}, Ca^{2+}), and maize stover and grain yields.

Methods

Field experiments were established in two sites. The experiment was implemented in a randomized complete block design, replicated four times. They were carried out for two consecutive seasons. Data were subjected to analysis of variance (ANOVA) and mean separated using Duncan's Multiple Range Test.

Results

Results showed that liming led to significant increases in soil pH and a reduction in exchangeable acidity. Use of $CaCO_3$ recorded the highest pH increase in the extremely (+19%) and moderately (+14%) acidic sites. The application of all lime types and sole fertilizer increased soil available P in both seasons and sites. Maize grain yields were lower in treatments receiving sole fertilizer and sole lime compared to lime and fertilizer combinations. $CaCO_3$ + fertilizer recorded the highest grain yield in both the extremely (5.34 t ha^{-1}) and moderately (3.71 t ha^{-1}) acidic sites.

Conclusions

In the extremely acidic site, lime should be applied together with fertilizers. $CaCO_3$ was the best in ameliorating acidic soil in terms of reducing soil acidity and increasing P availability, and improving maize grain yields.

Keywords:
Soil acidity, lime, maize, nitrogen, phosphorus

INTRODUCTION

Soil acidity is a major yield-limiting factor for crop production worldwide. It is estimated that 4 billion hectares, approximately 30% of the world's total land area, are affected by soil acidification (Osman, 2013). Acidic soils in the Sub-Saharan African (SSA) region and Kenya cover 29% and 13% of the total land area, respectively (Kisinyo *et al*., 2013, Gicheru, 2012.). The acidic soils in Kenya cover the high potential croplands of central and western Kenya regions (Kisinyo *et al*., 2013). Acidic soils have high amounts of aluminum (Al) and hydrogen (H) ions toxicities which cause a decline in soil microbial activity, deficiency of essential nutrient elements, and retardation of plant growth (Kathpalia and Bhatla, 2018). Kenyan farmers in most maize growing regions use improved maize varieties and landraces, which are sensitive to low P (<5 mg P kg^{-1}) and high Al^{3+} saturation (>20%) (Zingore *et al*., 2015). Maize grain yields are reduced by about 16% in P deficient soils and by 28% in soils with high aluminum toxicity (Ligeyo, 2007).

The central highlands of Kenya cover areas with high crop production. The region is densely populated with densities exceeding 1000 people km^2 (Mugwe *et al*., 2009b, Willy *et al.,* 2019). This high population has caused increased land subdivision into small fragments (0.5 ha^{-1} ha per household) (Mucheru-Muna *et al.,* 2007). With the increase in population and high demand for food, the land has been exposed to continuous cultivation coupled with the use of inappropriate fertilizers, causing a buildup of soil acidity and soil chemical degradation (Mucheru-Muna *et al.,* 2007; Mugwe *et al.,* 2009a; Mucheru-Muna *et al.,* 2014). Soils in Tharaka Nithi are comparable to other agricultural soils in the tropics, which have been reported to have high P-fixation capacities, low available P, and high Al toxicity (Zingore *et al.,* 2015; Adamtey *et al*., 2016; Omenda *et al*., 2021). Mineral fertilizer application has become mandatory to increase yields in multi-nutrient deficient soils. However, the use of mineral fertilizers has exacerbated soil acidity leading to poor maize grain yields with 0.5 to 1.5 t ha^{-1} yr^{-1} reported in the region (Mati, 2006; Mugendi *et al.,* 2007; Mugwe *et al*., 2009a; Mucheru-Muna *et al.,* 2014; Muindi, 2016).

To ameliorate the highly weathered and acidic soils with low available P, lime application has been recommended. Liming increases soil pH, Ca and Mg contents, base saturation and increases both plant rooting system and P uptake in high P fixing soil (Hodges, 2010; Qaswar *et al.,* 2020). Liming materials differ in origin, particle sizes, nutrient composition, and neutralizing power (Anderson *et al.,* 2013). These characteristics may influence the effectiveness of the limes. The common liming materials in the Kenyan market are calcium oxide (CaO) and ground limestone composed mostly of calcium carbonate ($CaCO_3$), both of which exist in powdery form. Mbakaya (2014) reported that the use of $CaCO_3$ with inorganic fertilizers increased maize grain yield from 0.5 t ha^{-1} to 5 t ha^{-1}. Kisinyo *et al.* (2014) indicated that the effectiveness of lime in ameliorating acidic soil followed an increasing trend of 1 to 6 t ha^{-1} CaO where they recommended 2 t ha^{-1} of lime to be applied by smallholder farmers. The powdered formulation increases surface area for quicker soil reaction (Reddy & Subramanian, 2017). Fine lime is not easy to apply evenly on the surface, it drifts, and less portions of the particles will land unevenly. For maximum effectiveness, granular lime is finely ground limestone processed into fertilizer-sized pellets, thus reducing dust associated with very fine-sized particles. Lime can be spread accurately and evenly, thus convenient for farmers (Higgins *et al.,* 2012; Drew *et al.,* 2012). Granulated lime is protected from wind drift, and the uniform texture removes large, nonreactive particles that may take a longer period to disintegrate (Oates, 2007; Higgins *et al.,* 2012). In the US, Rasnake (2002) used granular lime and reported increased soybean yields of up to 3 t ha^{-1} and improved plant health in long-term studies.

Despite the potential of using liming materials in Kenya to increase crop yields, there is limited use in agricultural production, particularly among smallholder farmers. This is perhaps due to limited knowledge on lime usage, availability, and high hauling costs (Okalebo *et al*., 2009). Thus, before recommending the use of any of the lime types to smallholder farmers, it is essential to determine their effects on soil chemical properties. Furthermore, the low uptake of liming technology could be due to limes' unknown quality and effectiveness in improving soils and crop production. Therefore, it was vital to investigate the agronomic effectiveness of different types of lime in reducing soil acidity and improving maize yields in Tharaka Nithi County. We tested the hypothesis that three limes (one granular and two powdered), either sole or combined with inorganic fertilizer, will increase soil pH, reduce exchangeable soil acidity, increase P availability and optimize maize yields.

Materials and methods

Geographic Location and description of study sites

The experiment was conducted in Kirege and Kangutu in Meru South Sub-County of Tharaka Nithi County, Kenya. Meru South sub-county is at an altitude of 1500 m and is located in the Upper Midland zone 2 (UM2) agro-ecological zone with an annual rainfall range of 1200 to 1400 mm (Jaetzold *et al.,* 2007). Kirege site is located at a latitude of 0°20'16.7"S and longitude 37°36'51.7"E and Kangutu is located at an altitude of 0°33'84"S and longitude 37°68'31 E. Rainfall distribution pattern is bimodal, the long rains (LR) fall from March to May and short rains (SR) from October to December each year (Jaetzold *et al.,* 2007). Maize (*Zea mays* L.) is predominantly grown in the area. Humic Nitisols are the main soil types; they are typically deep and highly weathered with moderate to high inherent fertility (Jaetzold *et al.,* 2007). The initial soil characterization data of the soils in Kangutu and Kirege is presented below.

Table 1: Initial soil physical and chemical properties of Kirege and Kangutu soils (0 -20 cm), Meru South Sub-County of Tharaka Nithi County, Kenya

Soil Parameters	Kirege	Kangutu
Soil pH-H_2O	4.14	5.08
Exch. Acidity (C mol kg^{-1})	0.49	0.29
Total Nitrogen (%)	0.18	0.16
Total Org. Carbon (%)	1.7	1.51
Phosphorus (Mehlich) mg kg^{-1}	22.65	16.25
Potassium (C mol kg^{-1})	0.19	0.29
Calcium (C mol kg^{-1})	2.30	2.80
Magnesium (C mol kg^{-1})	1.14	3.76
Manganese (C mol kg^{-1})	0.59	0.60
Copper ppm	1.15	5.12
Iron ppm	46.04	23.57
Zinc ppm	8.08	58.85
Sodium (C mol kg^{-1})	0.19	0.21
Sand (%)	4.88	10.44

Silt (%)	11.50	16.75
Clay (%)	83.62	72.81
Texture Class	Clay	Clay

The moderately acidic site (Kangutu) received higher cumulative rainfall compared to the extremely acidic site (Kirege). In Kirege, 616.7 mm and 385.4 mm was received in LR2016 and SR2016, respectively (Figure 1). In Kangutu, the cumulative rainfall for LR2016 and SR2016 was 936 mm and 426 mm. Rainfall declined throughout the cropping season in both sites. Meteorological droughts and dry spells were experienced. Drought spells frequently occurred, for example, a seven-week drought ensued six weeks after planting during the SR2016 season (Figure 1).

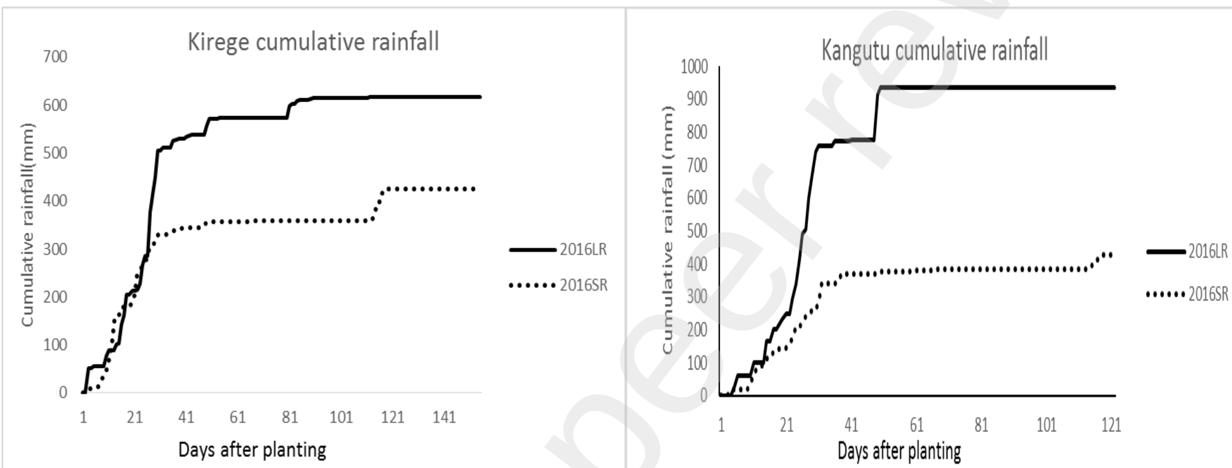

Figure 1: Cumulative rainfall during the 2016 long rains (LR2016) and short rains (SR2016) in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya

Rainfall was unavailable during the high water requirement period; for instance, most rainfall (>90%) had been received at 50% flowering in SR2016 Kirege. Rainfall amounts affect the amount of soil water, and variation in climatic factors such as precipitation, temperature, and changes in their distribution cause more frequency of extreme events (IPCC, 2007).

Experimental Design

The field experiment was set in Kirege and Kangutu sites in the Meru-South sub-county in Tharaka Nithi County. The experiment was set following a randomized block experimental design with eight treatments replicated four times per site.

Table 2: Treatments at Kangutu and Kirege experimental sites, Meru South, Kenya

Treatment:	**Description**
Control	No inputs
Fertilizer	DAP (60 kg P ha^{-1}) + UREA (60 kg N ha^{-1})
$CaCO_3$	2 t ha^{-1} $CaCO_3$
CaO	2 t ha^{-1} CaO
$CaCO_3$+Fertilizer	2 t ha^{-1} $CaCO_3$ + (60 kg P ha^{-1} + 60 kg N ha^{-1})
CaO+Fertilizer	2 t ha^{-1} CaO + (60 kg P ha^{-1} + 60 kg N ha^{-1})

CaO.MgO	2 t ha^{-1} Granulated CaO.MgO
CaO.MgO+Fertilizer	2 t ha^{-1} Granulated CaO.MgO + (60 kg P ha^{-1} + 60 kg N ha^{-1})

Plots sizes of 4.5 m by 3.0 m were marked and guard rows set with 1.0 m spacing—three types of lime: Granulated CaO.MgO lime and two powdered limes, calcium carbonate ($CaCO_3$) and burnt lime (CaO) were used. Analyses of the limes indicated that the amounts of Calcium Carbonate Equivalent, Ca, and Ca+Mg varied among the limes.

Table 1: Selected chemical properties of lime types used in the experiment

Lime type	**Ca**	**Mg**	**Ca+Mg**	**CCE**
$CaCO_3$	29.23	5.4	34.63	86.58
CaO	32.33	0.63	32.6	82.58
CaO.MgO	33.41	1.53	34.94	87.35

The limes were manually applied uniformly one month before planting at the recommended rate of 2 t ha^{-1} in the first season (2016 Long Rain). Diammonium phosphate (DAP) fertilizer was applied during planting, and four weeks after planting, UREA fertilizer was applied in both seasons. The rates used were recommended for optimum crop production in the area P fertilizer at 60 kg P_2O_5 ha^{-1} (Micheni *et al*., 2002) and lime at 2 t ha^{-1} (Okalebo *et al*., 2002). Maize variety H516 was used as the test crop and was planted with the rows spaced at 50 cm within and 75 cm between them. Disease, weeds, pests, and cultural management practices were carried out through the seasons.

Data collection

Soil sampling was done before the experiment and after harvest in each season using an Edelman soil auger. Samples from 0-20 cm depth were collected using the zigzag method (Carter and Gregorich, 2008). The soil samples were analyzed to determine soil texture, soil pH, organic carbon, exchangeable acidity, available P, total N, and exchangeable bases (K^+, Mg^{+2}, Ca^{2+}). Maize was harvested, and data on total stover fresh weight, grain moisture content, and after drying stover (t ha^{-1}) and grain yield (t ha^{-1}) was taken. Maize grain yield was expressed at a 12.5% moisture level.

Laboratory and Data analysis

Soil texture was determined using the hydrometer method or Bouyoucos (Okalebo *et al*., 2002). Soil pH water was measured in a 1:2.5 soil-water ratio (Ryan *et al*., 2001). Exchangeable acidity was determined using titration method according to Sark and Hader (2005) and Okalebo *et al*. (2002). Soil extractable P and exchangeable cations (K, Na, Ca, and Mg) were determined by Mehlich -3 procedures (Bolland *et al.,* 2003; Penn *et al.,* 2018). Soil organic carbon was determined by the modified Walkley-Black method (Nelson and Sommers, 1982; Bahadori and Tofighi 2016). The soil total nitrogen content of the sampled soil was determined following Kjeldahl digestion, distillation, and titration procedure as described by Page *et al*. (1982).

Maize above-ground biomass, grain yields, and selected soil properties data were subjected to analysis of variance (ANOVA) using SAS (9.3). Means separation was done using Duncan's

Multiple Range Test (DMRT). Pair-wise comparison of the initial and final soil properties parameters was subjected to student t-test.

Results

Soil Chemical Properties

Soil pH varied significantly ($p<0.05$) among treatments before and after the experimental period. Treatments with lime significantly increased soil pH. Sole fertilizer and control treatments recorded a decrease in soil pH. In Kirege, the highest ($p<.001$) pH increase over the baseline during the LR2016 (+11.1%) and SR2016 (+19.8%) seasons was recorded in $CaCO_3$ treatment. In Kangutu, $CaCO_3$ and $CaCO_3$ + fertilizer treatment recorded the highest pH % increase during SR2016 (+14.1%) and LR2016 (+6.26%) seasons.

Table 2: Changes in soil pH water under various treatments in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya

Treatment	Baseline	LR2016	% change[1]	T-test, *p*[1]	SR2016	% change[2]	t-test, *p*[2]
Kirege							
$CaCO_3$	4.05^{bc}	4.5^{ab}	11.11	0.003	4.85^{ab}	19.8	0.006
$CaCO_3$+Fert	4.25^{a}	4.63^{a}	8.94	0.011	4.98^{a}	17.2	0.001
CaO	4.08^{abc}	4.43^{ab}	8.58	0.0008	4.78^{ab}	17.2	<.0001
CaO +fert	4.1^{abc}	4.45^{ab}	8.54	0.0009	4.8^{ab}	17.1	0.0001
CaO.MgO	3.95^{c}	4.33^{b}	9.62	0.005	4.68^{b}	18.5	0.0008
CaO.MgO+Fert	4.3^{ab}	4.64^{a}	7.91	0.0007	4.99^{a}	16.0	<.0001
Fertilizer	4.1^{abc}	4.08^{c}	-0.48	0.162	3.98^{c}	-2.93	0.823
Control	4.13^{abc}	4.05^{c}	-1.94	0.982	4.0^{c}	-3.14	0.569
%CV	*3.34*	*3.4*			*2.8*		
P value	*0.04*	*<.0001*			*<.0001*		
Kangutu							
$CaCO_3$	5.06^{a}	5.45^{a}	7.71	0.004	5.77^{a}	14.1	0.003
$CaCO_3$+fert	5.11^{a}	5.43^{a}	6.26	0.04	5.67^{ab}	11.1	0.03
CaO	5.072^{a}	5.31^{a}	4.69	0.019	5.5^{b}	9.4	0.04
CaO +fert	5.11^{a}	5.3^{a}	3.72	0.08	5.55^{ab}	8.6	0.015
CaO.MgO	5.03^{a}	5.26^{a}	4.68	0.03	5.55^{ab}	9.5	0.002
CaO.MgO+fert	5.01^{a}	5.23^{a}	4.39	0.007	5.47^{b}	9.18	0.006
Fertilizer	5.1^{a}	5.09^{c}	-0.1	0.89	4.86^{b}	-4.7	0.018
Control	5.03^{a}	4.96^{b}	-1.39	0.39	4.94^{c}	-1.79	0.85
%CV	*3.36*	*2.75*			*2.73*		
P value	*0.92*	*<.0001*			*<.0001*		

Means not sharing a common letter in a column are significantly different at 5 % Probability level
[1]Pairwise t-test comparison between baseline value and LR2016
[2]Pairwise t-test comparison between baseline value and SR2016

The application of lime types significantly decreased soil exchangeable acidity at the end of the experiment. In Kirege, $CaCO_3$ treatment recorded the highest % decrease of -52.6% (SR2016) and -15.5% (LR2016). Sole $CaCO_3$ treatment recorded the highest % decrease of -50% (SR2016) and -41.67% (LR2016), respectively, in Kangutu. Sole fertilizer and control treatments showed increases in exchangeable acidity in both seasons and sites.

Table 3: Changes in Exchangeable Acidity (C mol kg^{-1}) under various treatments in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya

Treatment	Baseline	LR 2016	% change[1]	T-test, *p*[1]	SR 2016	% change[2]	T-test, *p*[2]
Kirege							
$CaCO_3$	0.5^{a}	0.425^{bc}	-15.5	0.057	0.237^{b}	-52.6	0.0002
$CaCO_3$+Fert	0.48^{a}	0.4^{c}	-14.7	0.05	0.25^{b}	-47.9	0.002
CaO	0.5^{a}	0.425^{bc}	-15.0	0.05	0.275^{b}	-46.0	0.002
CaO +fert	0.5^{a}	0.425^{bc}	-15.0	0.057	0.262^{b}	-45.6	0.004
CaO.MgO	0.5^{a}	0.425^{bc}	-15.0	0.057	0.275^{b}	-45.0	0.002
CaO.MgO+fert	0.45^{a}	0.4^{c}	-11.1	0.18	0.262^{b}	-41.8	0.015
Fertilizer	0.48^{a}	0.5^{b}	4.2	0.39	0.5^{a}	4.2	0.391
Control	0.5^{a}	0.56^{a}	12.0	0.057	0.57^{a}	15.0	0.181
%CV	*6.62*	*10.95*			*15.39*		
P value	*0.262*	*0.0004*			*<.0001*		
Kangutu							
$CaCO_3$	0.3^{a}	0.175^{b}	-41.67	0.015	0.17^{b}	-50	0.015
$CaCO_3$+fert	0.27^{a}	0.175^{b}	-35.19	0.091	0.15^{b}	-44.4	0.039
CaO	0.3^{a}	0.2^{b}	-33.33	0.091	0.175^{b}	-41.7	0.013
CaO +fert	0.25^{a}	0.2^{b}	-20.00	0.181	0.175^{b}	-30.0	0.041
CaO.MgO	0.27^{a}	0.225^{b}	-16.67	0.181	0.2^{b}	-25.9	0.048
CaO.MgO+fert	0.28^{a}	0.23^{ab}	-28.57	0.091	0.2^{b}	-42.9	0.006
Fertilizer	0.27^{a}	0.325^{a}	20.4	0.05	0.35^{a}	29.63	0.18
Control	0.3^{a}	0.32^{ab}	6.67	0.391	0.325^{a}	8.3	0.391
%CV	*22.48*	*29.27*			*33.41*		
P value	*0.575*	*0.018*			*0.003*		

[1]Pairwise t-test comparison between baseline value and LR2016

[2]Pairwise t-test comparison between baseline value and SR2016

Soil available P increased in all treatments in both seasons and sites compared to the control. Notably, significant (p<.0001) increases in the soil available P were recorded in treatments with lime application with and without fertilizer. $CaCO_3$+fert treatment recorded a significantly highest % increase in both sites and seasons.

Table 4: Changes in available P under various treatments in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya

Treatment	Baseline	LR2016	% change[1]	t-test *p*[1]	SR2016	% change[2]	t-test, *p*[2]
Kirege							
$CaCO_3$	26.25^{a}	33.5^{bc}	27.6	0.032	37.73^{cd}	40	0.011
$CaCO_3$+fert	21.25^{a}	47.37^{c}	122.9	0.001	61.5^{a}	189.4	0.003
CaO	28^{a}	32.12^{abc}	14.7	0.024	40.25^{cd}	43.1	0.013
CaO +fert	23.75^{a}	43.37^{d}	82.6	0.005	64^{d}	169.4	0.007
CaO.MgO	27^{a}	34.37^{c}	27.2	0.013	37.75^{cd}	39.8	0.022
CaO.MgO+fert	25^{ab}	53.5^{ab}	114	0.006	68^{a}	172	0.009
Fertilizer	28.75^{a}	54.87^{a}	90.8	0.004	70^{ab}	143.4	0.005
Control	21.25^{a}	20.3^{d}	-4.4	0.099	18.75^{e}	-11.7	0.28

%CV	35.65	13.4			15.59		
P value	0.076	<.0001			<.0001		
Kangutu							
$CaCO_3$	17.5^{a}	20.63^{bc}	17.8	0.003	21.752^{c}	24	0.02
$CaCO_3$+fert	15.75^{a}	30.12^{a}	91.2	0.0001	34.5^{a}	119	0.0002
CaO	17.5^{a}	19.85^{bc}	13.6	0.001	24.25^{bc}	21	0.004
CaO +fert	15^{a}	24.5^{b}	63.3	<.0001	30^{b}	100	<.0001
CaO.MgO	16.75^{a}	19.35^{c}	15.7	0.001	19^{c}	13	0.018
CaO.MgO+fert	15^{a}	24.25^{bc}	61.7	0.018	29.5^{b}	97	0.03
Fertilizer	15^{a}	21.88^{bc}	45.8	0.02	25.75^{bc}	72	0.05
Control	17.5^{a}	15.55^{bc}	-10.0	0.068	18^{c}	-14	0.461
%CV	16.96	11.96			15.41		
P value	0.63	0.0009			<.0001		

Means not sharing a common letter in a column are significantly different at 5% Probability level
[1]Pairwise t-test comparison between baseline value and LR2016

[2]Pairwise t-test comparison between baseline value and SR2016

The treatments with lime had different effects in raising Ca^{2+} with sole $CaCO^{3+}$ (+65%) and $CaCO_3$ (+60%) recording the highest increments in Kirege and Kangutu, respectively. Decline in Ca^{2+} were recorded in control and sole fertilizer treatments. Similarly, treatments with lime application recorded significant increases in Mg saturation. In Kirege, $CaCO_3$ treatment had highest significant (p=0.0342) increase of (+202%). Sole fertilizer and control treatments recorded a decrease of (-23%) and (-36%), respectively. All treatments in Kangutu recorded increases in Mg saturation. $CaCO_3$ recorded the highest increase (+201%).

Table 5: Changes in available Ca^{2+} and Mg^{2+} under various treatments in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya

	Ca^{2+} (C mol kg^{-1})			**Mg^{2+}** (C mol kg^{-1})		
Treatment	Baseline	SR16	T test, p	Baseline	SR16	T test, p
Kirege						
$CaCO_3$	1.8^{a}	2.85^{ab}	0.013	0.39^{ab}	1.18^{a}	0.034
$CaCO_3$+fert	1.9^{a}	3.15^{a}	0.038	0.21^{b}	0.96^{ab}	0.005
CaO	1.93^{a}	2.65^{ab}	0.018	0.78^{a}	1.14^{a}	0.003
CaO +fert	1.75^{a}	2.47^{bc}	0.022	0.46^{ab}	0.98^{ab}	0.003
CaO.MgO	1.7^{a}	2.27^{c}	0.042	0.34^{ab}	0.99^{ab}	0.000
CaO.MgO+fert	1.77^{a}	2.37^{c}	0.023	0.45^{ab}	1.21^{a}	0.05
Fertilizer	1.85^{a}	1.7^{d}	0.391	0.73^{ab}	0.56^{b}	0.178
Control	1.85^{a}	1.67^{d}	0.61	0.69^{ab}	0.44^{b}	0.121
%CV	16.12	22.34		65.05	38.01	
P value	0.95	0.007		0.02	0.0385	
Kangutu						
$CaCO_3$	1.975^{bc}	3.15^{ab}	0.003	1.3^{b}	3.92^{a}	0.002
$CaCO_3$+Fert	2.15^{abc}	3.4^{ab}	0.014	1.58^{ab}	3.93^{a}	0.004

CaO	1.95^{bc}	2.65^{bc}	0.029	1.78^{ab}	3.07^{ab}	0.007
CaO +fert	2.45^{a}	3.25^{ab}	0.011	2.11^{a}	3.85^{a}	0.028
CaO.MgO	2.35^{ab}	3.52^{a}	0.004	1.84^{a}	3.52^{a}	0.034
CaO.MgO+Fert	1.9^{bc}	2.83^{abc}	0.004	1.14^{b}	3.87^{a}	0.001
Fertilizer	1.75^{c}	1.68^{d}	0.86	1.96^{ab}	1.87^{c}	0.076
Control	2.4^{ab}	2.12^{cd}	0.74	1.88^{a}	1.82^{bc}	0.075
	0.025	18.38	27.58	27.58	19.13	0.744
P value	16.72	0.0003	0.046	0.046	0.0004	

In Kirege, significant ($P \leq 0.05$) increases in soil total nitrogen in comparison to the baseline were recorded in CaO.MgO+ fert (p=0.008), $CaCO_3$+fert (p=0.01) and CaO +fert (p=0.018). All treatments in Kangutu recorded a decline in total N, which were not significant. Sole fertilizer treatment recorded the highest (-37.5%) decline in total N. The effect of the lime types with and without fertilizer on soil organic carbon were not significant in comparison to the baseline. The K saturation in the soil showed that experimental soil had adequate level of K saturation and the changes were not significant.

Table 6: Changes in total Nitrogen, Total Organic Carbon and K under various treatments in Kirege and Kangutu, Meru South Sub-County of Tharaka Nithi County, Kenya

	Total Nitrogen %			**Total Org. Carbon %**			**K** (C mol kg^{-1})		
Treatment	**Baseline**	**2016SR**	**T-test,*p***	**Baseline**	**2016SR**	**T-test,*p***	**Baseline**	**2016SR**	**T-test,*p***
Kirege									
$CaCO_3$	0.148^{b}	0.16^{a}	0.34	1.14^{c}	1.21^{b}	0.089	0.187^{a}	0.2^{a}	0.46
$CaCO_3$+fert	0.165^{ab}	0.193^{a}	0.01	1.45^{ab}	1.82^{a}	0.158	0.175^{a}	0.225^{a}	0.34
CaO	0.165^{a}	0.175^{a}	0.219	1.45^{ab}	1.51^{ab}	0.134	0.17^{a}	0.175^{a}	0.63
CaO +fert	0.158^{a}	0.188^{a}	0.018	1.58^{ab}	1.78^{a}	0.268	0.175^{a}	0.18^{a}	0.63
CaO.MgO	0.135^{a}	0.14^{a}	0.135	1.50^{ab}	1.56^{ab}	0.485	0.175^{a}	0.195^{a}	0.09
CaO.MgO+fert	0.15^{a}	0.18^{a}	0.008	1.62^{a}	1.76^{ab}	0.198	0.185^{a}	0.175^{a}	0.18
Fert	0.16^{a}	0.175^{a}	0.101	1.41^{abc}	1.79^{a}	0.053	0.175^{a}	0.185^{a}	0.49
Control	0.177^{ab}	0.172^{a}	0.53	1.46^{bc}	1.27^{ab}	0.179	0.15^{a}	0.13^{a}	0.45
%CV	10.14	10.37		14.35	13.84		15.78	24.36	
P value	0.032	0.97		0.014	0.031		0.796	0.79	
Kangutu									
$CaCO_3$	0.17^{a}	0.16^{a}	0.27	1.51^{a}	1.53^{a}	0.79	0.27^{a}	0.31^{a}	0.18
$CaCO_3$+fert	0.17^{a}	0.16^{a}	0.31	1.49^{a}	1.55^{a}	0.52	0.35^{a}	0.39^{a}	0.01
CaO	0.17^{a}	0.14^{a}	0.15	1.34^{a}	1.59^{a}	0.21	0.34^{a}	0.36^{a}	0.81
CaO +fert	0.18^{a}	0.14^{a}	0.06	1.34^{a}	1.44^{a}	0.27	0.28^{a}	0.31^{a}	0.54
CaO.MgO	0.15^{a}	0.14^{a}	0.63	1.32^{a}	1.39^{a}	0.40	0.30^{a}	0.32^{a}	0.54
CaO.MgO+fert	0.16^{a}	0.14^{a}	0.31	1.32^{a}	1.43^{a}	0.38	0.26^{a}	0.29^{a}	0.60
Fert	0.16^{a}	0.1^{a}	0.34	1.34^{a}	1.46^{a}	0.47	0.26^{a}	0.265^{a}	0.86
Control	0.15^{a}	0.14^{a}	0.73	1.38^{a}	1.45^{a}	0.55	0.23^{a}	0.235^{a}	0.95
%CV	13.05	7.69		11.26	14.28		75.47	66.81	

P value	0.53	0.55	0.482	0.88	0.994	0.959

Maize yields

Maize yields were significantly affected by the treatments. During both seasons in Kangutu, treatments with fertilizer either sole or plus lime recorded the highest stover and grain yields. A similar trend was observed in Kirege site. Generally, treatments with sole lime had comparable yields with the control. Lower yields were recorded in Kirege in comparison to Kangutu. Moreover, the yields recorded in both sites were low in comparison to the control. In Kangutu, the highest maize stover yield of 5.27 t ha^{-1} (LR2016) and 5.27 t ha^{-1} (SR2016 season) were recorded in treatment receiving $CaCO_3$+fertilizer. Similarly, in Kirege, the highest maize stover yield was recorded in $CaCO_3$+fertilizer treatment during the LR2016 (5.16 t ha^{-1}) and SR2016 (3.38 t ha^{-1}) seasons. The control treatment recorded the lowest stover yields in both seasons and sites.

Table 9: Maize Stover and grain yields (t ha^{-1}) under different treatments at Kangutu and Kirege sites, Meru South Sub-County of Tharaka Nithi County, Kenya

	LR2016		**SR**2016	
Treatment	**Grain yield (t ha^{-1})**	**Stover yield (t ha^{-1})**	**Grain yield (t ha^{-1})**	**Stover yield (t ha^{-1})**
Kangutu				
$CaCO_3$+fert	2.55^{a}	4.66^{a}	1.22^{a}	5.27^{a}
CaO.MgO+fert	2.05^{ab}	3.60^{ab}	1.20^{a}	4.29^{ab}
CaO +fert	1.99^{ab}	3.17^{bc}	1.04^{ab}	4.39^{a}
Fert	1.90^{ab}	3.24^{bc}	1.18^{a}	4.24^{ab}
CaO	1.37^{b}	2.59^{bc}	0.44^{bc}	2.22^{b}
$CaCO_3$	1.29^{b}	2.48^{bc}	0.46^{bc}	2.25^{bc}
CaO.MgO	1.19^{b}	2.37^{bc}	0.41^{bc}	2.00^{c}
Control	1.18^{b}	2.27^{c}	0.20^{c}	1.74^{c}
P value	0.019	0.004	0.008	0.003
CV (%)	34.22	26.28	58.42	40.78

	LR2016		**SR**2016
Treatment	Grain Yield	Stover Yield	Stover Yield
Kirege			
CaCO3+fert	3.11^{a}	5.16^{a}	3.38^{a}
CaO +fert	2.24^{a}	5.13^{a}	2.25^{b}
Fert	2.17^{a}	4.23^{a}	1.73^{b}
CaO.MgO+fert	2.04^{a}	3.99^{a}	2.02^{b}
CaO	0.45^{b}	0.97^{b}	0.40^{c}
CaCO3	0.40^{b}	1.23^{b}	0.57^{c}
CaO.MgO	0.38^{b}	0.97^{b}	0.43^{c}
Control	0.24^{b}	0.67^{b}	0.28^{c}
P value	<.0001	<.0001	<.0001
%CV	57.42	37.24	51.81

* Means not sharing a common letter in a column are significantly different at 5% Probability level

The highest grain yields in Kangutu were recorded in $CaCO_3$+fert (2.55 t ha^{-1}) treatment during the LR2016 season which corresponded to a 116% increase over the control. During the SR2016 season, grain yields increased by 500% and 510% respectively, in comparison to the control in CaO.MgO+fert (1.2 t ha^{-1}) and $CaCO_3$+fert (1.22 t ha^{-1}). In Kirege during the LR2016, season the highest maize grain yields increased by 1195% and 833% under $CaCO_3$+fert (3.1 t ha^{-1}) and CaO + fert (2.24 t ha^{-1}) respectively, in comparison with control. During the SR2016 season, there was a decline in total rainfall amounts that led to total crop failure hence no grains were harvested.

Discussion

The high soil acidity levels in Meru South recorded in the initial soil characterization are in line with findings of Gitari *et al.* (2015) who reported low soil pH of <4.5 in Central highlands of Kenya. In Kangutu, the pH attained at the end of the experiment in treatments that were limed was optimum for maize productivity. A pH range of 5.5 -7.1 is optimum for maize growth according to Abdulaha-Al Baquy *et al.* (2018). The increase in pH could be attributed to basic cations (Ca^{2+} and Mg^{2+}) and anions (CO_3^{2-}) in lime that are able to exchange H^+ in exchange sites to form H_2O + CO_2. H^+ leave space behind which cations occupy on the exchange sites resulting in reduction in soil acidity (Wang *et al.,* 2014). McLaughlin *et al*. (2011) reported that significant chemical changes occur within 4–6 weeks in the soil after application of lime when the soil has sufficient moisture. The slow change in soil pH in comparison to other studies might have been caused by inadequate soil moisture due to poor and erratic rainfall recorded in this study.

Treatments with $CaCO_3$ lime had significant increases in pH and this could be due to its quality especially Calcium Carbonate Equivalent (CCE). Conversely, low CCE in CaO might have led to the low pH changes. CaO.MgO lime treatments despite high amount of Ca had lower increases in pH in comparison to treatments with $CaCO_3$. This phenomenon could be attributed to its larger granular particles, which create low surface area contact with the soil unlike the ground limes. CaO.MgO+fert in Kirege recorded lower changes in pH and this could be attributed to the low soil moisture due to poor rainfall in both seasons. Granular lime is made of fine lime particles which are bound using binding agents. The binding agents present could have slowed down reaction in comparison to the powdered $CaCO_3$ lime which reacted faster in the soil. CaO.MgO+fert recorded higher pH increase than in CaO and this could be due to the burning process involved in making CaO that makes it caustic (Oates, 2007). Lime application with and without fertilizer led to significant reduction in soil exchangeable acidity in comparison to the baseline. Exchangeable acidity is key in determining aluminic phytotoxicity, which is closely correlated with the rate of exchangeable aluminum (Reuss & Johnson, 2012). Caires *et al.* (2011) reported that exchangeable acidity significantly reduced in soil when lime was applied due to precipitation of Al^{3+} as $Al(OH)_3$. The observed decline in soil pH in the sole fertilizer treatment in LR in both sites corroborates with findings of Mugendi *et al*. (1999), who reported that application of mineral fertilizer led to a general reduction in pH. Mineral fertilizers have been reported to cause the addition of H^+ ions to cation exchange complex of soil causing an increase in soil acidity (Mucheru-Muna *et al*., 2007; Havlin *et al.,* 2016).

In Kirege during the LR2016 season the change in exchangeable acidity in treatments with lime was not significant and could be due to presence of high aluminum ions in soils. Aluminum ions have been reported to buffer soil from pH changes (Ulrich *et al*., 2012). Conversely, there was no significant difference among the lime types in the decrease in soil exchangeable acidity. It is probable that use of different lime types precipitated most of the Al and the exchangeable acidity measured was likely due to H^+. $CaCO_3$ lime was highly effective in reducing exchangeable acidity (Al^{3+} + H^+) and this could be attributed to its quality, particularly its Calcium Carbonate Equivalent. In line with this, Awkes (2009) reported that Calcium Carbonate Equivalent and Fineness Factor influenced effectiveness of lime. Furthermore, Opala (2017), in a study in Western Kenya recommended the use of 2 t ha^{-1} of CaO lime to reduce Al toxicity.

The initial soil available phosphorus (P) levels in Kirege and Kangutu P are classified as below the critical level of extractable phosphorus for maize (*Zea mays* L.) (Redi *et al.,* 2016). The SR2016 season had relatively higher amounts of soil available P than in the first season LR2016, which could be ascribed to the residual effects of P fertilizer and lime. McLaughlin *et al.* (2011) reported that rapid adsorption of P into the surface of soil particles is followed by slow conversion into less available forms such as mineral phosphates. Therefore, P from the phosphate fertilizer is available in the first season and subsequent seasons after application, thus their residual effects. The limes increased in soil P to adequate levels. This could be due to the reversal of the effect of acidic soils that are deficient in available P. Murphy & Stevens (2010) noted that low pH levels immobilize portions of applied P due to precipitation of P as insoluble Al phosphates. Fertilizer and lime application resulted in significantly higher soil P availability than the sole application of either. Kisinyo *et al*. (2013) noted that lime led to reduced P sorption, making both native phosphorus and fertilizer available for plant absorption. The range of available P increases due to the lime application is in line with Miheretu *et al.* (2014), who reported that application of 92 kg ha^{-1} P_2O_5 and 725 kg lime ha^{-1} led to a 770% P in acidic loam soils of Ethiopia. In the acidic soils of Kakamega County, Kenya, Kiplangat *et al.* (2013) also noted that using 0.8 t ha^{-1} $CaCO_3$ lime +52 kg P ha^{-1} led to an increment in available phosphorus (Bray) from 3 to 8 mg P kg^{-1}.

Treatments with lime led to an increment in Ca^{2+} and Mg^{2+}; this was anticipated since they were the main constituents of the limes used and were deposited to the soil. Moreira *et al.* (2015) reported that lime application led to the increase in Ca^{2+} and Mg^{2+} saturation percentage on the exchange sites of the soil colloid and carbonate reactions increased soil pH in soil solution. The gradual effect of lime could be attributed to its slow reactivity to release Ca^{2+} and/or Mg^{2+} ions, but its effects last longer in contrast to other organic and inorganic inputs (Kisinyo *et al.,* 2014).

The initial amount of total N and organic C in these soils was low (Hazelton and Murphy, 2016). At the end of the experiment, the total nitrogen increase in Kirege is attributable to increased organic matter decomposition. The use of lime led to an increase in pH, which favored soil microbial activity leading to increased organic matter decomposition Heinze *et al.* (2010). Fageria & Baligar (2008) also noted an increment in mineralization of organic N in acid soils due to lime application averaged at 2% of the total soil N and a positive correlation in increases of pH, C: N ratio and total N in the soils. The low soil total N in Kangutu at the end of the experimental period could be due to plant uptake, soil nitrogen immobilization and leaching due higher rainfall than in Kirege (Figure 1). Onwonga *et al.* (2010) reported total soil N decline through the growth period of maize and attributed it to immobilization of N. Similarly, Diacono & Montemurro (2011) reported that high nitrates leaching in a study with manure and mineral fertilizer led to a decline in soil total N.

At the end of the experiment, lime application did not significantly affect soil organic carbon in comparison to the baseline. Mugwe *et al.* (2009b) reported that SOM decline was due to faster SOM mineralization than its accumulation, caused by moist and warm conditions that favor decomposition. In line with this, crop removal and continuous cultivation cause breakdown of soil aggregates, leading to decomposition of SOM (Nair, 2019). The insignificant increase in soil organic carbon could be due to a rise in soil biological activity and plant productivity. Higher yields from liming soil through decaying crop residues and dying roots cause an increase in organic matter, Briedis *et al.* (2012) reported similar observations. Aye *et al*. (2016) indicated that lime use stimulates soil biological activity for a short period causing speeding up of organic matter turnover rates in the soil. The results of K saturation indicated that the amount of K saturation in the soil was adequate. White & Brown (2010) considered range K amounts of 1 to 5% to be suitable for soil productivity. The insignificant K^+ increase could be due to impurities present in the limes (Brett *et al.,* 2005).

The poor yields recorded in both sites and seasons could be attributed to the erratic rainfall reported during this study. In the SR2016 season in Kirege, the drought prolonged and led to total crop failure: resulting to no grain yields. Srinivasarao *et al.* (2013) and Gitari *et al.* (2018) noted that rainfall amount and distribution influence crop production in rain-fed agriculture. The high yields obtained in plots with lime could be attributed to the positive effects of liming. Studies have reported that the application of both lime and P fertilizer increased soil available P and its utilization on Kenyan acid soils (Kisinyo *et al*., 2013; Opala *et al*., 2017). Although the application of sole lime improved soil pH and amount of P, it did not automatically increase yields during the study.

Higher yields were obtained in treatments with P fertilizer, probably due to an increase in soil available P, which is essential for plant growth and grain production. Lime has long-term residual effects; hence not all the benefits may be realized in the first season of its application (Halvin *et al*., 2006). This is in line with Mbakaya (2014), who attributed an increment in maize yields to increased application of $CaCO_3$ lime and inorganic fertilizers; the yields were in order of; agricultural lime+ fertilizer > fertilizer> lime >control. Nekesa *et al*. (2007) indicated that CaO lime and P fertilizer use led to the highest significant increase ($p < 0.01$) above the control with a mean of 5.30 t ha^{-1} and sole CaO had significantly ($p<0.01$) lower grain yields than the other soil amendment materials. Moreover, liming material with 73% CaO and 2-3% MgO significantly increased maize grain yield, with 6 t ha^{-1} lime treatment having the highest (11.9 t ha^{-1}) yield (Andric *et al*., 2012). The high yields observed in $CaCO_3$+ fertilizer treatment than in the CaO.MgO + fertilizer and CaO+ fertilizer treatments could be due to higher Calcium Carbonate Equivalent in $CaCO_3$, and therefore, it released more Ca and Mg to the soil. $CaCO_3$ had an advantage over the other calcite (CaO and CaO.MgO) limes since it added both Ca and Mg to the soil. Similarly, Rasnake *et al.* (2002) noted that magnesium carbonate could reduce soil acidity than calcium carbonate. The granulated MgO+fertilizer treatment, despite high CCE, had lower yields relative to $CaCO_3$ lime, and it could be due to lignosulfonate binding agents and granular lime distribution pattern.

The binding agents in the granular lime must be broken down by microbial action or solubilization before Ca, and Mg is released to the soil solution. The low rainfall (Figure 1) during the seasons and the low pH recorded in Kirege could have led to low microbial activity, as noted by Gitari (2015), and this could have slowed the reaction speed of the granular lime. Furthermore, Owino (2015) indicated that maize yields were significantly higher in powdered and granular limes after the first cropping season by 43 and 30%, respectively, above the control.

The granular lime spread on the soil as granules led to small concentrated zones (spots) of lime after the dissolution of the binding agent; the spots were still present at the end of the experimental period. The fine, powdery limes (CaO, $CaCO_3$), in comparison, were spread as more of dust; therefore, the limes were distributed more evenly, unlike in concentrated spots. Therefore, the powdered limes had a higher surface area contact with the soil. Similar observations were made by Arizzi & Cultrone (2012). Conversely, Owino (2015) indicated that due to the manufacturing process of dolomitic granulated lime, it is more expensive than ground powdered lime. Additionally, the second season after lime application with fertilizer did not result in statistically significant yield increases relative to the sole fertilizer-only treatment.

CONCLUSION

Soil pH and exchangeable acidity changed positively (increased and decreased, respectively) in treatments that had lime either sole or in combination with fertilizer. Control and fertilizer treatments, on the other hand, recorded negative changes. Soil phosphorus significantly increased in treatments that had a combination of lime plus fertilizer. Treatments with mineral fertilizer (Sole fertilizer, $CaCO_3$ + mineral fertilizer, CaO + mineral fertilizer, $CaO.MgO$ + fertilizer) consistently affected maize plant positively as observed through enhanced stover and grain yield.

It is evident that sole application of lime ($CaCO_3$, CaO, $CaO.MgO$) reduced exchangeable acidity, improved soil pH and P in the short term, but this did not translate to increased yields. This is an implication that sole lime application in the experiment was not sufficient in ameliorating depleted acidic soils and restoring the lost nutrients. This could be attributed to an inadequate amount of P released from liming the soil. Furthermore, yields could have been limited by inadequate N and poor rainfall. Therefore, in this region, adding fertilizer to the soil is a key component to realize increased yields. Powdered $CaCO_3$ lime had the highest impact in alleviating soil acidity in terms of pH increase, soil available P increment, and Maize growth, stover, and grain yield.

This study highlights the possibility of improving agricultural production in the tropical sub-humid regions experiencing erratic rainfall through the combined use of fertilizer and lime for soil fertility restoration and increasing yields. However, from the study it emerged that yield differences between the three lime types were marginal within the period under consideration. There is a pressing need to research on long-term effects of the three lime types on crop performance and soil properties in the sub-humid tropics. Furthermore, research needs to be conducted to evaluate the economic efficiency, synergetic and residual effects with other soil amendments and fertilizers such as manure, compost, mineral fertilizers, cover crops, among other options, with the limes.

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