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Research Article

Effects of Unburned Lime on Soil pH and Base Cations in Acidic Soil

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Sustainable agriculture is threatened by the widespread soil acidity in many arable lands of Rwanda. The aim of this study was to determine the quality of unburned limes and their effects on soil acidity and base cations in acidic soils of high land of Buberuka. The lime materials used were agricultural burned lime and three unburned lime materials, Karongi, Musanze, and Rusizi. The test crop was Irish Potato. All lime materials were analyzed for Calcium Carbonate Equivalent (CCE) and Fineness. A field trial in Randomized Complete Block Design was established in 2011 at Rwerere research station. The treatments comprised of the four lime materials applied at four levels: 0, 1.4, 2.8, and 4.3 t ha^{-1} of CCE. Soil cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were determined by extraction method using atomic absorption spectrophotometer for Ca and Mg and flame photometer for K and Na. The Al^{3+} was determined using potassium chloride extraction method. Experimental soil baseline showed that the soil was very strongly acidic (2.8 cmol kg^{-1} Al^{3+}). The unburned limes were significantly ($P < 0.001$) different in terms of CCE and fineness. A higher CCE was recorded in agricultural burned and Rusizi unburned limes (86.36% and 85.46%, resp.). In terms of fineness, agricultural burned and Musanze unburned lime were higher (70.57 and 63.03%, resp.). Soil acidity significantly affected from 4.8 to 5.6 pH and exchangeable Al reduced from 2.8 cmol kg^{-1} to 0.16 cmol kg^{-1} of Al^{3+}. Similarly all cations affected by unburned limes application, significantly ($P < 0.001$) Ca saturation increased from 27.44 to 71.81%, Mg saturation from 11.18 to 36.87% and significantly ($P < 0.001$) Al saturation reduced from 58.45 to 3.89%. The increase of Mg saturation was observed only with Karongi unburned lime application. This study recommends therefore, the use of 2.8 t ha^{-1} of $CaCO_3$ of Rusizi or Musanze unburned lime as alternative to the agricultural burned lime for improving soil acidity and base cations in acidic soils.

1. Introduction

The constraints of sustainable agriculture can be partly attributed to continuous cropping, soil acidity [1], and inadequate soil fertility management [2]. The sustainable agriculture is threatened by widespread acidity in many parts of the tropical region, and applications of lime [3] to these soils have been reported to significantly improve soil fertility. Acidity affects the fertility of soils through nutrient deficiencies (P, Ca, and Mg) and the presence of phytotoxic nutrient such as soluble Al [4].

The population pressure in Rwanda triggers subsistence agriculture and is being continuously done on hills and mountains, while soil acidity is covering about one third of arable soils [5]. To feed the growing population, exploitation of all agricultural resources for sustainable agriculture and soil fertility improvement are the most important interventions to rely on.

The effect of lime is long lasting but not permanent [6]. When values of exchangeable Ca^{2+}, Mg^{2+}, and pH fall below optimum levels for a given crop species, liming should be repeated. The base enrichment especially of Ca^{2+} ions in soil will neutralize exchangeable Al [7] thus enhancing root growth. The base cations include K, Ca, Mg, and Na, and the base saturation is the proportion of the CEC (cations exchange capacity) occupied by these base cations. A relatively high base saturation of CEC (70 to 80%) should be maintained for most cropping systems, since the base saturation determines in large measure the availability of bases for plant uptake and strongly influences soil pH as well. Low base saturation levels results in very acid soils and potentially toxic cations such as Al and Mn in the soil. A high base saturation (>50%) enhances Ca, Mg, and K availability and prevents soil pH decline. Low base saturation (<25%) is indicative of a strongly acidic soils that may maintain Al^{3+} activity high enough to cause phytotoxicity [8]. Highly weathered tropical soils such as Oxisols have very low levels of exchangeable Ca and crops grown on such soils exhibit Ca deficiency when exchangeable Ca is <1 cmol kg^{-1} [9]. The application of limestone (calcium carbonate) and or dolomitic lime (Ca and Mg bicarbonate) increases soil exchangeable Ca and Mg, respectively. The improvement of plant growth in acidic soil is not due to addition of basic cations (Ca and Mg) but is caused by the increasing pH which reduces toxicity of phytotoxic levels of Al [10]. In acidic soils, most of the Ca present would exist in soluble form, but both soluble and exchangeable Ca decreases with decreasing soil pH [11]. When Ca^{2+}, K^+, and H^+ concentration increase in the soil, they induce Mg uptake to be decreased in plant due to competitive inhibition [12]. Mg is also a poor competitor with Al and Ca for the exchange sites; it tends to accumulate in the solution phase and is therefore prone to leaching [13]. Thus, a greater attention has to be made when liming to prevent cations imbalance in the soil.

Locally available carbonates are relatively common in many countries of sub-Saharan Africa and are well suited for small-scale mining and processing [14]. The lime production through burning in vertical kilns [15] consume large amounts of firewood (energy) and cause environmental hazard such as the release of greenhouse gasses (GHG) including carbon dioxide (CO_2) to the atmosphere. The production of one ton of lime emit around 0.785 t of CO_2 due to mineralogical transformation [16]. Contrary, the production of unburned lime is environment friendly because they do not require burning energy and the CO_2 emission is null. In Rwanda, there is three main limestone deposits in western region (Karongi and Rusizi districts) and northern (Musanze and Gakenke districts) region of Rwanda. However, the production of lime in many parts of limestone mines in the country is targeting construction purpose and not for agriculture benefit. In addition, all of the available limestone materials have not been evaluated and compared to determine their effects on soil acidity and base cations. The objective of this study was therefore to determine quality of unburned limes and to evaluate their effects on the improvement of soil base cations saturation, soil acidity and available phosphorus, and yield of potato in acidic soils.

2. Materials and Methods

2.1. Experiment Details and Lime Application. The study was carried out at Rwerere Research station located in Burera District in Northern Province of Rwanda. Rwerere Research station lies in the agro-bio-climatic zone of highlands of Buberuka in northern parts of Rwanda. It has an altitude ranging from 2060 up to 2312 meters above sea level. The relief is characterized by steeply sloping hills connected either by steep sided valleys or by flooded marshes. Annual rainfall ranges from 1400 to 1800 mm and Annual average minimum and maximum temperature is 9°C and 25°C, respectively. Population density is 522 per km^2 with farm land holding ranging from 0.15 to 0.2 ha per household [17]. This implies conversion of degraded land into arable land and continuous farming on unsuitable hills and mountains. Before establishment of trial, soil fertility analysis showed that the soil was very strongly acidic [8] with soil texture of loamy sand, soil pH of 4.8, exchangeable Al^{+3} of 2.8 cmol kg^{-1}, ECEC of 4.8 cmol kg^{-1} and 42.5% of base saturation. The level of organic matter was 2.2% while Nitrogen was 0.11%, available P (BrayII) was 3.6 mg kg^{-1} (Table 1).

Table 1: Soil properties of experimental site before trial establishment in 2012A season, 2011.

Soil properties	
pH_W	4.8
pH_{KCl}	3.7
Exchangeable Al (cmol kg^{-1})	2.8
Total exchangeable acidity (cmol kg^{-1})	8.2
Organic Carbon %	1.3
Organic matter %	2.24
Total nitrogen %	0.11
Available P (mg kg^{-1})	3.63
Base saturation %	42.5
Exchangeable Ca (cmol kg^{-1})	1.3
Exchangeable Mg (cmol kg^{-1})	0.5
Exchangeable K (cmol kg^{-1})	0.12
Exchangeable Na (cmol kg^{-1})	0.01
ECEC (cmol kg^{-1})	4.8
Clay %	8.24
Silt %	11.9
Sand %	79.8

The field trial had 13 treatments arranged in randomized complete block design (RCBD) and was established in September, 2011. The treatments comprised of four lime materials applied at three levels (1.4, 2.8 and 4.2 t ha^{-1} of $CaCO_3$ equivalent) and control. Each experimental unit was 2.4 × 3 m in size. The treatments were replicated three times and the randomization was done within each block. Application of limes was done two weeks before planting by broadcast method and tilled in immediately after application. Lime requirement (LR) was determined following the method described by Kamprath [18] due to its ability to neutralize all extractable Al in soil. This method neutralizes exchangeable

Table 2: Limes quality (CCE, Fineness).

Limes sources	CCE (%)	Fineness (%)
Agricultural burned lime	86.67	70.57
Musanze unburned lime	66.67	63.03
Karongi unburned lime	73.33	55.63
Rusizi unburned lime	86.00	56.90
LSD	**17.926**	**9.132**
P value	**0.018**	**0.003**

LSD: Least significant differences of means (5% level).

Al in the soil at the rate of 85–90% [5] and has been applied successfully in different countries [19]. The calculation of unburned lime rates (ULR) needed was done using (1)

$$\text{Unburned lime rate} = \frac{\text{Rate of pure lime}}{\text{CCE (unburned lime)}} * 100. \quad (1)$$

The unburned lime requirement rate ($t\,ha^{-1}$) depends on its quality in terms of CCE. Unburned lime with low CCE implies its higher quantity in reducing soil acidity compared to pure lime. Taking into consideration of resources poor farmers, this study evaluated three rates (0.5: economic rate, 1: normal rate and 1.5: high rate) which were equivalent to 1.4, 2.8 and 4.2 $t\,ha^{-1}$, respectively, of pure lime (100% of CCE).

Kirundo (Irish potato variety) was used in this study as test crop. Planting was done with an intrarow spacing of 0.3 m and inter-row spacing of 0.8 m. A 300 $kg\,ha^{-1}$ blanket application of (Nitrogen, Phosphorus and Potassium) NPK was done following the recommended rates by Rwanda Agriculture Board (RAB).

2.2. Measurements. The potassium chloride extraction method was used to determine exchangeable Al^{3+} [20]. All base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were determined by extraction method using atomic absorption spectrophotometer for Ca and Mg and flame photometer for K and Na [21]. Available P was determined using Bray and Kurtz P-II method.

The yield was determined by weighing total fresh tubers per plot. The relative agronomic efficiency (RAE) of the unburned limes was then calculated to determine more effective local lime relatively to agricultural lime. RAE was calculated as the ratio [22] using the following equation:

$$\text{RAE} = \frac{\text{Yield (unburned lime)}}{\text{Yield (agricultural burned lime)}} * 100. \quad (2)$$

2.3. Statistical Analysis. The data were subjected to analysis of variance (ANOVA) using GenStat 14th edition. Means separation was performed using Turkey's test at 0.05 level of significance and mean comparisons were done using least significant difference (LSD).

3. Results and Discussion

3.1. Selected Chemical and Physical Property of Lime Quality. The CCE (as chemical property determining lime quality) of unburned and agricultural burned limes were significantly different ($P = 0.01$ at $\alpha = 5\%$), it varies from 66.6% to 86.6% (Table 2). The agricultural burned lime and Rusizi unburned lime had similar and higher CCE compared to Musanze and Karongi unburned limes. The fineness (as physical property determining lime quality) was significantly different ($P = 0.003$) among lime types and ranged from 55.6 to 70.6 (Table 2). The agricultural burned lime was the finest compared to the three unburned limes.

The observed CCE in this study agree with the findings of Crawford and Su [23], who reported CCE of Rwandan travertine (unburned lime) to have CCE varying from 59.7 to 126%. Similarly, Beernaert [5] reported CCE variation within and between mining sites of local limes in Rwanda. The variability was attributed to the quantity of Ca, Mg, impurities and treatments (burning) of limestone as reported by several authors [5, 23–26].

The highest fineness factor of agricultural burned lime compared to the three unburned limes was attributed to the effect of heating limestone at high temperature (900–1200 kcal), crushing and sieving during its manufacture. Similar observations have been made by Millar et al. [27] who reported that fineness through various treatments (calcination, crushing, and sieving) of limestone increases the solubility of limes. The results of fineness factor observed in this study were similar to those reported by Crawford and Su [23]. These authors reported the fineness factor of Rwandan local limes to vary between 28.4 and 97.7%.

3.2. Effect of Lime on Soil Acidity and Available Phosphorus. The application of lime significantly increased soil pH and available phosphorus. The soil pH was significantly different ($P = 0.004$) among plots. The highest pH was recorded in plots that had Rusizi unburned lime and burned lime (Figure 1). The application of lime decreased amounts of soil exchangeable Al. The decrease of Al in the soil varied significantly ($P = 0.001$) from the types and rates of limes (Figure 1). The agricultural burned, Rusizi, and Musanze unburned limes at 4.2 and 2.8 $t\,ha^{-1}$ had relatively similar effects in reducing exchangeable Al. At lime rate of 1.4 $t\,ha^{-1}$, both agricultural burned and Musanze unburned lime had similar effects in reducing Al and they reduced 2.16 and 2.06 $cmol\,kg^{-1}$, respectively. In general, Karongi unburned lime had the least effects in reducing soil acidity based on low effect on exchangeable Al (Figure 1). The effects of limes on available phosphorus also were significantly different ($P < 0.001$). However, soil available P decreased in the control treatments, while increased in other plots (Figure 1).

The findings observed on soil pH changes in soil agree with the findings of many authors [28–30] who reported the increase of 0.4 to 0.9 units of soil pH after unburned limes application in acidic soils of Rwanda. The effects observed on exchangeable Al are corroborated by the findings of Fox [31] who reported reduction of exchangeable Al and Aluminium saturation to adequate levels following application of lime in acidic soil. Other authors such as Oates and Kamprath

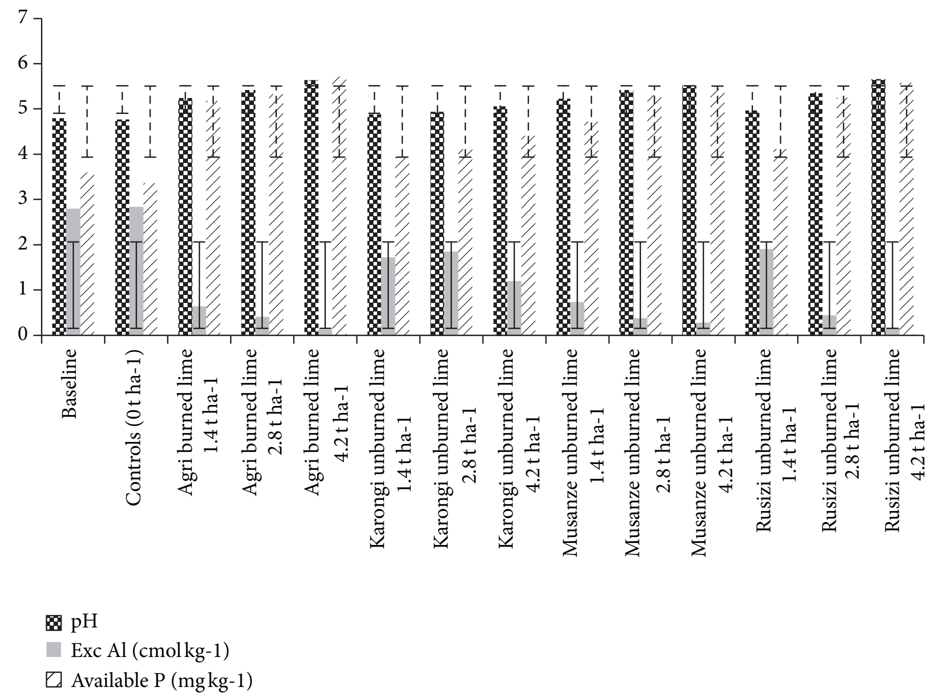

Figure 1: Effects of agricultural burned and unburned limes on soil pH, exchangeable Al, and available P.

[32], Conyers et al. [33], Synder and Leep [25], Caires et al. [34], and Crawford and Su [23] and Awkes [35] have reported a decrease of exchangeable Al following liming of acidic soils. Agricultural burned lime, Rusizi, and Musanze unburned limes were more effective than Karongi unburned lime in increasing available P possibly because of their effects in raising soil pH and reducing exchangeable Al. Similarly, Fageria [36] reported an increase of soil phosphorus as pH increased from 5.0 to 6.5, due to release of P ions from Al and Fe oxides, which are responsible of P fixation. Furthermore, Nurlaeny et al. [37] reports that, acidic soils are naturally deficient in available P and significant portions of applied P are immobilized due to precipitation of P as insoluble Al phosphates. The range of available P increase recorded is in agreement with the findings of Clements and McGrowen [38] who reported an increase ranging from 0 to 8 mg kg^{-1} of Bray P in acidic loam sandy soils of New South Wales in the United State of America (USA). Ruganzu [30] also reported an increase of available phosphorus from 3 to 13 mg kg^{-1} after application of travertine (local lime) combined with fertilizer in acidic soils of Crete Zaire-Nile (Karongi district) and central plateau (Huye district) in Rwanda.

3.3. Effects of Limes on Soil Exchangeable Cations Saturation. Ca, Mg, and Al saturation were significantly ($P \leq 0.001$) affected by both application of agricultural burned and unburned limes. The lime rate of 2.8 t ha^{-1} of agricultural burned, Rusizi, and Musanze unburned limes had similar effects in reducing Al saturation. Karongi unburned lime applied at all rates was the lowest in reducing Al saturation than other limes. However, potassium and sodium saturation were not significantly affected by lime application (Table 3).

The high increase of Ca saturation observed with agricultural burned, Rusizi and Musanze unburned limes than in Karongi unburned lime could be attributed to the fact that calcite lime releases more Ca in soil solution that dolomitic lime as reported by Fageria and Stone [39]. The application of 4.2 and 2.8 t ha^{-1} of agricultural burned lime, Rusizi unburned lime were able to bring Ca saturation at adequate level in the soil which is estimated at 65 to 85% by Hazelton and Murphy [40]. The highest Mg saturation recorded in the plots with Karongi unburned lime compared to the other limes could be attributed to its dolomitic nature. The results are in accordance with the findings of Fageria and Stone [39] who reported increase of Mg content in acidic soils as result of liming. Beernaert [5] also reported the increase of Mg in soil following application of dolomitic lime in acidic soil of Rwanda. The reduction of Al saturation recorded in this study were in accordance with the findings of Ruganzu [30] who reported 49% reduction of Al saturation after application of travertine combined with *Tithonia diversifolia* in Rubona acidic soils. According to Abbott [41], the adequate level of Al saturation in soil should be <5%. Markedly, only application of 4.2 t ha^{-1} of agricultural burned and Rusizi unburned lime were able to reduce Al saturation to 3.1 and 3.9%, respectively.

Despite the fact that K and Na saturation were not affected by limes, according to Abbott [41] and Hazelton and Murphy [40], the baseline of K and Na saturation were in adequate range where it was ranged from 1 to 5% for K and at 0 to 1% for Na.

Table 3: Exchangeable cations saturation (%) as affected by limes.

Treatments	Ca (%)	Mg (%)	K (%)	Na (%)	Al (%)
Baseline	27.44	11.18	2.64	0.28	58.45
Controls(0 t ha^{-1})	27.98	11.73	2.30	0.07	57.91
Agricultural burned lime 1.4 t ha^{-1}	64.11	15.3	3.55	0.09	16.96
Agricultural burned lime 2.8 t ha^{-1}	62.6	25.33	3.08	0.07	8.96
Agricultural burned lime 4.2 t ha^{-1}	75.09	18.03	3.67	0.09	3.1
Karongi unburned lime 1.4 t ha^{-1}	35.04	31.11	2.71	0.07	31.06
Karongi unburned lime 2.8 t ha^{-1}	30.12	36.04	3.06	0.03	30.74
Karongi unburned lime 4.2 t ha^{-1}	34.21	36.87	7.66	0.07	21.19
Musanze unburned lime 1.4 t ha^{-1}	59.94	18.07	3.19	0.09	18.71
Musanze unburned lime 2.8 t ha^{-1}	68.34	18.81	3.24	1.00	9.51
Musanze unburned lime 4.2 t ha^{-1}	69.31	20.45	3.33	0.08	6.83
Rusizi unburned lime 1.4 t ha^{-1}	41.24	14.22	3.15	0.04	41.34
Rusizi unburned lime 2.8 t ha^{-1}	64.84	19.97	3.65	0.05	11.48
Rusizi unburned lime 4.2 t ha^{-1}	71.81	20.27	3.93	0.08	3.89
P value	**<0.001**	**0.001**	**0.463**	**0.278**	**<0.001**
LSD	**11.552**	**6.568**	**3.236**	**0.043**	**14.580**

LSD: Least significant differences of means (5% level).

Table 4: Effects of limes on potato yield ($P < 0.001$ and LSD 3.28) and RAE (%).

Lime rates	Yield (kg ha^{-1})				RAE (%)		
	Agricultural lime	Karongi lime	Musanze lime	Rusizi lime	Karongi lime	Musanze lime	Rusizi lime
Control (0 t ha^{-1})	14.32	14.32	14.32	14.32	—	—	—
1.4 t ha^{-1} (1/2 rate)	18.88	17.88	19.63	18.06	80.43	113.04	82.61
2.8 t ha^{-1} (full rate)	22.47	19.62	22.15	21.08	65.85	95.12	82.93
4.2 t ha^{-1} (1.5 rate)	24.82	19.23	24.9	21.85	47.62	100	72.38

RAE = 100: equal efficiency of local lime and agricultural lime; RAE > 100: more efficiency than agricultural lime; RAE < 100: less efficiency than agricultural lime.

3.4. Effects of Limes on Potato Tuber Yield and Relative Agronomic Efficiency (RAE). The yield of Irish potato was significantly ($P = 0.01$ at $\alpha = 5\%$) affected by the application of limes. Notably, agricultural burned lime, Musanze, and Rusizi unburned limes applied at lime rate of 2.8 t ha^{-1} had relatively similar effects. However, the lowest yield was obtained in the control plots. The unburned limes were different in their RAE where Musanze unburned lime applied at 1.4 t ha^{-1} had the highest RAE (113.04%) compared to application of the other unburned lime rates (Table 4). The application of 4.2 t ha^{-1} of Musanze unburned lime had RAE (100%), which means it had the same effectiveness as agricultural burned lime (Table 4).

The high yield obtained in plots that were limed was probably due to the positive effects of liming on soil properties. The agricultural burned and unburned limes improved the overall soil base saturation. Markedly, when a little amount of lime or unburned lime applied in acidic soils, it results to the changes in soil properties and other nutrients [5] which in turn affect potato production positively. These findings are in agreement with Harelimana [42] and Kayitare [29] who reported that unburned limes increased Irish potato yield in acidic soils of Rwanda. The high RAE of Musanze unburned lime compared to the other unburned limes could be attributed to its fineness and CCE.

4. Conclusion

The agricultural burned lime, Rusizi and Musanze unburned limes had different quality. A higher calcium carbonate equivalent (CCE) was observed in agricultural burned and Rusizi unburned limes (86.6% and 86%, resp.). This indicates that the two lime types are comparable. In terms of fineness, agricultural burned and Musanze unburned limes were higher (70.57 and 63.03%, resp.) compared to the other two limes. This could be an indication of their higher effectiveness observed in this study. The application of 4.2 and 2.8 t ha^{-1} of agricultural burned lime, Rusizi and Musanze unburned limes had similar effects in increasing Ca saturation and reducing Al saturation. These imply that unburned limes could be used in alternative to agricultural burned lime which is very expensive to farmers. In addition, the unburned lime do not possess burning effects, hence provides farmers with safer material to work with and with easy manipulation (handling practices). Furthermore, the production of agricultural burned lime was reported to cause environmental hazard through the emission of greenhouse gasses. Therefore this study recommends the use of unburned limes instead of relying on agricultural burned lime in improving base cations and available phosphorus in acidic soils.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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