EFFECTS OF DIFFERENT LIMES ON SOIL PROPERTIES AND YIELD OF IRISH POTATOES (S*olanum tuberosum*. L) IN BURERA DISTRICT, RWANDA

By

ATHANASE NDUWUMUREMYI (BSc.)

Reg No: A148EA/20180/2010

A THESIS SUBMITTED IN PARTIAL FULFILMENT FOR THE DEGREE OF MASTER OF SCIENCE IN INTEGRATED SOIL FERTILITY MANAGEMENT OF KENYATTA UNIVERSITY, KENYA

November, 2013

DECLARATION

I **Athanase Nduwumuremyi**, declare that this thesis is my original work and has not been presented for a degree in any other university or any other award.

Signature______________________ Date_______________

Athanase Nduwumuremyi (BSc)

Department of Agricultural Resource Management

We confirm that the work reported in this thesis was carried out by the candidate under our supervision and has been submitted with my/our approval as university supervisors.

Signature______________________ Date_______________

Dr. Jayne Mugwe
Chairperson and Lecturer,
Department of Agricultural Resource Management,
Kenyatta University, Kenya

Signature______________________ Date_______________

Dr. Vicky Ruganzu
Director of Natural Resources Management,
Western Zone Research Division,
Rwanda Agriculture Board (RAB), Rwanda

DEDICATION

This work is dedicated to my beloved wife Justine Mupenzi and our sons Rugero Ervin Baruck and Rugero Sean Gadiel.

ACKNOWLEDGEMENTS

I express my thanks to the Almighty God who gave me life and strength to accomplish this work. I sincerely thank my supervisors Dr. Jayne Njeri Mugwe and Dr. Vicky Ruganzu for their professional guidance and tireless efforts to assist me during this work. I thank Dr. Benjamin O. Danga for orientation and sharpening the initial idea for this work. I acknowledge the contribution received from all academic staff at Kenyatta University and particularly Department of Agricultural Resource Management, during my stay in Kenya.

I also sincerely thank Mr. Mbonyitwari Aphrodis and Assistance Fund for Genocide Survivors in Rwanda (FARG) for the enormous support to my basic education. I am indeed grateful to the Alliance for Green Revolution in Africa (AGRA) for financial support to undertake my Masters Degree at Kenyatta University. The Government of Rwanda deserve my thanks for providing study leave and other related support during my master's studies. I appreciate technical and laboratory support from Mr. Makelele Kilyobo, the head of Higher Institute of Agriculture and Animal Husbandry (ISAE) soil laboratory.

I am highly grateful to my wife and son for love and care when I was doing this work. Finally, I am very grateful to my brothers and sisters for their love, support and encouragement during my studies. All other colleagues and friends who have both directly and indirectly contributed to the success of this work, I thank you all and may God bless you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

Al: Aluminium

ANOVA: Analysis of Variance

Ca: Calcium

$CaCO_3$: Calcium Carbonate

CaO: Calcium Oxide

CCE: Calcium carbonate equivalence

CEC: Cations Exchanges Capacity

Cmol: Cent mole

ECEC: Effective Cations Exchanges Capacity

EDTA: Ethylene Diamine Tetraacetic Acid

FARG: Fond d'Assistance aux Rescapes du Génocide (Assistance Fund for Genocide Survivors in Rwanda)

FF: Fineness Factor

ISAE: Institut Supérieur d'Agriculture et d'Elevage (Higher Institute of Agriculture and Animal Husbandry)

ISAR: Institut des Sciences Agronomique du Rwanda (Rwanda Agriculture Research Institute)

K: Potassium

KCl: Potassium Chloride

LE: Lime Effectiveness

LSD: Least Significance Different

Mg: Magnesium

MINAGRI: Ministere de l'Agriculture et d'Elevage (Ministry of Agriculture and Animal husbandry)

Na:	Sodium
NISR:	National Institute of statistics of Rwanda
P:	Phosphorus
pH:	Potential Hydrogen ions (Measurement of acidity)
pH_{KCl}:	Soil pH measured in suspension KCl
pH_w:	Soil pH measured in suspension water
RAB:	Rwanda Agriculture Board
RAE:	Relative Agronomic Efficiency
REE:	Relative Economic Efficiency
RCBD:	Randomized completely block design
SAS:	Statistical Application System
SED:	Standard Errors of Differences of means
SHF:	Small Household farmer
SSA:	Sub-Sahara Africa
WAP:	Week after Application

ABSTRACT

The problem of acidic soils is complex and threatens food production in many parts of Africa and Rwanda in particular. Rwanda is a small land locked country in sub-Saharan Africa and its population density is currently the highest in the region and continues to grow. Agriculture supports 82% of the population and hence it is the most important sector that needs to be explored in order to enhance food security. The major objective of this study was to evaluate the quality of agricultural and local liming materials, their effects on selected soil physical and chemical properties and yield of Irish potatoes in Burera district. This was achieved through a laboratory based quality analysis and a field experiment. The field trial followed a randomized complete block design (RCBD) with three replications and it was established in September, 2011. The treatments comprised of the four lime materials (Agricultural lime, Karongi, Musanze and Rusizi liming materials) applied at three levels (1.4, 2.8 and 4.2 t ha^{-1} of $CaCO_3$ equivalent) and control. Soil properties were monitored over a period of 16 weeks (112 days) after limes application. The data collected were subjected to analysis of variance (ANOVA) and t-test. The findings showed that, agricultural and Rusizi limes had the highest CCE (86.36 % and 85.46%, respectively). In terms of fineness factor (FF), agricultural lime and Musanze lime had higher FF compared to other limes. Lime rate of 2.8 t ha^{-1} of Musanze and agricultural limes had similar and highest effects in increasing soil pH. At the rate of 2.8 t ha^{-1} they increased the soil pH by 0.65 and 0.64 units, respectively. On the other hand, at a rate of 4.2 t ha^{-1}, Rusizi lime had a higher Lime Efficiency (LE) (102.3%) in increasing soil pH than Musanze and agricultural lime (LE of 100% respectively). Lime rate of 4.2 t ha^{-1} of agricultural, Rusizi and Musanze limes reduced exchangeable Al. The effectiveness of Musanze lime at the rate of 2.8 t ha^{-1} had the highest LE (100.8%) among all the limes making it the best in reducing exchangeable Al, while Karongi lime was the poorest. Lime rate of 4.2 t ha^{-1} of agricultural lime had the highest effect in increasing available phosphorus compared to other limes while Karongi lime had the lowest effects in increasing available phosphorus. Lime application rate of 1.4 and 4.2 t $ha^{-1}$of agricultural lime significantly ($p<0.001$) reduced the ECEC. At the rate of 2.8 t ha^{-1}, agricultural and Musanze limes increased 0.24% and 0.21% of total nitrogen, respectively. Notably, all lime rates of Karongi lime were the lowest in increasing total nitrogen. Musanze lime had higher Relative Agronomic Efficient (RAE) than other local limes. At a rate of 1.4 t ha^{-1}, Musanze lime had 113.04% of RAE, an indication of yield increase by 13.03%. Economically, lime rates of 1.4t ha^{-1} of Musanze lime had the highest economical efficiency (121.81%), which makes it to be more economically efficient than other limes and rates. Therefore, this study recommends the use of Musanze lime applied at a rate of 2 to 4 t ha^{-1} in acidic soils of Burera district.

CHAPTER ONE

1. INTRODUCTION

1.1 General Background

Agriculture is the most important sector of the Rwandan economy supporting 82% of the population (NISR, 2009). Irish potatoes (*Solanum tuberosum*.L) underpin Rwanda's food security (FAOSTAT, 2008). Per capita consumption of Irish potatoes is very high, estimated at 125 kg per person, thus making potato the country's second most important staple crop and source of calorie intake after cassava (FAOSTAT, 2008). Whereas the national average production of potato in Rwanda is estimated at 9.0 t ha^{-1} (FAOSTAT, 2008), the yields reported for a majority of the small household farmers (SHF) is estimated at 5-6 t ha^{-1}, which is four times lower than the yields of 25 t ha^{-1}, attained by progressive farmers using best production practices under similar rain-fed conditions. This yield gap can be partly attributed to continuous cropping, soil acidity (Kiiya *et al.,* 2006) and inadequate soil fertility management (Berga *et al.,* 2001).

The production of Irish potatoes is threatened by widespread acidity in many parts of Rwanda, and applications of lime and phosphorus have been reported to significantly improve yields of Irish potato (Yamoah *et al.,* 1996). Problems of acid soils (pH less than 5) are widespread in Rwanda affecting approximately 45% of the total arable land or about 60% of the highland areas, which are the major growing areas of Irish potato (Goossens, 2002). Potato requires a considerable amount of nitrogen, and the continuous widespread use of the ammonium or urea based N fertilizers contributes to the soil acidification (Brett *et al.,* 2005). Acidity affects the fertility of soils through nutrient deficiencies (P, Ca and Mg) and the presence of phytotoxic nutrients such as soluble Al and Mn (Awad *et al.*, 1976). Application of lime reduces Al toxicity, improves pH, Ca, Mg and increases both P uptake in high P fixing soil and plant rooting system (Black, 1993). Nevertheless, the use of lime alone is insufficient to rehabilitate poor or depleted soils. The best practice is one that combines lime, organic manure and inorganic fertilizers (Mukuralinda, 2007).

The use of liming materials in Rwanda (Yamoah *et al.*,1992) demonstrate that even small locally produced local limes and liming materials can be used to increase crop production on acidic soils. In some areas of Rwanda, the use of 2-4 tonnes per hectare of local limestone or dolomite resources has proved to be agronomically effective, significantly enhancing the yield of wheat, beans and potatoes (Yamoah *et al.*, 1992). Locally available carbonates are relatively common in many countries of sub-Saharan Africa and are well suited for small-scale mining and processing (Van Straaten, 2002).

Rwanda has relatively good sources of agricultural lime mainly in the Western (Karongi and Rusizi districts) and the Northern (Musanze district) Provinces of Rwanda. However, all of the available local liming materials have not been evaluated and compared to determine their solubility and effects on soil pH and crop productivity in Rwanda.

1.2 Problem Statement and justification

Irish Potatoes (*Solanum* *tuberosum*. L) supports Rwanda's food security, but its production is threatened by widespread soil acidity. There are several sources of lime in Rwanda and some local production is currently done using traditional methods and techniques. Despite the lime availability and its high potential in alleviating soil acidity, there is limited use in agricultural production by smallholder farmers. Some of the limiting factors to widespread use of lime in Rwanda are; lack of awareness among farmers on its use, lack of appropriate recommended rates, and high cost and unknown quality of the available agricultural limes. Furthermore, knowledge on the effectiveness of various lime sources in correcting soil acidity is lacking due to limited studies done in the region. Information on lime quality, effectiveness in reducing soil acidity and in improving crop yields is vital in lime selection and formulation of recommendations rates that are necessary for spurring farmer uptake of the liming technology. The aim of this study was therefore to fill this gap by evaluating local limes (travertine) from different sources and their effectiveness on soil properties and production of Irish potatoes in Burera district, Rwanda.

1.3 Research questions

i. What is the quality of agricultural lime and three local limes in terms of physical and chemical properties?

ii. What is the effect of agricultural and local limes on selected soil nutrients and soil pH?

iii. What is the effect of agricultural and local limes on growth and yield performance of Irish potato?.

1.4 Objectives

The main objective was to evaluate the quality and effects of three local lime sources on soil acidity and Irish potatoes yields in Burera district of Rwanda. To achieve this, the following specific objectives were addressed:

i. To determine selected physical and chemical properties of agricultural lime and three local liming materials
ii. To evaluate the effect of agricultural and local limes on selected soil nutrients and soil pH.
iii. To evaluate the effect of agricultural and local limes on growth and yield performance of Irish potato.

1.4 Research hypotheses

The hypotheses for the study were:

a) Agricultural lime and three main local limes significantly differ in their physical and chemical properties.
b) Application of agricultural and local limes in the soil significantly improves nutrients availability and increases soil pH.
c) Application of agricultural lime results in significantly higher yields of Irish potato than application of local limes.

1.5 Significance of the study

The findings of this study are useful to smallholder potato farmers who possess small sizes of land, are resource poor and have difficulties in managing acidic soils. The findings will also contribute to the existing knowledge on quality of available local limes, their appropriate rates, effects on soil properties and yield of Irish potato. In addition, the information is envisaged to be used by the regional agricultural field staff and/or agricultural extension officers in advising farmers on how to manage acidic soils. This may contribute to creating awareness among potatoes growing farmers on the importance of applying lime and lead to increased usage of the most effective local lime. This would lead to increase in the yield and profitability of Irish potato and consequently contribute in alleviating hunger and poverty among smallholder farmers in Rwanda.

1.6 Conceptual framework

Acidic soils infertility is serious agricultural production constraint in Rwanda (Yamoah *et al.*, 1990). Soil acidity is one of the most yield limiting factors for crop production. Potato requires a considerable amount of Nitrogen, which if applied as fertilizers containing ammonium or urea in combination with high rainfall regime contributes to the acceleration of the soil acidification (Brett *et al.*, 2005). Liming materials combined with efficient use of fertilizers and best agricultural practices can increase crop production on acidic soils (Yamoah *et al.*, 1992). Liming raises soil pH, and Ca and Mg contents, and reduces aluminium concentration (Fageria and Stone, 2004). The combination of fertilizers and lime application at an appropriate rate brings several chemical and biological changes in the soil, which improves crop yields on acid soils. Adequate liming eliminates soil acidity and toxicity of Al, improves availability of Ca, P, Mg, and reduces loss of cations through leaching. Figure (1) summarizes conceptual framework of this study.

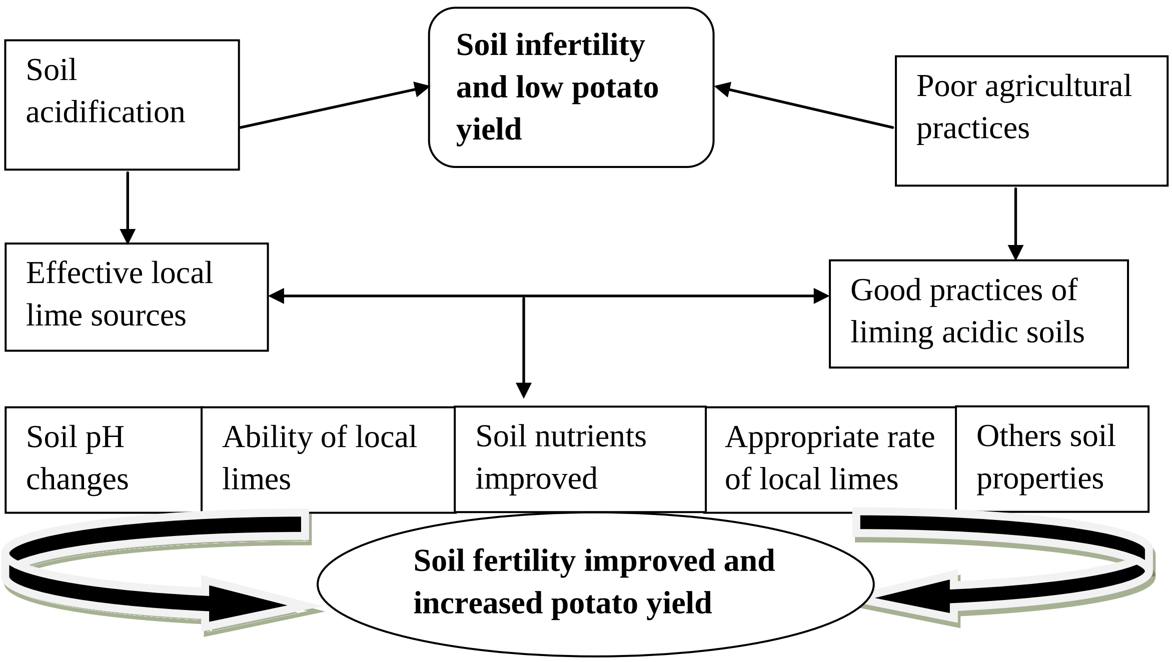


Figure 1: Conceptual framework

CHAPTER TWO

2 LITERATURE REVIEW

1.1 Overview

The goal of this chapter is to review the critical points of current knowledge including substantive findings as well as theoretical and methodological contributions to the subject matter. The thematic areas covered are; causes of soil acidity, its effects on soil properties and crop productivity. The contents of this chapter are based on previous research done on soil acidity, liming and their effects on Irish potato yield.

2.2 Soil pH and acidification

Soil pH is a measure of the number of hydrogen ions in the soil solution; the higher the concentration of hydrogen ions, the more acidic the solution is. Understanding soil pH is essential for the proper soil management and optimum crop productivity. In aqueous (liquid) solutions, an acid is a substance that donates hydrogen ions (H^+) to some other substance (Tisdale *et al.*, 1993). Soil pH is an excellent chemical indicator of soil quality. Theoretically, soil acidity is quantified on the basis of hydrogen (H^+) and aluminium (Al^{3+}) concentrations of soils (Fageria and Baligar, 2008).

Soil acidity occurs when there is a build up of acid forming elements in the soil. The production of acid in the soils is a natural process; caused by rainfall and leaching, acidic parent materials and organic matter decay (Havlin, 2005) hence many soils in high rainfall areas are inherently acidic (McCauley *et al.,* 2009). Acidification is a slow process but it is accelerated by agriculture through; use of some fertilizers, soil structure disturbance and harvest of high yielding crops (Fageria and Baligar, 2008). As soils become more acidic, plants intolerant to acidic conditions are negatively affected leading to productivity decline. The aim of attempting to adjust soil acidity is to neutralize pH and Al toxicity but the most important is to replace lost cations nutrients, particularly calcium and magnesium (Fageria and Baligar, 2008). This can be achieved by adding limestone to the soil (Maheshwari, 2006) and farmers can improve the soil quality of acidic soils by liming to adjust pH to the levels needed by the crop to be grown.

2.2.1 Soil acidification and Aluminium toxicity

Soils become acidic for several reasons. The most common source of hydrogen ion is the reaction of aluminium ions with water. Aluminium toxicity in combination with low pH (Budianta and Vanderdeelen, 1995) is one of the major reasons that render acidic soils unsuitable for the growth of many plants in the humid tropic countries. The forms of aluminium ions present vary with pH (Fageria and Baligar, 2008). The increased soil acidity causes solubilisation of Al, which is the primary source of toxicity to plants at pH below 5.5 (Kariuki *et al*., 2007). As observed by Carson and Dixon (1979), under very acidic conditions of pH less than 4.5, the major form of aluminium is Al^{3+}, and pH between 4.5- 6.5, aluminium-hydroxyl dominates. As the pH increases, exchangeable Al^{3+} precipitates as insoluble Al hydroxyl forms at a rate of 1000 fold decrease for each unit increase in pH (equation 1).

$$Al^{3+} + H_2O \leftrightarrow Al\,(OH)_2 + H^{+} \qquad \text{Equation [1]}$$

The equation (1) explains the reaction of aluminium-hydroxyl in very acid soils. However, at pH greater than 6.5, aluminium becomes increasingly soluble as negatively charged aluminates form (Haynes, 1984). The heavy rainfall can also contribute to the soil acidification by natural causing parent materials to be acidic due to leaching of cations (Fageria *et al*., 1990). There are other important causes of soils acidification, such as, ammonium fertilizers, release of organic acids in decomposition of crop residues or organic wastes (Sparks, 2003) and continuous cultivation of legumes (Bolan and Hedley, 2003). The acidification caused by the use of ammonium fertilizers are explained by the release of H^+ (equation 2).

$$NH^{+}_{4} + 2O_2 \leftrightarrow NO_3^{-} + H_2O + 2H^{+} \qquad \text{Equation [2]}$$

The acidification due to legumes is explained by higher absorption of basic cations of legumes and the release of H^+ ions by the root of legume crops to maintain ionic balance, and during N_2 fixation through a function of carbon assimilation (Bolan and Hedley, 2003).

2.3 Soil acidity and crop responses

Soil pH affects crops in many ways and its effects are mostly indirect, through its influence on chemical factors and biological processes. Chemical factors include aluminium (Al) toxicity, calcium (Ca) and phosphorus (P) and magnesium (Mg) deficiencies; (Uchida and Hue, 2000). Optimum nutrient uptake by most crops occurs at a soil pH near 7.0. The nutrients availability such as nitrogen, phosphorus and potassium is generally reduced as soil pH decreases. Phosphorus is particularly sensitive to pH and can become a limiting nutrient in strongly acid soils. Thus, reduced fertilizer use efficiency and crop performance can be expected when soil acidity is not properly controlled (McFarland *et al.*, 2005). Hardy *et al.* (1990) reported exchangeable Al to affect crops by shallow rooting, poor use of soil nutrients, and Al toxicity.

2.3.1 Irish potato (*Solanum tuberosum .L*) response to liming

Irish potato needs heavy amounts of fertilizers and tuber yields are seriously affected in soils with shortages of P and K. Excessive N on the other hand sharply diminishes tuber yields (Kanzikwera *et al*., 2001). Therefore potato production requires strict management regimes. Yamoah *et al.* (1992) found that in Rwanda, potato yield can be significantly increased by residual lime. Potato yields at lower lime differed from those at the higher rates by about 30%, again substantiating a much longer residual effect with the use of higher rates (Folscher *et al.*, 1986). The growth of potato was observed to be more vigorous in the high lime plots than in the low lime plots (Yamoah *et al.*, 1992). Hester (1936) reported 25 to 29% increase in potato yield due to small applications of lime on soil with a pH of 5.2.

In Burera district (one district of highlands of Rwanda), potato is largely grown; in this region soils have low organic matter content and a pH < 5. Plant nutrients are most available at soil pH levels near 6.5; potatoes grown in soils near pH 6.5 produce higher yields with less fertilizer (Rosemary, 1991). The ideal pH for Potato ranges from 5.2 to 6.5 (Adams, 1984). The beneficial effects of liming on crop growth are often related to neutralization of Al and not directly to the change in pH.

2.4 Liming and its advantages in acidic soils

Liming is an important practice to achieve optimum yields of all crops grown on acid soils. According to Kaitibie *et al.* (2002), liming is the most widely used long-term method of soil acidity amelioration, and its success is well documented (Scott *et al.*, 2001). Application of lime at an appropriate rate brings several chemical and biological changes in the soils, which are beneficial or helpful in improving crop yields on acid soils (Fageria and Beligar, 2008).

Liming raises soil pH, base saturation, and Ca and Mg contents, and reduces aluminium concentration in acidic soils (Fageria and Stone, 2004). Plant growth improvement in acid soil is not due to addition of basic cations (Ca, Mg), but it is due to increasing pH that reduces toxicity of phytotoxic levels of Al (Fageria and Beligar, 2008). The acidic soils are naturally deficient in total and plant available phosphorus. This is because significant portions of applied P are immobilized due to precipitation of P as insoluble Al phosphate or chemisorptions to Al oxide and clay minerals (Nurlaeny *et al.*, 1996). The liming of acidic soils result in the release of P for plant uptake; this effect is often referred to as ‘‘P spring effect’’ of lime (Bolan *et al.*, 2003). Increase in availability of P in the pH range of 5.0 to 6.5 is associated with release of P ions from Al and Fe oxides, which is responsible for P fixation (Fageria, 1989). But at high pH (> 6.5) soluble P precipitate as Ca phosphate (Naidu *et al*., 1990).

Soil microbiological properties can serve as soil quality indicators. Soil acidity restricts the activities of beneficial microorganisms, except fungi, which grow well over a wide range of soil pH (Brady and Weil, 2002). Liming acidic soils enhance the activities of beneficial microbes in the rhizosphere and hence improve root growth by the fixation of atmospheric nitrogen because neutral pH allows more optimal conditions for free-living N fixation (Stephen, 2011). It can also suppress pathogens and producing phytohormones; enhancing root surface area to facilitate uptake of less mobile nutrients such as P and micronutrients and mobilizing and solubilising unavailable nutrients (Baligar and Fageria, 1999).

According to McBride (1994), increasing soil pH through liming can significantly affect negatively the adsorption of heavy metals in soils. Soil properties such as organic matter content, clay type, redox potential, and soil pH are considered the major factors that determine the bioavailability of heavy metals in soil (Treder and Cieslinski, 2005). Hence, liming certainly helps in reducing availability of heavy metals to crop plants.

Soil acidity is also responsible for low nutrient use efficiency by crop plants. Fageria and Baligar (2004) reported that liming acidic soils improved the use efficiency of P, and other micronutrients by upland rice genotypes. In this study, efficiency of these nutrients was higher under a pH of 6.4 than with pH 4.5. The liming improves efficiency of nutrients through soil acidity management by improving their availability, and enhanced root system (Fageria and Baligar, 2004).

Calcium released from applied lime in soil has been reported to enhance plant resistance to several plant pathogens (Fageria and Baligar, 2008), including *Erwinia phytophthora*, *R. solani*, *Sclerotium rolfsii*, and *Fusarium oxysporum* (Kiraly, 1976). Haynes (1984) reported that calcium forms rigid linkages with pectic chains and thus promotes the resistance of plant cell walls to enzymatic degradation by pathogens. Therefore, liming provides calcium, which can contribute to build up plant resistance to some pathogens.

Finally, liming has been promoted as mitigation option for lowering soil N_2O emissions when soil moisture content is maintained at field capacity (Clough *et al.*, 2004). Since soil pH has a potential effect on N_2O production pathways, and the reduction of N_2O to N_2, it has been suggested that liming may provide an option for the mitigation of N_2O emission from agricultural soils (Stevens *et al.*, 1998).

2.5 Causes of soil acidity and constraints of using lime in Rwanda

Rwanda is a small landlocked country under heavy population pressure. Rwanda's population density is currently the highest in SSA (Rurangwa, 2013). It is still a very rural society, and many families live in rural hillside areas. The urban concentrations are grouped around administrative centres. The Rwandan economy is based largely on rainfed agricultural production of small, semi-subsistence, and increasingly fragmented farms. Farming is intensive and fields are concentrated on steep hillsides (NISR, 2009). This results in soil acidity, low fertility, accelerated soil erosion and low crop yields (Yamoah, 1990). The risk of erosion is increased by the need of smallholders to cultivate slopes of up to 55% and farming land that is not suitable for crop production. Smallholder potato farmers in the northern Rwanda grow and harvest potatoes throughout the year because of land scarcity (Goossens, 2002) leading to loses of over 15 tonnes of topsoil each year. The cost and transport of local limes and other liming materials are the major constraints in liming practices adoption in Rwanda; the lime handling methods are also impediments for the lime usage among poor farmers in Rwanda. Fine products of lime with high neutralizing value are preferred (Scott *et al.,* 1992) to overcome all of these limitations.

2.5.1 Sources of liming materials in Rwanda

There are large mines of local limes (travertine and dolomite rocks) in Rwanda and exploitation of the main deposits is possible (Beernaert, 1999). Liming products (ground travertine and more or less burned limes) are at present almost exclusively produced in large quantity in Musanze and Rusizi districts. The annual production is 9,000 ton/year (MMCF, 1993). Although, travertine and dolomite mines are abundant in Rwanda, only 30 % are coherent rocks, required for the production of lime reserved for construction (SOFRECO, 2001). The remaining 70 % occur as loose sandy travertine, which is not suitable to be used in construction (SOFRECO, 2001). From an agronomic and economical point of view, it would be logical to reserve the coherent rock fraction for lime production to be used in construction and to exploit the sandy fraction for agricultural purposes, using a more simple and low cost treatment (MMCF, 1993). Very often, there is more variation in the CaO and MgO content of local limes of the same deposit, as compared with travertine of different deposits. Therefore, there is a need of homogenizing the mixture of local liming material from same deposit (mine).

2.5.1.1 Travertine group

Travertine is limestone with high Ca content ($CaO>40\%$) and low magnesium content ($MgO<3\%$) (SOFRECO, 2001). Travertine is found in recent formations of Pleistocene age and is a less compact, soft rock, which is easily extractable without explosives. Beernaert (1999) reported that, travertine has a cationic (Ca/Mg) ratio of

13-15, which is much higher than the optimal ratio of 4-5. This can cause disequilibria in the cation balance and affect soil fertility (Beernaert, 1999). Kayonga and Goud (1989) observed that ground travertine rocks raised soil pH by 0.5 units, reduced exchangeable Al, increased base saturation, and introduced disequilibria between the exchangeable cations. These rocks have a suitable chemical composition to eliminate aluminium toxicity in acid soils but cause nutrient imbalance and hence create new problems.

2.4.1.2 Dolomite rocks

A dolomite rock is limestone with high content of magnesium (CaO 30%; MgO 20%) (SOFRECO, 2001). The dolomite rocks of Rwanda include dolomite limestone, dolomite marbles of Mbarara Island and dolomites (Gillet and Brogniez, 1991). These are hard rocks used for building and construction and which need explosives and more sophisticated cutting, drilling and grinding equipment, for their extraction. Although records show the existence of very large reserves of dolomite deposits in Karongi (Gillet and Brogniez, 1991), very little is known about their agronomic efficiency. The report by Wouters and Gourdin (1989) showed that dolomite rocks can successfully eliminate soil acidity and Al toxicity but their chemical composition with a cation (Ca/Mg) ratio close to 1 is not suitable for agriculture.

2.6 Fertilizers and lime combination

Liming experiments in plateau and hills of Rwanda showed that addition of lime alone is insufficient to rehabilitate poor or depleted soils (Mukuralinda, 2007). The use of fertilizers is therefore essential. However, choice and use of the appropriate fertilizers is also important since some fertilizers can exacerbate soil acidity. The best practice is one that combines lime, organic manure and inorganic fertilizers (Mukuralinda, 2007). This has been observed to be the most appropriate technique of addressing the problem of soil acidity and enhancing soil fertility in Rwanda (Ruganzu, 2009). Significant yield increases have been observed in areas where the organic and inorganic nutrients sources have been applied together with lime, particularly in the research stations (Nabahungu, 2003). In Rwanda, RAB advices farmers to use lime together with mineral fertilizers for improving soil productivity in acidic soil (Musabyimana, 2012 in personal communication). However there is a need to evaluate and confirm whether there is a synergic benefit of combining fertilizers and lime in Rwandan acidic soil context.

2.7 Solubility of lime

Lime is lowly soluble in water, so particles must be finely ground to neutralize soil acidity for a reasonable period of time (Snyder and Leep, 2007). Even very small changes in the sizes of the particles have a major effect on the time required to dissolve them (Snyder and Leep, 2007). Effectiveness depends on the purity of the liming material and how finely it is ground. The purity of lime is rated by laboratory measurement of Calcium Carbonate Equivalent (CCE). The lower the CCE value, the more lime you will need to neutralize the soil's acidity (Larry Oldham, 2000). When lime (e.g., $CaCO_3$) is added to a moist soil, the following reactions will occur:

(1) Lime is dissolved (slowly) by moisture in the soil to produce Ca^{2+} and hydroxide (OH^-): $CaCO_3 + H_2O\ (\text{in soil}) \rightarrow Ca^{2+} + 2OH^- + CO_2\ (\text{gas})$ Equation [3]

(2) Newly produced Ca^{2+} will exchange with Al^{3+} and H^+ on the surface of acid soils:

Ca^{2+} + [Soil particle + Al^{3+} and H^{+}] → [Soil particle + Ca^{2+}] + Al^{3+} + H^{+} Equation [4]

(3) Lime produced OH^{-} will react with Al^{3+} to form solid Al $(OH^{-})_3$, or it will react with H^{+} to form H_2O as shown in equations 5 and 6.

$$3OH^{-} + Al^{3+} \rightarrow Al\,(OH)3\ \ (solid)$$ Equation [5]

$$OH^{-} + H^{+} \longrightarrow H_2O$$ Equation [6]

Thus, liming eliminates toxic Al^{3+} and H^{+} through the reactions with OH^{-}. Excess OH^{-} from lime will raise the soil pH, which is the most recognizable effect of liming. Another benefit of liming is the added supply of Ca^{2+}, as well as Mg^{2+} if dolomite [Ca, Mg $(CO_3)_2$] is used. Calcium and Mg are essential nutrients for plant growth, yet they are often deficient in highly weathered acid soils (Uchida and Hue, 2000).

2.7.1 Efficiency and quality of liming materials

Quality of liming material is very important in correcting soil acidity (Snyder and Leep, 2007). The source of lime, its characteristics, composition and the purity of lime are very important parameters for effective use of lime (Kemperl, and Maček, 2009). The efficacy of liming materials is a key factor in determining its utilisation as profitable crop yield must be realised. The efficiency of a liming material is determined by its acid neutralising potential, particle size distribution, availability and convenience of spreading (Foth and Ellis, 1996).

Many terms are used when describing the efficiency of liming materials, and commonly used terms are relative neutralizing value (RNV), effective neutralising value (ENV) and effective calcium carbonate equivalence (ECCE) (Synder and Leep, 2007). The methods to determine the quality and efficiency of liming materials are based on the neutralising value (NV) and particle size distribution and various formulas have been developed (Snyder and Leep, 2007). The NV is determined by the chemical composition and the mineralogy of the liming material and is a measure of the amount of acid neutralising compounds expressed as the percentage of calcium carbonate equivalence (CCE), with pure calcium carbonate rated 100% (McFarland *et al.*, 2001). The efficiency of liming material is determined by its effective calcium carbonate equivalence (ECCE), an estimation of the effectiveness represented as percentage and is the product of CCE and the fineness factors of the various particle size fractions (Snyder and Leep, 2007). The key factors in determining the efficiency of liming materials are its chemical composition and particle size distribution (Table 1).

Table 1: Particle size and efficiency factors of limes

Particle size(mesh sieving size)	**Opening size(mm)**	**Efficiency factor**
>8	>2.36	0
8-60	2.36-0.25	0.5
<60	<0.25	1.0

Source: Halvin *et al*., 2005

In addition to the efficiency of a liming material, its efficacy (amount of material required to adjust soil pH to the desired level for profitable crop production) depends on the liming potential of the material, initial soil pH, clay content and buffer capacity of the soil (Snyder and Leep, 2007).

Studies on the effect of particle size on soil pH and crop yield have shown that liming with finer liming materials results in increments in soil pH over shorter time periods, and generally higher soil pH and crop yields (Huang *et al.*, 2007) The degree of fineness indicates the speed with which lime materials will neutralize soil acidity. Fineness is measured by the proportion of processed agricultural lime which passes through a sieve with an opening of a particular size (Peter *et al.,* 2006). A 60-mesh sieve, which is the standard for comparisons of lime fineness and efficiency rating of 100%, is assigned (Caudle, 1991).

2.8 Lime application

Methods, frequency, depth, and timing of liming are important practices in improving liming efficiency and crop yields on acidic soils (Fageria and Baligar, 2008). To get maximum benefits from liming or for improving crop yields, liming materials should be applied in advance of crop sowing and thoroughly mixed into the soil to enhance its reaction with soil exchange acidity (Fageria and Baligar, 2008). The best method is broadcasting it as uniformly as possible and mixing thoroughly within the topsoil (plough layer). Liming frequency is mainly determined by intensity of cropping, crop species planted, and levels of Ca^{2+}, Mg^{2+}, Al, and pH in a soil after each harvest. The effect of lime is long lasting but not permanent (Fageria and Baligar, 2008). When values of exchangeable Ca^{2+}, Mg^{2+}, and pH fall below optimum levels for a given crop species, liming should be repeated (Fageria and Baligar, 2008).

Effects of lime do last longer than those of most other amendments (Fageria and Baligar, 2008). However, it is rarely necessary to lime more frequently than every 3 years (Caudle, 1991). The residual effect of coarse lime material is greater than with finer lime material because large lime particles react slowly with soil acidity and tend to remain in the soil longer (Fageria and Baligar, 2008). A reasonable depth of 20 cm is required. Timing of lime application is important in achieving desirable results. Lime should be applied as early as possible before planting of crop to allow it to react with soil colloids and to bring about significant changes in soil chemical properties (Fageria and Baligar, 2008). Soil moisture and temperature are determining factors for lime to react with soil colloids. In Oxisols, significant chemical changes can take place 4–6 weeks after applying liming materials so long as soil has sufficient moisture (Fageria, 2001a). Hence, to obtain desirable results, it is not necessary to wait for a longer period of time after applying lime.

2.8 Lime requirement

According to Soil Science Society of America (1997), lime requirement is defined as the amount of liming material, as calcium carbonate equivalent, required to change a volume of soil to a specific state with respect to pH or soluble Al content. However, in economic terms, lime requirement can be defined as the quantity of liming material required to produce maximum economic yield of crops cultivated on acid soils (Ruganzu, 2009). Practically, different approaches are available in order to predict the limestone rate required to attain an adequate level aiming to avoid Al toxicity towards plant growth. One of the methods for predicting the lime requirement is to monitor the evolution of exchangeable Al (Kamprath, 1970). The base enrichment especially of Ca^{2+} ions in soil will neutralize exchangeable Al thus enhancing root growth (Bell and Bessho, 1993). Hakim *et al.* (1989) reported that the optimal lime rate to improve some food crops planted in the Ultisol is 6 tons $CaCO_3$ per ha, then, over liming will occur at doses exceeding 12 tons per ha. Many extracting solutions have been proposed to estimate the extractable Al and still KCl is the predominant (Oates and Kamprath, 1983). The non-readily exchangeable Al is estimated to be associated with organic matter, interlayer Al, and hydroxy-Al polymers that contribute to the active acidity in the soil solution (Oates and Kamprath, 1983).

2.10 CEC, base saturation, buffering capacity and soil acidity

The CEC affects the way a soil should be managed for crop production and environmental protection. For example, a soil with a low CEC (less than 5 cmol kg^{-1}) generally has a low clay and organic matter content, low water holding capacity, requires more frequent lime and fertilizer additions, and is subject to leaching of NO_3, NH_4^+, K and perhaps Mg (Wambeke, 1995). Such soils will have lower yield potential than soils with higher CEC under the same level of management, but high productivity can be maintained by intensive management. These soils are usually easier to cultivate than soils with higher CEC since they drain more rapidly, and added nutrients are highly available for plant uptake. Soils with CEC greater than 20% may have high clay content, moderate to high organic matter content, high water holding capacity, less frequent need for lime and fertilizers (except N), and low leaching potential for cationic nutrients (Garrison, 1989). On the other hand, their physical properties may make it difficult for a farmer to cultivate, irrigate or maintain good aeration. Such soils are also more prone to K fixation unless soil K levels are inherently high (Soil Survey Division Staff. 1993). The base cations include K, Ca, and Mg, (and Na, when present) and the base saturation is the proportion of the CEC 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 (Wambeke, 1995). 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 (Soil Survey Division Staff. 1993). Low base saturation (<25%) is indicative of a strongly acidic soils that may maintain Al^{3+} activity high enough to cause phytotoxicity (Soil Survey Division Staff. 1993).

The resistance of soils to changes in pH of the soil solution is termed as buffering. In practical terms, buffering capacity for pH increases with increase in the amount of clay and organic matter (Soil Survey Division Staff, 1993). Thus, soils with high clay and organic matter content (high buffer capacity) will require more lime to increase pH than sandy soils with low amounts of organic matter (low or weak buffering capacity).

2.11 Liming effects on Ca and Mg in soil

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} (Cregan *et al.*, 1989). 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 (Marschner, 1995). In acidic soils, most of the Ca present would exist in soluble form, but both soluble and exchangeable Ca decreases with decreasing soil pH (Haynes and Ludecke, 1981).When Ca^{2+}, K^{+}, and H^{+} concentration increase in the soil, they induce Mg uptake to be decreased in plant due to competitive inhibition (Clark, 1984). 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 (Myers *et al.,* 1988). Thus, a greater attention has to be made when liming to prevent cations imbalance in the soil.

CHAPTER THREE

3 RESEARCH METHODOLOGY

3.1 Description of the study site

The study was carried out at Rwerere Research station located in Burera district in Northern Province of Rwanda (Figure 2)

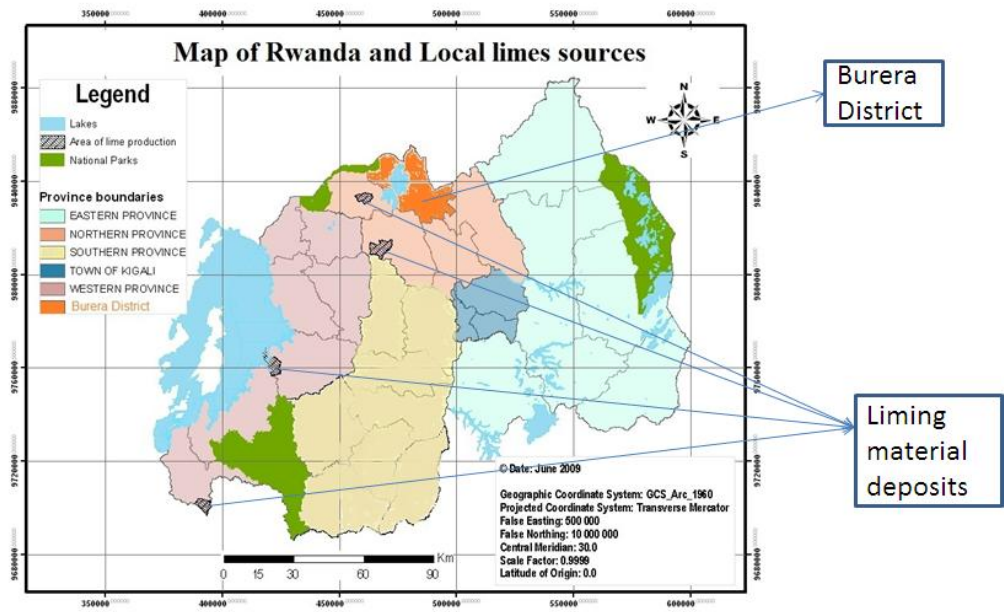


Figure 2 : Map of Rwanda showing lime deposits and Burera district

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 valleys steep sided or by flooded marshes. Annual rainfall ranges from 1400 to 1800 mm while annual average minimum and maximum temperature is 9°C and 25°C, respectively (Zeller *et al*.,2011). Population density is 522 per km^2 with farm land holding ranging from 0.15 to 0.2 ha per household (CITT, 2006). This implies conversion of degraded land into arable land and continuous farming on unsuitable hills and mountains. Soils are classified in USDA system as Oxisols (Franzel *et al.*, 1985). Irish potato (*Solanum tuberosum* L.) is one of the predominant crops followed by climbing beans (*Phaseolus vulgaris* L.), maize (*Zea mays* L.), wheat (*Triticum spp* L.), sorghum (*Sorghum spp* L.), banana (*Musa spp*. L) and various exotic and indigenous vegetables.

3.2 Collection of limes and laboratory analysis

Three local limes; Musanze, Karongi and Rusizi were collected from their respective mining sites (Mpenge site in Musanze district, Gishyita site in Karongi district and Bugarama site in Rusizi district) and taken to the laboratory at High Institute of Agriculture and Animal Husbandry (ISAE) in Musanze district for chemical and physical properties analysis. They were analysed for Ca (%) and Mg (%), Calcium Carbonate Equivalent (CCE in %), pH, fineness factor (FF in %), Effective calcium carbonate equivalent (ECCE in %) and moisture (%).

The Ca (%) and Mg (%) were analysed by EDTA Method (Hesse, 1971), the titration was done with EDTA 0.01N. The CaO (%) and MgO (%) were determined by multiplying Ca with conversion factor of 1.3992 and Mg with conversion factor of 1.6578 (Marcus, 2009). The CCE (%) was calculated using the formula CCE (%) = (Ca+ Mg) x 2.5 (Hesse, 1971). The pH water and pH KCl of limes were determined using a pH meter at a 1:2.5 lime: water/KCl ratio (Page *et al*., 1982). Fineness factor was determined by mechanically sieving the lime through a stag of 4 sieves of various aperture dimensions (2, 1, 0.5 and 0.2 mm) resulting to 5 classes of lime. The particles obtained were multiplied by efficiency factor of 0, 0.5 and 1 as described by Halvin *et al*. (2005). The ECCE was determined following equation 7 (Peter et al., 2006).

$$\text{ECCE}\ (\%) = \frac{\text{CCE} * \text{Fineness factor}}{100} \qquad \text{Equation [7]}$$

Moisture content was determined gravimetrically by weighing and oven drying the lime at 105^{o}C then re-weighing and the loss in weight considered as the amount of percent moisture loss (Carter and Gregorich, 2008).

3.3 Calculation of lime requirement

Lime requirement (LR) was determined following the method as outlined by Kamprath (1970) -due to its ability to neutralize all extractable Al in soil. In this method LR is determined by multiplying the factor (Table 2) by extractable Al (cmol kg^{-1}). The factor depends on the amount of organic matter in the soil (table 2). For soils with 4 to 5% organic matter content, lime application rates should be increased by 20 % (David *et al.,* 2011).

Table 2: Factors used to determine lime requirement (LR)

Factor	Organic matter (%)	extractable Al (cmol kg^{-1})
1-1.5	< 2.5	1
1.5-2	2.5-4	1
2	> 4	1

Source: Crawford *et al.*, (2008)

The soil organic matter of the experimental site was 2.2% hence a factor of 1 was used. The importance of considering this factor is related to the need for neutralization of H^{+} ions released from organic matter decomposition (Beernaert, 1999). This method neutralizes exchangeable Al in the soil at the rate of 85-90% (Beernaert, 1999) and has been applied successfully in different countries (Sanchez, 1976). In the current study, calculation of lime rates (L Rates) needed was done using equation (8) (Crawford *et al.*, 2008). It resulted in three rates: 0.5, 1 and 1.5 which were equivalent to 1.4, 2.8 and 4.2 t ha^{-1}, respectively, of pure lime (100% of CCE) (Table 3).

$$\textbf{Liming rate} = \frac{\textbf{LR}(\textbf{calculted rate of pure lime})}{\textbf{CCE}\ (\textbf{local lime})} * \textbf{100} \qquad \textbf{Equation}\ [\textbf{8}]$$

Table 3: Rates of limes used in the study

Lime sources	**0.5 rate (1.4t ha^{-1})**	**Full rate (2.8t ha^{-1})**	**1.5 rate (4.2t ha^{-1})**
Agricultural lime	1.6	3.2	4.8
Musanze lime	2.1	4.2	6.3
Rusizi lime	1.6	3.2	4.8
Karongi lime	2	4	6.1

The local lime requirement rate (t ha^{-1}) depends on its quality in terms of CCE. Local lime with low CCE implies its higher quantity in reducing soil acidity compared to pure lime.

3.4 Field experiment

3.4.1 Field experimental design

A field experiment was set at Rwerere research station. The experimental design was a randomized complete block design (RCBD) with 13 treatments replicated thrice and randomized within block (Figure 3). The treatments comprised of three local limes from different districts (Musanze, Rusizi and Karongi) applied at three levels: 1.4, 2.8 and 4.2t ha^{-1}. Agricultural lime was included as a reference and a control with no lime application was also included in the treatments. Each experimental unit was 2.4 X 3 m in size (Figure 3).

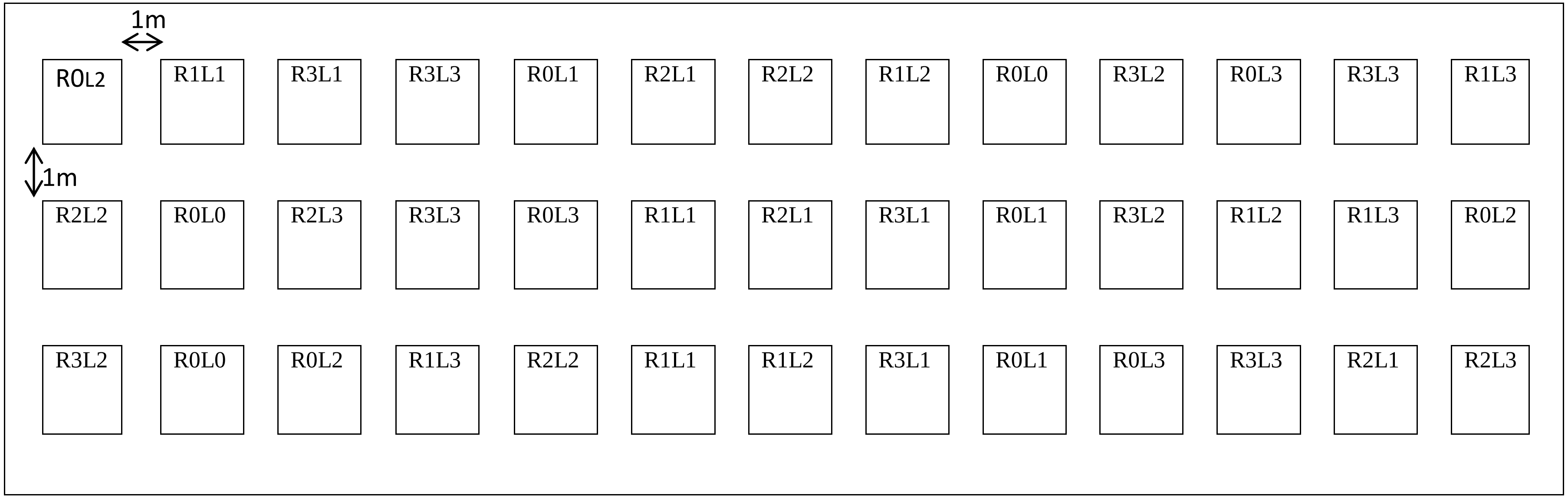


Figure 3: Field experimental layout at Rwerere research station

Legend:

R0L0: Control 0t ha^{-1} R0L1: Agricultural lime 1.4t ha^{-1} R1L1: Musanze lime 1.4t ha^{-1} R2L1: Karongi lime 1.4t ha^{-1}

R3L1: Rusizi lime 1.4t ha^{-1} R0L2: Agricultural lime 2.8t ha^{-1} R1L2: Musanze lime 2.8t ha^{-1} R2L2: Karongi lime 2.8t ha^{-1}
R3L2: Rusizi lime 2.8t ha^{-1} R0L3: Agricultural lime 4.2t ha^{-1} R1L3: Musanze lime 4.2t ha^{-1} R2L3: Karongi lime 4.2t ha^{-1}
R3L3: Rusizi lime 4.2t ha^{-1}

3.4.2 Field experiment management

The land was prepared using hand hoe (first and second ploughing) before lime application. Application of limes was done two weeks before planting by broadcasting method. Kirundo (Irish potato variety) was used in this study. Planting was done with an intra-row spacing of 0.3 m and inter-row spacing of 0.8 m. A blanket application of 300kg $NPK_{17\text{-}17\text{-}17}$ was done following the recommendation of Rwanda Agriculture Board (RAB).

3.5 Data collection

3.5.1 Agronomic data

Growth parameters and yields of Irish potato were determined in this experiment. The growth parameters included germination rate, plant height and number of plants per hole. The yield was determined by weighing total fresh tubers per plot and tubers calibration by potatoes calibrating equipment. Tubers' dry matter was determined by first sun drying for 4 days followed by oven drying at 75^{o}C until constant weight.

3.5.2 Soil sampling and analysis

Soil sampling was done before setting up the experiment and later at 6 weeks after lime application (WAP), 12 WAP and at harvest (16 WAP). Composite samples from 0 – 20 cm depth were taken using the zigzag method (Carter and Gregorich, 2008). The samples were air-dried and ground before analysis in the laboratory. The samples were analyzed for soil pH, soil organic C, total N, available P, Effective Cations Exchange Capacity (ECEC), exchangeable Al^{3+} and base saturation (Ca^{2+},

Mg^{2+}, K^{+} and Na^{+}). Soil moisture and soil texture were also determined. However, at 6 and 12 WAP, selected soil chemical properties; soil pH, exchangeable Al^{3+}, available P and exchangeable Ca were analysed.

Soil Organic C was analysed following Walkley and Black modified method (Piper, 1942). Total N was determined by Kjeldahl Method (Page *et al*., 1982). Available P was determined using Bray and Kurtz P-II method (Bray and Kurtz, 1945) where the readings were done by spectrophotometer at 660 nm of absorbance. ECEC was the sum of Ca^{2+}, Mg^{2+}, K^{+}, Na^{+} and Al^{3+} (Kamprath, 1970). The potassium chloride extraction method was used to determine Exchangeable Al (Page *et al*., 1982). The base cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) were determined by the extraction method using atomic absorption spectrophotometer for Ca and Mg and flame photometer for K and Na (IITA, 1979). The soil texture was determined using hydrometer method (Gee and Bauder, 1986). Soil moisture content was determined gravimetrically at 105^{o}C as described by Carter and Gregorich (2008).

3.5.3 Lime Efficiency (LE)

Soil pH, Al saturation and potato yield were determined to know the efficiency of local limes treatments in correcting soil pH, reducing Al saturation and increasing potato yield. The relative agronomic efficiency (RAE) and relative economic efficiency (REE) of the local limes were then calculated to determine more effective local lime relatively to agricultural lime. The LE, RAE and REE were calculated as the ratio (Mercy and Ezekiel, 2007) using equation 9.

$$\text{LE}(\%)\text{on pH} = \frac{\text{Soil pH (local lime)}}{\text{Soil pH (agri lime)}} * 100 \qquad \text{Equation [9]}$$

The relative economic efficiency (REE) of local limes also was analyzed in the same manner as agronomic efficiency:

$$\text{REE}(\%) = \frac{\text{Revenue (local lime)}}{\text{Revenue (agri lime)}} * 100 \qquad \text{Equation [10]}$$

3.6 Data management and statistical analysis

The data were subjected to Analysis of variance (ANOVA) using Genstat software 14th edition (Payne et al., 2011). To compare two means between treatments t-test was used. Means separation was performed using Turkey's test at 0.05 level of significance.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

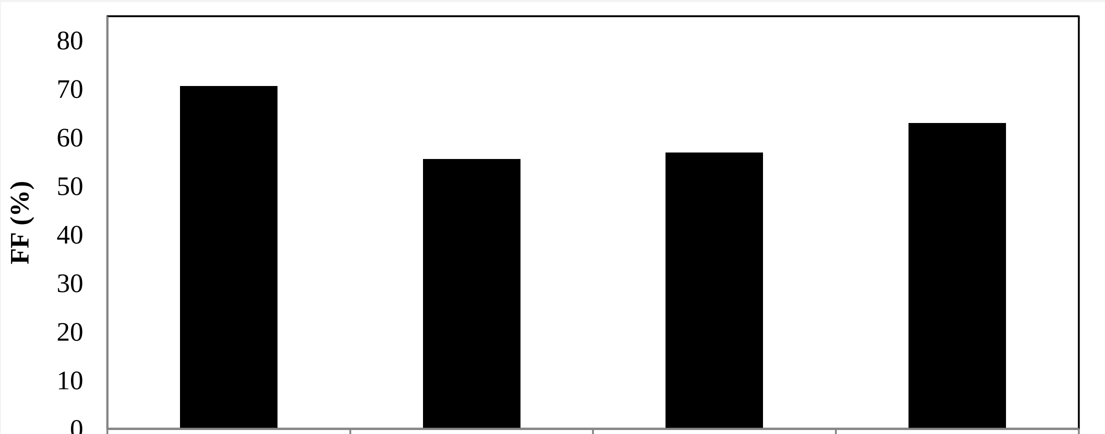
4.1 Overview

This chapter gives a detailed presentation and discussion of the results. The findings are presented thematically following the study objectives: physical and chemical properties of agricultural and local limes, effects of limes on soil nutrients and soil pH and lastly effects of limes on growth and yield of Irish potato.

4. 2 Physical and chemical properties of agricultural and local limes

4.2.1 Fineness factor (FF) of agricultural and local limes

The fineness factor, as one physical property determining lime quality, was significantly different (p=0.003) among lime types and ranged from 55.6 to 70.6 with SED 2.85. The agricultural lime was the finest compared to the three local limes. Within the local limes, Musanze lime was the finest (Figure 4).



	Agricultural lime	Rusizi local lime	Karongi local lime	Musanze local lime
FF	70.6	55.6	56.9	63

Figure 4: Fineness factor of liming materials

Musanze lime was also soft and easy to extract (not requiring very sharp equipment) thus its higher fineness compared to other local limes. Rusizi and Karongi limes had bigger (coarse) particle portions which reduced their efficiency factors (Table 4) and consequently affected their fineness factor.

Table 4: Particle (%) sizes of agricultural, Musanze, Rusizi and Karongi limes

Lime sources	**> 2 mm**	**2-0.2 mm**	**< 0.2 mm**
Agricultural lime	16	15.9	16.8
Musanze lime	25.8	11.2	13.9
Rusizi lime	14.6	5.6	25.5
Karongi lime	10.4	13.7	27
Efficiency factor	**0**	**0.5**	**1**

Efficiency factor of 0: Very less degradable, 0.5: Less degradable, 1: quick degradable

The highest fineness factor of agricultural lime compared to the three local 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.* (1958) who reported that, fineness through various treatments (calcination, crushing, sieving) of limestone, increases the solubility of limes. The amount of particle sizes and their efficiency factors affect fineness factor of limes which could compromise its effectiveness with time. Halvin *et al*. (2005) reported that the efficiency factor of one (for lime with smaller particles < 0.2mm) is an indication of high solubility (degradability) and efficiency of lime in changing soil properties. The results of fineness factor observed in this study were similar to those reported by Crawford *et al.* (2008). These authors reported the fineness factor of Rwandan local limes to vary between 28.4 and 97.7%. They further reported that the effectiveness of limes reduced when fineness was less than 60%. This implies that Rusizi and Karongi limes were below the recommended range by about 5%. The fineness factor observed in the agricultural lime indicates that it could be more effective in reducing soil acidity compared to other limes.

4.2.2 Selected chemical properties of liming materials

The results showed that, Ca content in the various limes were significantly different (p<0.001) (Table 5). Agricultural lime and Rusizi local had similar and higher amount of Ca while Karongi lime had the lowest. Mg amount was also significantly different among limes (p<0.001). Agricultural, Rusizi and Musanze limes had the same and lower amount of Mg while the highest was recorded in Karongi lime. The CCE of limes were significantly different (p=0.01) and ranged from 66.2% to 86.36% (Table 5). The agricultural lime and Rusizi lime had similar and higher CCE compared to Musanze and Karongi limes.

Table 5: Some chemical characteristics of liming materials

Lime sources	Ca	Mg	Ca + Mg	CCE	ECCE	Soluble $CaCO_3$
Agricultural lime	33.87	0.67	34.54	86.36	60.95	25.13
Rusizi lime	33.03	1.16	34.19	85.46	47.51	0.33
Karongi lime	16.9	10.49	27.39	68.48	39.1	0.1
Musanze lime	25.48	1	26.48	66.2	41.55	0.27
p Value	**<0.001**	**<0.001**	**0.01**	**0.01**	**0.001**	**<0.001**
LSD	**4.866**	**1.252**	**5.089**	**12.723**	**8.415**	**1.918**

LSD= Least significant differences of means (5% level)

The results showed that ECCE of limes were significantly different (p=0.001). Agricultural lime had the highest ECCE of 60.95 % compared to the three local limes. On the other hand, all local limes had similar ECCE. The amount of soluble $CaCO_3$ of limes were also significantly different (p<0.001) among the lime types. Agricultural lime had the highest amount of soluble $CaCO_3$ compared to the three local limes (Table 5).

The different Ca and Mg amount in limes could be attributed to inherent characteristic of rocks as described by Gillet and Brogniez (1991) and Beernaert (1999) who observed that Karongi lime are classified as dolomitic lime because of its high content of Mg. The CCE difference observed among limes could be attributed to the quantity of Ca and Mg content. Agricultural lime and Rusizi lime had equal and higher Ca quantity, which explained their highest CCE while Musanze and Karongi limes had comparatively equal Ca+Mg content, which were the lowest and hence the low CCE observed. The ranges of CCE in this study agree with the findings of Crawford *et al.,* (2008), who reported CCE of Rwandan travertine (local lime) to vary between 59.7 and 126% of CCE. Similarly, Beernaert (1999) reported CCE variation within and between mining sites of local limes in Rwanda. The quantity of Ca, Mg, impurities and treatments (burning) of limes have been reported by several authors (Verhaeghe, 1963; Munyangabe, 1993; Beernaert, 1999; Snyder and Leep, 2007; Crawford *et al.,* 2008) to be a major cause of CCE variation among limes.

The highest ECCE observed in agricultural lime could be attributed to its higher CCE and fineness factor compared to the three local limes. These results are corroborated by the findings of Peter *et al.* (2006) who reported that ECCE of lime is affected by its CCE and fineness factor. Also, Snyder and Leep, (2007) and Crawford *et al.* (2008) reported that the possible causes of limes' ECCE variation are their CCE, fineness factor and impurities. Results of studies of local limes done in Rwanda (Beernaert, 1999, Munyangabe, 1993, Verhaeghe, 1963) did not consider ECCE as one of elements of lime quality, which is important in estimating lime efficiency (Peter *et al.,* 2006). The effectiveness of lime could be explained either by its CCE or FF (Peter *et al.,* 2006). According to Crawford *et al.* (2008), ECCE <50% implies low effectiveness of limes. As per the observed ECCE, only agricultural lime had ECCE >50%, an indication that it could be the most effective than other limes.

The difference observed in solubility of $CaCO_3$ was probably due to the burning treatment of limestone for producing agricultural lime. Similarly, Millar *et al.* (1958) reported the loss of CO_2 of carbonate as gas and CaO remains as solid after burning limestone which enhances the solubility of agricultural lime.

4.2.3 pH_w, pH_{KCl} and moisture content of limes

The pH of limes was significantly different (p<0.001). Agricultural lime was more alkaline (pH_w = 12.5 and pH_{KCl} = 11.7) compared to the three local limes. Musanze and Karongi limes had relatively similar pH_w levels. Rusizi lime was the lowest in level of pH_w (Table 6). On the other hand, in terms of pH_{KCl}, Musanze lime had lowest level compared to other limes (Table 6).

Moisture content of the liming materials was significantly different (p=0.021). Agricultural lime had the highest moisture content. However, Karongi lime had the lowest moisture compared to other local limes (Table 6). This implies that agricultural lime could be quicker degradable compared to Karongi lime.

Table 6: pH_w, pH_{KCl} and Moisture (%) of limes

Lime sources	**pH_W**	**pH_{KCl}**	**Moisture**
Agricultural lime	12.5	11.7	32.5
Rusizi lime	7.9	7.1	23.5
Karongi lime	8.4	7.2	14.5
Musanze lime	8.7	6.9	18.5
P Value	<0.001	<0.001	0.021
LSD	0.709	0.0883	10.57

LSD= Least significant differences of means (5% level)

The high alkalinity of agricultural lime was possibly due to the calcination process (Millar *et al.,* 1958) which is known to reduce the impurities responsible for acidification (Snyder and Leep, 2007).

The highest moisture content of agricultural lime and lowest moisture content of Karongi could be attributed to their particle sizes because fine particles have higher ability to absorb humidity than the coarse ones. The results of limes' moisture content were within the range reported by Crawford *et al.* (2008), who found the moisture content of Rwandan limes to be in range of 0.3 to 32.5%.

4.3 Effects of limes on soil nutrients and soil pH

4.3.1 Initial soil properties

Results of soil properties before establishment of the experiment showed that the soil was highly acidic with pH_W of 4.8 and pH_{KCl} of 3.7 (Table 7). The soil also had exchangeable Al^{+3} of 2.8 cmol kg^{-1}, ECEC of 4.8 cmol kg^{-1} and 42.5% base saturation. The level of organic matter was 2.2%, while nitrogen and phosphorus were 0.11% and 3.63 mg kg^{-1}, respectively. According to USDA textural triangle (Appendix 3), soil texture was classified as loamy sand (Table 7).

Table 7: 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	2.2
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

Soil with such pH is classified as very acidic (Soil Survey Division Staff, 1993). The low available P could be explained by the low pH levels/acidity of the soils that leads to P fixation into unavailable forms (Nurlaeny *et al.*, 1996). The results implied that soil at the experimental site in this study had fertility problems and hence not suitable for crop production.

4.3.2 Effects of limes on soil pH_W

At 6 weeks after lime application (WAP), agricultural, Musanze and Rusizi limes applied at different rates increased soil pH_w by 0 to 0.18 units though insignificantly (p= 0.897 and LSD=0.202). Although at 12 WAP there was an increase of pHw, there was no significant difference among treatments. Karongi lime just like the control treatment had no noteworthy effect on the soil pH_w (Table 8). At 16 WAP, limes effects on soil pH_w was significantly different (p=0.004). Application of lime at the rate of 2.8 and 4.2 t ha^{-1} of agricultural, Rusizi and Musanze limes were not significantly different in increasing soil pH_w. The highest pH changes were recorded in plots that had Rusizi lime (increase of 0.86 units) and agricultural lime (increase of 0.84 units). The lime applied at the rate of 1.4 t ha^{-1} also affected soil pH_w; agricultural and Musanze lime had relatively similar effect while Rusizi and Karongi also had relatively similar effects in increasing soil pH_w (Table 8).

Table 8: Unit change of soil pH_w by limes at 6, 12 and 16 WAP

Treatments	**6 WAP**	**12 WAP**	**16 WAP**
Control (0 t ha^{-1})	-0.03	-0.04	-0.03
Agricultural lime 1.4t ha^{-1}	+0.1	+0.25	+0.44
Agricultural lime 2.8t ha^{-1}	+0.07	+0.41	+0.62
Agricultural lime 4.2t ha^{-1}	+0.15	+0.61	+0.84
Karongi lime 1.4t ha^{-1}	-0.02	+0.03	+0.08
Karongi lime 2.8t ha^{-1}	-0.02	+0.05	+0.14
Karongi lime 4.2t ha^{-1}	-0.02	+0.15	+0.26
Musanze lime 1.4t ha^{-1}	+0.04	+0.21	+0.43
Musanze lime 2.8t ha^{-1}	+0.15	+0.47	+0.62
Musanze lime 4.2t ha^{-1}	+0.09	+0.55	+0.72
Rusizi lime 1.4t ha^{-1}	+0.01	+0.27	+0.17
Rusizi lime 2.8t ha^{-1}	+0.13	+0.38	+0.55
Rusizi lime 4.2t ha^{-1}	+0.18	+0.62	+0.86
p value	0.897	0.326	0.004
LSD	0.202	0.267	0.212

LSD= Least significant differences of means (5% level)

The effects of agricultural, Rusizi and Musanze limes could be attributed to their quality, especially CCE and fineness factor (FF). The findings observed on soil pH_w changes in soil after liming are comparable to those found by Ruganzu (2009) who reported the increase of 0.7 to 0.8 units after application of travertine (local lime) combined with organic matter (*Tithonia diversifolia*). Kayitare (1997) reported an increase of 0.4 to 0.6 units of pH_w after travertine or lime application in Irish potato crop in Rwanda. Hartmann (1993) also reported an increase of 0.9 units of soil pH within the first season, and almost 0.1 units at each season up to 6 seasons following travertine combined with organic manure application in acidic soils of Rwanda.

Local limes generally showed higher lime effectiveness (LE) (Figure 5). Rusizi lime applied at 4.2 t ha^{-1} had 102.3% of LE, which means higher effectiveness than agricultural lime. Musanze lime applied at 2.8 t ha^{-1} had LE of 100% (Figure 5). This indicated that Musanze lime and agricultural lime had comparatively similar effectiveness. On the other hand, Karongi lime had the lowest LE when compared to the other local limes (Figure 5).

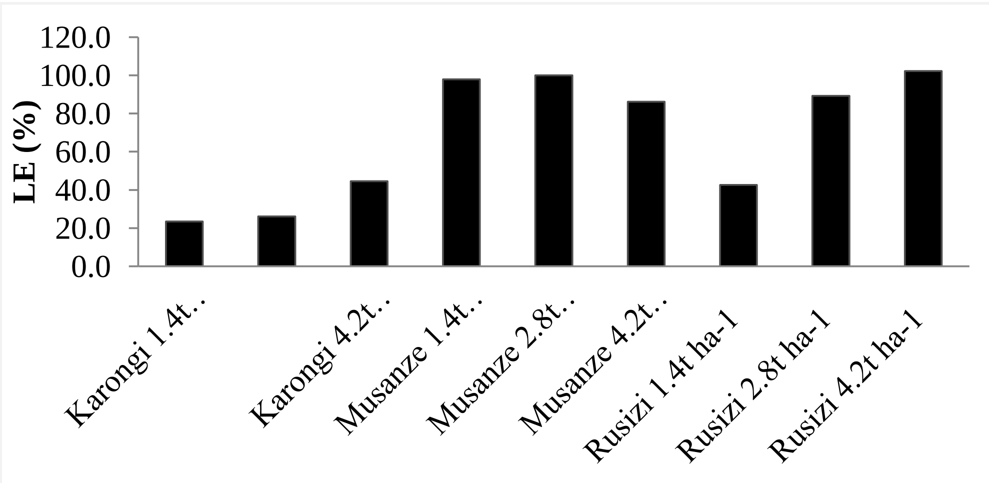


Figure 5: Effectiveness of local limes in increasing soil pH_w

(LE=100: Equal efficiency of local lime and agricultural lime; LE>100: More efficiency than agricultural lime; LE<100: Less efficiency than agricultural lime)

The low effectiveness of Karongi lime on soil pH_w could be attributed to its coarse particle sizes and compared to other limes. These results are in agreement with the findings of many studies on limes quality (Snyder and Leep, 2007; Beernaert, 1999; Conyers *et al.,* 1996) which reported hardness and coarse particles to reduce effectiveness of limes.

4.3.3 Effects of limes on soil pH_{KCl}

At the start of the experiment pH_{KCl} was 3.7 (Table 9). At 6 WAP, the lime types at different rates increased 0 to 0.55 units of pH_{KCl} though not significant (p=0.908) among interaction of limes and rates. However at 12 WAP, the limes applied at different rates significantly (p<0.001) increased soil pH_{KCl} up to 0.73 units. At 12 WAP, the highest (0.9 units) increase in pH_{KCl} was recorded in Rusizi lime applied at 4.2 t ha^{-1} while the lowest (0.38 units) was recorded in Karongi lime applied at the same rate. This indicates that Rusizi lime applied at 4.2 t ha^{-1} was the most effective in increasing pH_{KCl}. Also, at 16 WAP, the type of limes and their rates significantly affected soil pH_{KCl} (p<0.001) (Table 9). Lime application rate at 4.2 t ha^{-1} of agricultural, Rusizi and Musanze limes had similar effect in increasing soil pH_{KCl}. However, at the rate of 1.4 t ha^{-1}, all the liming materials had relatively similar effect on the soil pH (Table 9).

Table 9: Unit change in soil pH_{KCl} by limes at 6, 12 and 16 weeks after application

Treatments	**6 WAP**	**12 WAP**	**16 WAP**
Control (0 t ha^{-1})	+0.05	+0.03	+0.03
Agricultural lime 1.4t ha^{-1}	+0.45	+0.55	+0.58
Agricultural lime 2.8t ha^{-1}	+0.43	+0.63	+0.70
Agricultural lime 4.2t ha^{-1}	+0.55	+0.73	+0.93
Karongi lime 1.4t ha^{-1}	+0.21	+0.34	+0.38
Karongi lime 2.8t ha^{-1}	+0.27	+0.41	+0.45
Karongi lime 4.2t ha^{-1}	+0.37	+0.40	+0.46
Musanze lime 1.4t ha^{-1}	+0.38	+0.34	+0.55
Musanze lime 2.8t ha^{-1}	+0.50	+0.67	+0.72
Musanze lime 4.2t ha^{-1}	+0.46	+0.68	+0.82
Rusizi lime 1.4t ha^{-1}	+0.24	+0.49	+0.38
Rusizi lime 2.8t ha^{-1}	+0.44	+0.56	+0.62
Rusizi lime 4.2t ha^{-1}	+0.52	+0.71	+0.90
p value	0.908	<.001	<.001
LSD	0.296	0.3179	0.253

LSD= Least significant differences of means (5% level)

The highest increase of soil pH_{KCl} observed in Rusuzi lime could be explained by its calcium carbonate equivalent (CCE) which was the highest and comparable to CCE of agricultural lime. However, the highest increase in pH_{KCl} in agricultural lime applied at 4.2 t ha^{-1} observed at 16 WAP could be attributed to lime quality based on FF and CCE which were the high compared to other limes. The soil pH_{KCl} results observed in this study were in agreement with other research findings (Regina, 2010; Beernaert, 1999; Hartmann, 1993 and Kayitare, 1997).

4.3.4 Effects of different liming materials on exchangeable Aluminium

At the start of the experiment, the amount of exchangeable aluminium in the soil was 2.8 cmol kg^{-1} (Table 7, section 4.3.1). At 12 and 16 WAP, exchangeable aluminium increased in the control treatment. Application of lime decreased amounts of soil exchangeable Al (Table 10). The decrease varied significantly (p=0.001) among the types of lime and rate in the different sampling periods (Table 10). This implies that limes and rates affects soil exchangeable Al differently. At 12 WAP, the highest decrease in exchangeable Al was recorded in Rusizi lime treatment at 4.2 t ha^{-1}. At 16 WAP, agricultural, Rusizi and Musanze limes at 4.2 and 2.8 t ha^{-1} had relatively similar effects in reducing exchangeable Al (Table 10). After 16 WAP, lime rate of 1.4t ha^{-1}, both agricultural and Musanze limes had similar effect in reducing exchangeable Al and they reduced 2.16 and 2.06 cmol kg^{-1} of exchangeable Al respectively. In general, Karongi lime had the least effect in reducing soil acidity based on its low effect on exchangeable Al (Table 10).

Table 10: Exchangeable Al (cmol kg^{-1}) changes at 6, 12 and 16 WAP

Treatments	**6 WAP**	**12 WAP**	**16 WAP**
Control	-0.01	+0.04	+0.04
Agricultural lime 1.4 t ha^{-1}	-0.63	-1.85	-2.16
Agricultural lime 2.8 t ha^{-1}	-0.62	-1.96	-2.39
Agricultural lime 4.2 t ha^{-1}	-0.81	-2.22	-2.67
Karongi lime 1.4 t ha^{-1}	-0.46	-0.54	-1.08
Karongi lime 2.8 t ha^{-1}	-0.54	-0.49	-0.95
Karongi lime 4.2 t ha^{-1}	-0.42	-0.89	-1.6
Musanze lime 1.4 t ha^{-1}	-0.54	-0.99	-2.07
Musanze lime 2.8 t ha^{-1}	-0.76	-2.13	-2.42
Musanze lime 4.2 t ha^{-1}	-0.69	-2.17	-2.52
Rusizi lime 1.4 t ha^{-1}	-0.52	-1.18	-0.89
Rusizi lime 2.8 t ha^{-1}	-0.75	-1.91	-2.36
Rusizi lime 4.2 t ha^{-1}	-0.81	-2.32	-2.64
p value	<.001	<.001	<.001
LSD	0.412	1.259	1.00

LSD= Least significant differences of means (5% level)

The effectiveness of agricultural and Musanze limes in reducing exchangeable Al could be attributed to their fineness factor, which could have increased Ca quantity released in soil solution. On the other hand, the ability of Rusizi lime in reducing more exchangeable Al than Karongi could be explained by its high CCE. Studies reported that CCE combined with good fineness factor (>60%) is adequate for lime solubility and release of Ca and Mg in the soil solution, which in turn reduces the amount of exchangeable Al (Peter *et al.*, 2006; Snyder and Leep, 2007; Crawford *et al.*, 2008; Awkes, 2010). The effects observed on exchangeable Al are corroborated by the findings of Fox (1979) 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 (1983); Conyers *et al*., (2003) and Caires *et al*., (2008) have reported a decrease of exchangeable Al following liming of acidic soils.

Musanze lime applied at 2.8 t ha^{-1} had LE (in reducing exchangeable Al) of 101.2%, thus it was more effective than the other limes in reducing exchangeable Al in the soil (Figure 6).

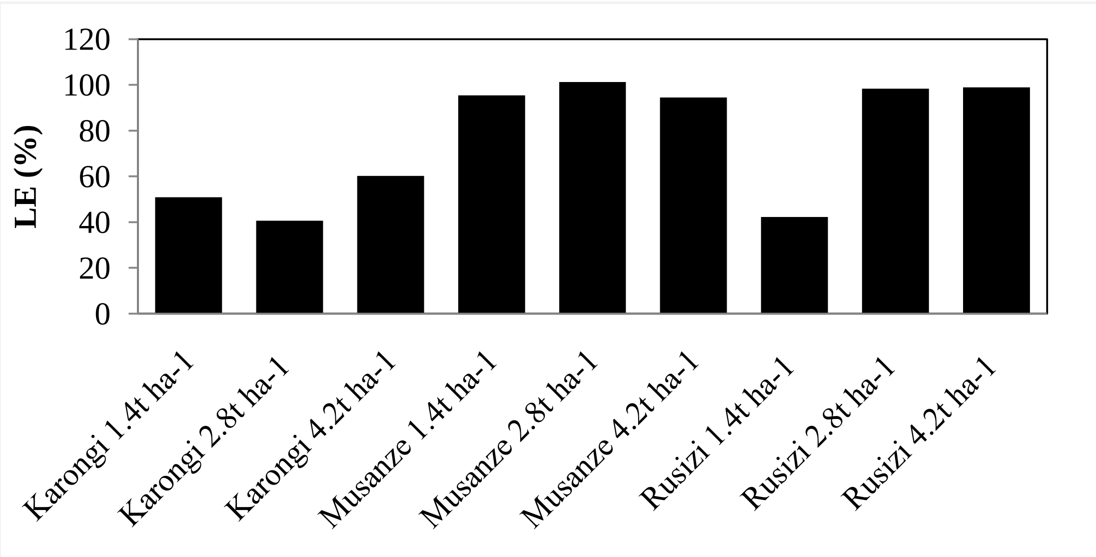


Figure 6: Effectiveness of local limes in reducing exchangeable Al

(LE=100: Equal efficiency of local lime and agricultural lime; LE>100: More efficiency than agricultural lime; LE<100: Less efficiency than agricultural lime)

The observation was attributed to its fineness factor. This was based on the observations reported by Crawford *et al.* (2008) that the effectiveness of lime is influenced by its fineness factor. Rusizi lime was more efficient in reducing exchangeable Al than Karongi lime (Figure 5) probably due to its quality, especially its CCE. Similarly, Snyder and Leep (2007) and Awkes (2010) reported the effectiveness of lime to be governed by its CCE and FF.

4.3.5 Effects of different liming materials on available phosphorous

At the beginning of the experiment, soil P was 3.6 mg kg^{-1} (Table 7, Section 4.3.1). Soil available P decreased in the control treatments, while application of all lime types increased soil available P at all sampling periods (Table 11). At 6 WAP, all lime types and rates were not significantly different (p=0.67) in increasing available phosphorus. However, at 12 and 16 WAP, the effects of limes on available phosphorus were significantly different (p<0.001). At 12 WAP, lime application increased soil available P with units ranging from 0.27 mg kg^{-1} in Karongi lime applied at the rate of 1.4 t ha^{-1} to 1.68 mg kg^{-1} in agricultural and Rusizi limes applied at 4.2 t ha^{-1}. At 12 WAP, the application of 4.2 t ha^{-1} of agricultural lime and Rusizi lime had similar effect while the application of 2.8 t ha^{-1} of agricultural lime and Musanze lime had similar effect. Notably, all liming materials applied at 1.4 t ha^{-1} had significantly different effect in increasing P (Table 10). This implies that any local limes in this study applied at low rate could replace agricultural lime.

Table 11: Changes in available P (mg kg^{-1}) as affected by limes at 6, 12 and 16 weeks after application

Treatments	**6 WAP**	**12 WAP**	**16 WAP**
Control (0 t ha^{-1})	-0.03	-0.20	-0.24
Agricultural lime 1.4t ha^{-1}	+0.57	+1.42	+1.58
Agricultural lime 2.8t ha^{-1}	+0.49	+1.59	+1.73
Agricultural lime 4.2t ha^{-1}	+0.94	+1.68	+2.12
Karongi lime 1.4t ha^{-1}	+0.04	+0.27	+0.34
Karongi lime 2.8t ha^{-1}	+0.19	+0.28	+0.51
Karongi lime 4.2t ha^{-1}	+0.15	+0.74	+0.81
Musanze lime 1.4t ha^{-1}	+0.42	+0.77	+1.12
Musanze lime 2.8t ha^{-1}	+1.16	+1.55	+1.71
Musanze lime 4.2t ha^{-1}	+0.42	+1.62	+1.85
Rusizi lime 1.4t ha^{-1}	+0.23	+0.81	+0.52
Rusizi lime 2.8t ha^{-1}	+0.94	+1.49	+1.65
Rusizi lime 4.2t ha^{-1}	+1.08	+1.68	+1.98
p value	0.67	<0.001	<0.001
LSD	0.96	1.06	0.87

LSD= Least significant differences of means (5% level)

Agricultural lime, Rusizi and Musanze limes were more effective than Karongi lime in increasing available P possibly because of their effects in raising soil pH and reducing exchangeable Al. Similarly, Fageria (1989b) 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.* (1996) reported 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. But the soil acidity correcting agents such as the use of local liming materials could reverse this situation and increase soil P to adequate levels. The range of available P increase recorded is in agreement with the findings of Clements and McGowen (1994) who reported an increase ranging from 0 to 8 mg kg^{-1} of Bray P in acidic loam sandy soils of New South Wales (USA). Ruganzu (2009) 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.

4.3.6 Effects of different liming materials on base saturation

The type of limes applied at different rates increased base saturation (%) significantly (p<0.001) compared to the control (Table 12). Base saturation increased significantly except in Rusizi applied at 1.4 t ha^{-1} and Karongi applied at 1.4 and 2.8 t ha^{-1}. The application of 4.2 t ha^{-1} of Rusizi and Musanze limes had the same level of significant effect in increasing base saturation. The application of 2.8 t ha^{-1} of Rusizi and agricultural limes also had comparatively similar significant effect. However, at lime application rate of 1.4 and 2.8 t ha^{-1} of Karongi and 1.4 t ha^{-1} of Rusizi limes, the effect did not significantly increase base saturation at 16 WAP (Table 12).

Table 12: Changes in base saturation (%) as affected by limes after 16 weeks of application

Treatments	**Baseline BS (%)**	**BS at 16 WAP**	**BS (%) increases**	**t-test**	**Significance**
Control (0 t ha^{-1})	41.55	42.09	+0.54	1.08	ns
Agricultural lime 1.4t ha^{-1}	41.55	83.04	+41.49	12.46	*
Agricultural lime 2.8t ha^{-1}	41.55	91.04	+49.49	83.25	**
Agricultural lime 4.2t ha^{-1}	41.55	96.9	+55.35	23.06	*
Karongi lime 1.4t ha^{-1}	41.55	68.94	+27.39	3.53	ns
Karongi lime 2.8t ha^{-1}	41.55	69.26	+27.71	4.15	ns
Karongi lime 4.2t ha^{-1}	41.55	78.81	+37.26	7.84	*
Musanze lime 1.4t ha^{-1}	41.55	81.29	+39.74	7.39	*
Musanze lime 2.8t ha^{-1}	41.55	90.49	+48.94	18.33	*
Musanze lime 4.2t ha^{-1}	41.55	93.17	+51.62	196.88	**
Rusizi lime 1.4t ha^{-1}	41.55	58.66	+17.11	1.6	ns
Rusizi lime 2.8t ha^{-1}	41.55	88.52	+46.97	65.84	**
Rusizi lime 4.2t ha^{-1}	41.55	96.11	+54.56	63.59	**

*Note: $t_{(2, 0.05)}$>4.0303= treatments are significantly different ;.ns: not significantly different; *: Significantly different at 0.05 level of significance; **:Significantly different at 0.01 level of significance*

The results of base saturation showed that all limes were able to increase base saturation significantly in the soil compared to the control. This implies that all limes brought base saturation to an adequate level in the soil. These findings are in agreements with those of Hazelton and Murphy (2007) who reported a saturation of >50% in soil to be adequate in soil. The observed effects of limes in increasing base saturation could be attributed to their ability to increase soil pH. The results are in agreement with the findings of Magdoff and Bartlett (1985) who reported pH values above 5.5 to induce approximately 100% of base saturation. Furthermore, Harelimana (1990), found an increase of 3 to 45% of base saturation after travertine (local lime) application in acidic soils of Rwanda. Hartmann (1993) applied 2 to 4 t ha^{-1} of lime and reported an increase of 69% of base saturation within one season in acidic soil of plateau central zone of Rwanda.

4.3.7 Effects of different liming materials on ECEC

At the start of the season, ECEC was 4.8 cmol kg^{-1}. The type of limes and rates affected effective cation exchange capacity (ECEC). The lime rates of 1.4 and 4.2 t ha^{-1} of agricultural lime affected ECEC negatively leading to a reduction by 1.042 and 0.855 cmol kg^{-1} of ECEC, respectively. Rusizi lime applied at rate of 2.8 t ha^{-1} also affected ECEC negatively (Table 13). However, the application of all lime rates for Musanze and Karongi limes did not significantly affect ECEC (Table 13).

Table 13: Effective Cations Exchanges Capacity (cmol kg^{-1}) affected by limes after 16 weeks after application

Treatments	**Baseline ECEC (%)**	**ECEC at 16 WAP**	**ECEC increase**	**t-test**	**Significance**
Control	4.835	4.8585	0.0235	0.2	ns
Agricultural lime 1.4t ha^{-1}	4.835	3.793	-1.042	-11.35	*
Agricultural lime 2.8t ha^{-1}	4.835	4.614	-0.221	-0.38	ns
Agricultural lime 4.2t ha^{-1}	4.835	3.98	-0.855	-4.55	*
Karongi lime 1.4t ha^{-1}	4.835	5.416	0.581	3.55	ns
Karongi lime 2.8t ha^{-1}	4.835	5.782	0.947	3.88	ns
Karongi lime 4.2t ha^{-1}	4.835	5.709	0.874	2.51	ns
Musanze lime 1.4t ha^{-1}	4.835	3.929	-0.906	-4.11	ns
Musanze lime 2.8t ha^{-1}	4.835	4.01	-0.825	-4	ns
Musanze lime 4.2t ha^{-1}	4.835	4.133	-0.702	-1.85	ns
Rusizi lime 1.4t ha^{-1}	4.835	4.44	-0.395	-1.2	ns
Rusizi lime 2.8t ha^{-1}	4.835	3.86	-0.975	-5.83	*
Rusizi lime 4.2t ha^{-1}	4.835	4.167	-0.668	-2.35	ns

*Note: $t_{(2, 0.05)}$>4.0303= treatments are significantly different ;.ns: not significantly different; *: Significantly different at 0.05 level of significance; **:Significantly different at 0.01 level of significance*

The negative effects of agricultural and Rusizi limes on ECEC could be attributed to their low Mg content and the ability of agricultural lime to affect soil properties within short period. This could cause cations imbalance in the soil as indicated by Hartmann (1993) who reported the possibility of agricultural lime to cause cations imbalance in acidic soil of central plateau zone of Rwanda. Beernaert (1999) reported that mixing dolomite and travertine could enhance cations balance in soil. Wambeke (1995) observed an inconsistency of ECEC in soil depending on the soil pH associated to high level of exchangeable aluminium and organic matter. This makes it difficult for lime to reduce or improve soil ECEC. Conversely, Akbulut and Arasan (2010) observed a decrease of ECEC by liming materials through reducing water absorption potential but Ruganzu (2009) andMathew and Rao (1997) reported increase of ECEC by liming. However, there are other factors to consider for improving ECEC such as: temperature, soil humus content, soil texture, status of the soil solution (Garrison, 1989) and pH value (Wambeke, 1995).

4.3.8 Effects of different liming materials on soil exchangeable cations saturation

At the end of the season, calcium saturation was significantly (*p* <0.001) affected by limes treatments. The treatments comprising of 4.2, 2.8 and 1.4 t ha^{-1} of agricultural lime, 4.2 and 2.8t ha^{-1} of Musanze and Rusizi limes had similar effects in increasing Ca saturation (Table 14). However, the lime rate of 1.4 t ha^{-1} of Musanze and Rusizi limes were significantly different. The application of 4.2 t ha^{-1} of agricultural, Rusizi limes and both application of 4.2 and 2.8 t ha^{-1} of Musanze lime were able to bring Ca saturation at adequate level in the soil, which is estimated at 65 to 85% by Hazelton and Murphy (2007). Mg saturation in the soil was also affected significantly (*p*<0.001) by limes. The highest Mg saturation was recorded in the plots with Karongi lime compared to the other limes (Table 14). This could be attributed to the high MgO content in the Karongi lime.

Despite a slight increase in K saturation, the effect of limes was not significantly different (*p*=0.463). However, the baseline amounts of K (2.64%) and the recorded values at 16 WAP were considered to be within the adequate range in the soil. This implies that the experimental soil had adequate K available for plant uptake. The effect of limes on Na saturation was not significantly different (*p*=0.278) (Table 14).

Aluminium saturation was significantly affected by limes (*p* <0.001). Application of 4.2 t ha^{-1} of agricultural and Rusizi limes had similar effects in reducing Al saturation

(Table 14). The lime rate of 2.8 t ha^{-1} of agricultural lime, Rusizi and Musanze limes had similar effects in reducing Al saturation. However, Karongi lime applied at all rates was the lowest in reducing Al saturation than other limes (Table 14). This could be attributed to its low quality in terms of CCE and fineness factor. Markedly, only application of 4.2 t ha^{-1} of agricultural lime and Rusizi lime were able to reduce Al saturation to 3.1 and 3.9%, respectively (Table 14).

Table 14: Exchangeable cations saturation (%) as affected by limes at the end of the season

Treatments	**Ca (%)**	**Mg (%)**	**K (%)**	**Na (%)**	**Al (%)**
Baseline	27.44	11.18	2.64	0.28	58.45
Control (0 t ha^{-1})	27.98	11.73	2.30	0.07	57.91
Agricultural lime 1.4t ha^{-1}	64.11	15.3	3.55	0.09	16.96
Agricultural lime 2.8t ha^{-1}	62.6	25.33	3.08	0.07	8.96
Agricultural lime 4.2t ha^{-1}	75.09	18.03	3.67	0.09	3.1
Karongi lime 1.4t ha^{-1}	35.04	31.11	2.71	0.07	31.06
Karongi lime 2.8t ha^{-1}	30.12	36.04	3.06	0.03	30.74
Karongi lime 4.2t ha^{-1}	34.21	36.87	7.66	0.07	21.19
Musanze lime 1.4t ha^{-1}	59.94	18.07	3.19	0.09	18.71
Musanze lime 2.8t ha^{-1}	68.34	18.81	3.24	1.00	9.51
Musanze lime 4.2t ha^{-1}	69.31	20.45	3.33	0.08	6.83
Rusizi lime 1.4t ha^{-1}	41.24	14.22	3.15	0.04	41.34
Rusizi lime 2.8t ha^{-1}	64.84	19.97	3.65	0.05	11.48
Rusizi lime 4.2t 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	11.5520	6.5684	3.2361	0.0430	14.58

LSD= Least significant differences of means (5% level)

According to Abbott (1989), this is within the adequate level of < 5%. The reduction of Al saturation recorded were in accordance with the findings of Ruganzu (2009) who reported 49% reduction of Al saturation after application of travertine in Rubona (Huye district) acidic soils.

The results of K saturation showed that experimental soil had adequate level of K saturation. This was in accordance with Abbott (1989) who considered a range of 1 to 5% amounts of K to be adequate for soil productivity. Just like K, the Na saturation results indicated that experimental soil had adeauqte levels. This is in agreement with Hazelton and Murphy (2007) who reported that adequate level of Na saturation in soil for better crops growth should range from 0 to 1% for Na.

The increase of Ca saturation in the plots with agricultural lime, Rusizi and Musanze limes could be attributed to the fact that calcite lime releases more Ca in soil solution than dolomitic lime as reported by Fageria and Stone (2004). On the other hand, Karongi lime, just like the control had no effects on Ca saturation (Table 14). This was attributed to the low amounts on Ca in the Karongi lime. The results showed an increase in Mg in Karongi lime. The observed Mg levels in Karongi limes were in agreement with the findings of Fageria and Stone (2004) who reported an increase of Mg content in acidic soils as result of liming. Beernaert (1999) also reported the increase of Mg in soil following application of dolomitic lime in acidic soil of Rwanda. This was attributed to the chemical composition of the Karongi limes which had high concentration of Mg cations.

4.3.9 Effects of different liming materials on soil total nitrogen

Soil total nitrogen slightly increased by limes application though insignificantly (p=0.441). All lime rates of agricultural and Musanze limes and 2.8 t ha^{-1} of Rusizi limes had relatively the same level of significant effect on soil total nitrogen. They increased 0.12 to 0.24% of total nitrogen in soil (Table 15). On the other hand, none of the lime rates of Karongi lime affected total nitrogen significantly (Table 15).

Table 15: Soil total nitrogen (%) as affected by limes at the end of the season (16 weeks after application)

Treatments	**Baseline Total N (%)**	**Total N (%) at 16 WAP**	**Total N (%) increases**	**t-test**	**Significance**
Control (0 t ha^{-1})	0.11	0.12	+0.01	2.55	ns
Agricultural lime 1.4t ha^{-1}	0.11	0.24	+0.12	5.29	*
Agricultural lime 2.8t ha^{-1}	0.11	0.35	+0.24	9.07	*
Agricultural lime 4.2t ha^{-1}	0.11	0.32	+0.21	8.91	*
Karongi lime 1.4t ha^{-1}	0.11	0.14	+0.02	0.97	ns
Karongi lime 2.8t ha^{-1}	0.11	0.14	+0.03	1.96	ns
Karongi lime 4.2t ha^{-1}	0.11	0.18	+0.06	2.63	ns
Musanze lime 1.4t ha^{-1}	0.11	0.29	+0.18	4.6	*
Musanze lime 2.8t ha^{-1}	0.11	0.33	+0.21	5.21	*
Musanze lime 4.2t ha^{-1}	0.11	0.29	+0.18	5.48	*
Rusizi lime 1.4t ha^{-1}	0.11	0.18	+0.07	1.16	ns
Rusizi lime 2.8t ha^{-1}	0.11	0.25	+0.14	4.36	*
Rusizi lime 4.2t ha^{-1}	0.11	0.20	+0.09	1.42	ns

*Note: $t_{(2, 0.05)}$>4.0303= treatments are significantly different ;.ns: not significantly different; *: Significantly different at 0.05 level of significance; **:Significantly different at 0.01 level of significance*

The increase of total nitrogen in some plots could be attributed to the decomposition of organic matter in the soil as a result of increased soil pH which favours soil microbial activities (Burgmann *et al.,* 2004). Bolan *et al*. (2003) reported the accumulation of organic matter in acidic soils which could be exploited by liming to release nutrients including nitrogen. Also, N transformation pathways such as nitrification can be affected by soil pH levels as observed by Alexander (1977) who reported that nitrification was completely null at soil pH below 4.5 and it gradually reduced at pH below 6.5.

4.3.10 Effect of different liming materials on organic carbon

Contrary to the other soil properties discussed earlier, lime types and rates did not significantly affect organic carbon in the soil (*p*=1.00). This could be attributed to the use of lime combined alone with 300kg $NPK_{17-17-17}$ compound fertilizer applied as blanket recommendation. In studies where increases of organic C is reported the authors applied organic materials. For instance, Ruganzu (2009) reported the increase of organic carbon when travertine was combined with organic materials. Mukuralinda (2007) also reported that better effects of liming are obtained when it is combined with organic manure.

4.4 Effects of different liming materials on growth and yield of Irish potato

4.4.1 Effect of different liming materials on number of potato plants

The type and rates of liming materials did not significantly affect (*p*=0.946) the number of Irish potatoes stems per hill. It is believed that the improvement of soil fertility by lime enhances crop productivity but in this study the number of potato stems per hill was not significantly different in the various treatments (Table 16).

Table 16: Effect of limes on number of potato stems per hill

Treatments	Number of stems per hill
Control (0 t ha^{-1})	4
Agricultural lime 1.4t ha^{-1}	3
Agricultural lime 2.8t ha^{-1}	3
Agricultural lime 4.2t ha^{-1}	3
Karongi lime 1.4t ha^{-1}	4
Karongi lime 2.8t ha^{-1}	5
Karongi lime 4.2t ha^{-1}	4
Musanze lime 1.4t ha^{-1}	4
Musanze lime 2.8t ha^{-1}	3
Musanze lime 4.2t ha^{-1}	3
Rusizi lime 1.4t ha^{-1}	4
Rusizi lime 2.8t ha^{-1}	3
Rusizi lime 4.2t ha^{-1}	3
***p* value**	**0.946**
LSD	**2.7**

LSD= Least significant differences of means (5% level)

Lack of significant difference observed in plots with different limes could be attributed to the fact that Irish potato stems per hill are influenced by the health and number of eyes of potato seeds (Personal communication with Mr. Ntizo Senkesha potato scientist at RAB). The potato seed was from RAB and was of good quality. This implies that all plots had similar numbers of potato stems.

4.4.2 Effect of different liming materials on sizes (mm) of potato tuber

Size of potato tubers were significantly affected by the type of lime and their application rates ($p<0.001$). Agricultural lime had the highest effect on potato tuber sizes and yielded bigger tubers compared to the three local limes. Remarkably, amongst the three local limes, Musanze lime was the best compared to the other local limes (Table 17). The lime rates of 4.2 and 2.8 t ha^{-1} of agricultural and Musanze limes had relatively similar effects on potato tuber sizes. However, the application rate of 1.4 t ha^{-1} of Rusizi, Karongi limes and control treatments had similar tuber size (Table 17).

Table 17: Effects of limes on size (mm) of potato tuber

Treatments	**Size of potato tuber (mm)**
Control(0 t ha^{-1})	36.12
Agricultural lime 1.4t ha^{-1}	45.17
Agricultural lime 2.8t ha^{-1}	55.5
Agricultural lime 4.2t ha^{-1}	56.83
Karongi lime 1.4t ha^{-1}	39.5
Karongi lime 2.8t ha^{-1}	43.17
Karongi lime 4.2t ha^{-1}	43.17
Musanze lime 1.4t ha^{-1}	42.5
Musanze lime 2.8t ha^{-1}	51.83
Musanze lime 4.2t ha^{-1}	53
Rusizi lime 1.4t ha^{-1}	40.33
Rusizi lime 2.8t ha^{-1}	47.83
Rusizi lime 4.2t ha^{-1}	50.17
***p* value**	**<0.001**
LSD	**5.565**

LSD= Least significant differences of means (5% level)

The observed difference in potato tuber size in plots with agricultural, Rusizi and Musanze limes could be attributed to their quality especially CCE and or fineness factor and their effect on soil pH levels. The bigger potato tubers in agricultural lime, Musanze and Rusizi limes plots could relate to the increase of available P and the reduction of exchangeable Al recorded in those plots.

4.4.3 Effects of different liming materials on fresh potato tuber yields

The type of lime applied and rates significantly (p=0.01) affected potato weight (Table 18). Musanze lime had the highest fresh potato tubers weight of 24.9 t ha^{-1} which was recorded in the plots with lime rate of 4.2 t ha^{-1}. It was followed by agricultural lime, then Rusizi and lastly Karongi limes. Notably, agricultural lime, Musanze and Rusizi limes applied at lime rate of 2.8 t ha^{-1} had relatively similar effects. However, the lowest weight was obtained in the control plots (Table 18).

Table 18: Effects of limes on fresh potato tubers yield

Treatments	**Fresh potato tuber yield (t ha^{-1})**
Control(0 t ha^{-1})	14.30
Agricultural lime 1.4t ha^{-1}	18.88
Agricultural lime 2.8t ha^{-1}	22.47
Agricultural lime 4.2t ha^{-1}	24.82
Karongi lime 1.4t ha^{-1}	17.88
Karongi lime 2.8t ha^{-1}	19.62
Karongi lime 4.2t ha^{-1}	19.23
Musanze lime 1.4t ha^{-1}	19.63
Musanze lime 2.8t ha^{-1}	22.15
Musanze lime 4.2t ha^{-1}	24.9
Rusizi lime 1.4t ha^{-1}	18.06
Rusizi lime 2.8t ha^{-1}	21.08
Rusizi lime 4.2t ha^{-1}	21.85
***p* value**	**<0.001**
LSD	**3.28**

LSD= Least significant differences of means (5% level)

The high yield obtained in plots that were limed was probably due to the positive effects of liming on soil properties. Liming improved overall soil properties: soil pH increased from 4.8 to 5.6, exchangeable Al reduced from 2.8 to 0.2 cmol kg^{-1}, available P increased from 3.6 to 5.7 mg kg^{-1} and total nitrogen increased from 0.11 to 0.35 cmol kg^{-1}. When little amount of lime or local lime were applied in acidic soils, it resulted to the changes in soil pH and other nutrients (Beernaert, 1999) which can affect potato production positively. These findings are in agreement with Harelimana (1990) who reported that local limes can be effective in increasing Irish potato yield in southern acidic soils of Rwanda. Kayitare (1997) also reported an increase in Irish potato yields and also reduced soil acidity after application of travertine or lime to acidic soils of Rwanda. The observation in plots with lime application rate of 4.2 and 2.8 t ha^{-1} were in agreements with the findings of

Habyarimana (1989) who reported 2 and 4 t ha^{-1} to induce similar effects on potato production.

4.4.4 Effects of different liming materials on potato tubers dry matter

Effect of different types of lime and application rates on potato tuber dry matter yield differed significantly among the treatments ($p<0.001$) (Table 19). The highest dry matter content (20.33 to 20.6%) was obtained in potato tubers harvested in control plots while the lowest dry matter content (16.9%) was recorded in potato tubers from plots with agricultural lime and Musanze lime. This could be attributed to the differential loss of water content in big and small size potato when are dried. It is an indication that when fresh yield increased, the water content in potato also increased and could reduce dry matter. The application of 4.2 and 2.8 t ha^{-1} had similar effect on potato tubers dry matter. The plots that yielded the highest quantity of fresh tubers had the lowest quantity of potato dry matter (Table 19).

Table 19: Effects of limes on potato tubers dry matter (%)

Treatments	**Potato tubers dry matter (%)**
Control(0 t ha^{-1})	20.69
Agricultural lime 1.4t ha^{-1}	19.67
Agricultural lime 2.8t ha^{-1}	18.13
Agricultural lime 4.2t ha^{-1}	16.93
Karongi lime 1.4t ha^{-1}	20.27
Karongi lime 2.8t ha^{-1}	19.17
Karongi lime 4.2t ha^{-1}	19.43
Musanze lime 1.4t ha^{-1}	18.57
Musanze lime 2.8t ha^{-1}	18.07
Musanze lime 4.2t ha^{-1}	16.9
Rusizi lime 1.4t ha^{-1}	20.37
Rusizi lime 2.8t ha^{-1}	19.2a
Rusizi lime 4.2t ha^{-1}	18.57
***p* value**	**0.001**
LSD	**2.332**

LSD= Least significant differences of means (5% level)

These findings are in agreement with the findings of Yamoah *et al.* (1992) who reported positive effects of liming on soil properties and increase in crop yield in Buberuka acidic soils, which consequently affected dry matter negatively. However, Khan *et al.* (2004) reported an increase of potato dry matter in plots treated with lime in acidic soils of Pakistan.

4.4.5 Relative Agronomic Efficiency (RAE %) of local limes on fresh potato tuber yield

The local limes were different in their RAE. Musanze lime applied at 1.4 t ha^{-1} had the highest RAE (113.04 %) compared to application of the other local lime (Table 20). Application of 4.2 t ha^{-1} of Musanze lime had RAE (100%), which means it had the same effectiveness as the agricultural lime. On the other hand, Rusizi lime had higher RAE compared to Karongi lime (Table 20).

Table 20: Relative agronomic efficiency (RAE %) of local limes on fresh potato tubers yields

Lime rates	**Karongi lime**	**Musanze lime**	**Rusizi lime**
Control (0 t ha^{-1})	-	-	-
1.4t ha^{-1} (1/2 rate)	80.43	113.04	82.61
2.8t ha^{-1} (full rate)	65.85	95.12	82.93
4.2t ha^{-1} (1.5 rate)	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

The high RAE of Musanze lime compared to the other local limes could be attributed to its fineness factors, ECCE and moisture content. However, agricultural lime compared to local limes was reported to abruptly affect soil properties and bring cations imbalance in soils which could affect the overall crop production (Beernaert, 1999).

4.4.6 Relative Economical efficiency (REE %) of local limes on fresh potato tuber yields

The local limes economically increased potato productivity (Appendix 4). Musanze lime was more economically effective than other local limes (Table 21). At lime application rate of 1.4, 2.8 and 4.2 t ha^{-1} of Musanze lime had the higher economic efficiency of121.81, 100.67 and 107.7%, respectively. However, the lowest economical efficiency (37.85%) was recorded for Karongi lime applied at 4.2 t ha^{-1}.

Table 21: Relative economic efficiency (%) of local limes on potato production

Lime rates	**Karongi lime**	**Musanze lime**	**Rusizi lime**
Control (0 t ha^{-1})	-	-	-
1.4t ha^{-1} (1/2 rate)	76.67	121.81	82.14
2.8t ha^{-1} (full rate)	60.45	100.67	82.44
4.2t ha^{-1} (1.5 rate)	37.85	107.7	69.59

RAE=100: Equal efficiency of local lime and agricultural lime; RAE> 100: More efficiency than agricultural lime; RAE<100: Less efficiency than agricultural lime

The highest economic efficiency observed in Musanze lime could be attributed to its low transport cost compared to the other limes. Musanze lime deposit is located near the experimental site while the other local lime deposits are far away from it. This implies the high transport cost of Rusizi and Karongi limes and hence reduces their economical efficiency. The results on economic efficiency of local limes were in agreement with Harelimana (1990) who suggested exploring the nearest lime deposits and applying 2 t ha^{-1} as economical lime rate in acidic soils of Rwanda. The results of this study were also supported by the findings of Fageria and Baligar (2008) who reported high cost of lime in most developing countries to cause low economic efficiency which consequently cause their minimal use and thus compromising on soil fertility and crop production. Coventry *et al.* (1989) also reported local liming materials to be applied in bulk and engage high transport cost which constrain their use by poor farmers.

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The results of selected physical and chemical properties of local and agricultural limes indicated that liming materials were of different quality. A high CCE was recorded in agricultural and Rusizi limes (86.36 % and 85.46%, respectively). This indicates that the two liming materials are comparable. Karongi and Musanze lime had lower CCE (68.48 and 66.2%, respectively). In terms of FF, agricultural and Musanze limes were higher (70.57 and 63.03%, respectively) compared to the other two limes. This could be an indication of their higher effectiveness in improving soil properties compared to the other limes.

The results of the effects of agricultural and local limes on selected soil nutrients and soil pH showed that all plots receiving lime recorded an increase in soil pH. However, lime rate of 2.8 t ha^{-1} of Musanze and agricultural limes had similar effects on soil pH. On the other hand, rate of 4.2 t ha^{-1} of Rusizi lime had a higher LE (102.3%) than Musanze and agricultural limes. Karongi lime applied at all rates was the lowest in changing soil pH.

Exchangeable Al was affected by the type of lime and rates of application. Lime application rate of 4.2 t ha^{-1} of agricultural, Rusizi and Musanze limes reduced 2.67, 2.64 and 2.52 cmol kg^{-1}, respectively while the rate of 2.8 t ha^{-1} of agricultural, Rusizi and Musanze limes exchangeable Al reduced by 2.39, 2.35, 2.42 cmol kg^{-1}, respectively. These meant that 4.2 and 2.8 t ha^{-1} had similar effects in reducing exchangeable Al. The effectiveness of Musanze lime at the rate of 2.8 t ha^{-1} had the highest LE (100.8%) among all the limes, making it the best in reducing exchangeable Al. Karongi lime had the least effect in reducing exchangeable Al. Available P was also positively affected by limes and their rates. Agricultural lime applied at a rate of 4.2 t ha^{-1} had the highest effect (2.12 mg kg^{-1}) compared to other limes. At a rate of 2.8 t $ha^{-1}$of agricultural, Musanze and Rusizi limes increased soil available P by 47, 46.5 and 45.8% (an increase of 1.72, 1.71 and 1.65 mg kg^{-1}), respectively. Markedly, all application rates of Karongi lime had the lowest effects on available Phosphorous.

The ECEC was also affected by limes and rates. Agricultural lime applied at rates of 1.4 and 4.2 t ha^{-1}, significantly affected ECEC negatively and reduced ECEC to 1.042 and 0.855 cmol kg^{-1}, respectively. Rusizi lime applied at rate of 2.8 t ha^{-1} also affected ECEC negatively and reduced 0.975 cmol kg^{-1}. On the other hand, Karongi lime slightly increased ECEC from 0.581 to 0.947 cmol kg^{-1}.

Agricultural lime and Musanze lime applied at rates of 2.8 and 1.4 t ha^{-1} significantly affected total nitrogen. At a rate of 2.8 t ha^{-1}, agricultural, Musanze and Rusizi limes increased 0.24%, 0.21% and 0.14 % of total nitrogen, respectively. Notably, all lime rates of Karongi lime were the lowest in increasing total nitrogen.

The results of the effects of agricultural lime and local limes on growth and yield of Irish potato showed that Musanze lime was agronomically effective than other local limes. At a rate of 1.4 t ha^{-1} Musanze lime had 113.04% RAE, an indication of

13.03% increase in potato yield. At the rate of 4.2 t ha^{-1}, agricultural and Musanze limes had similar RAE (100%). Economically, at the rate of 1.4, 2.8 and 4.2 t ha^{-1}, Musanze lime had the higher economic efficiencies (121.81, 100.67 and 107.7% respectively), which makes it an economically efficient hence a better lime than other limes.

5.2 Recommendations

Based on the findings the following recommendations were derived:

- Musanze local lime is recommended at the rate of 2 t ha^{-1} to effectively increase the soil pH to the levels conducive for optimal potato production by farmers.
- Should the government or non-governmental organizations decide to invest in local limes production, a grinding to at least to >60% of fineness factor should be considered in order to increase their efficiency. Also, the transport cost of the local limes is another limiting factor in their usage.

5.3 Areas of further research

Based on the findings, there is need to further analyse economic efficiency, residual and synergetic effects with other soil amendments and fertilizers such as manure, compost, mineral fertilizers, cover crops among other options, with the local limes. There is also a need for identification and quantifications/estimation of the total quantity of all local limes available in Rwanda.

REFERENCES

Abbott, T. (1989). *BCRI Soil testing method and interpretation*. Rydalmere: NSW agriculture and Fisheries.

Adams, F. (1984). *Soil acidity and liming, crop response on soil in tropics.* Wisconsin, USA.

Akbulut, S and Arasan, S. (2010). Variation of cation exchange capacity, pH and Zeta potential in expansive soils treated by additives. *International journal of civil and structural engineering, Volume 1*, 139-154.

Alexander, M. (1977). *In"Introduction to soil microbiology"* (second ed.). New york: Wiley.

Awad,A.S., Edwards, D.G. and Milhan, P.J. (1976). Effect of pH on soluble soil aluminium and on growth and composition of Kikuyu grass. *Journal of plant and soil sciences 45*, 531-542.

Awkes, M. M. (2009). *Comparison of calcium ameliorants and coal ash in alleviating the effects of subsoil acidity on maize root development near Middelburg, Mpumalanga.* Stellenbosch, South Africa: Faculty of Agrisciences, Stellenbosch University.

Baligar,V. C and Fageria, N. K. (1999). Plant nutrient effeciency. *Towards the second paradigm. In" Soil fertility, soil biology and plant nutrition interrelationships"* (pp. 183-204). Lavras: Brazilian soc. soil sci and university of Lavras.

Beernaert, F. (1999). *Feasibility study of production of lime and or ground travertine for manegement of acidic soils in Rwanda.* Brussels: Pro-Inter Project Consultants.

Bell, L. C. and Bessho, T. (1993). Assessment of aluminium detoxification by organic materials in ultisol using soil solution characterization and plant response. In K. Mulongoy, & R. Merckx, *Soil organic matter dynamics and sustainability of tropical agriculture* (pp. 317-330). Wiley-Sayce co-publication.

Berga, L., Siriri, D. and Ebanyat, P. (2001). Effect of soil amendments on bacterial wilt incidence and yield of potatoes in southernwestern Uganda. *African crop science journal 9*, 267-278.

Black, A. (1992). *Soil fertility evaluation and control.* London: Lewis Publisher.

Bolan, N. S and Hedley, M. J. (2003). Role of carbon, nitrogen and sulfur cycles in soil acidification. In D. Marcel, *In"Handbook of soil acidity"* (pp. 29-56). New York: Rengel. Z.

Brady, N. C and Weil, R. R. (2002). *The nature and properties of soils* (13 ed.). New Jersey: Prentice Hall.

Bray, R. H. and Kurtz, L. T. (1945). Determination of total organic and available forms of phosphorus in soils. *Soil Science*, 39-45.

Brett, U., Fenton, G. and Conyers, M. (2005). *Soil acidity and liming* (3 ed.). Wales: State of new South wales.

Budianta, D. and Vanderdeelen, J. (1995). Dynamics of exchaneable aluminium in ultisol. *International conference on soil resources and sustainable agriculture.* Kuala Lumpur, Malaysia.

Burgmann, H., Windmer, F. , Von Singler, W. and Zeyer, J. (2004). New molecular screening tools for analysis of free-living diazotrophs in soil. *Appl. Environ. Microbiol*, 240-247.

Caires, E. F., Pereira, P. R. S., Zardo, R. and Feldhaus, I. C. (2008). Soil acidicty and aluminium toxicity as affected by surface liming and cover oat residues under no-till system. *Soil Use Manage*, 302-309.

Carson, C. D., and Dixon, J. B. (1979). Acidity. In R. W. Finkl, *The Encyclopedia of Soil Science* (pp. 1-3). Pennsylvania.: Hutchinson & Ross Inc.

Carter, M. R and Gregorich, E. G. (2008). *Soil sampling and methods of analysis* (2 ed.). Taylor and Francis group.

Caudle, N. (1991). *Managing soil acidity.* North Caroline: North Carolina State University.

CIIT. (2006). *Energy Baseline for the UNEP-GEF Pilot Project on reducing the vulnerability of the energy sector to the impacts of climate change in Rwanda.* Manitoba, Canada: International Institute for Sustainable Development.

Clark, R. (1984). Physiological aspects of calcium and magnbesium and molybdenum deficiencies in plants. In F. Adams, *Soil acidicty and liming* (pp. 99-170). Madison: Wisconsin.

Clements, B. and McGrowen, I. (1994). *Strategic fertilizer use on pastures.* Orange, NSW: NSW agriculture.

Clough, T. J., Kelliher, F. M., Sherlockand, R. R. and Ford, C. D. (2004). Lime and soil moisture effect on nitrous oxide emissions from urine patch. *Soil sci. Soc. Am.J*, 1600-1609.

Cochrane.,T. T., Salinas, J. G and Sanchez, P. A. (1980). An equation for liming acid mineral soil to compensate for crop aluminium tolerance. *Trop Agric*, 133-140.

Conyers, M. K., Heenan D. P., McGhie, W. J. and Polie, G. P. (2003). Amelioration of acidity with time by limestone under contrasting tillage. *Soil tillage Res*, 85-94.

Conyers, M. K., Scott, B. , Fisher, R. and Lill, W. (1996). Predicting the field preformance of twelve commercial liming materials from southern Austraria. *J. Fert. Res*, 151-161.

Coventry, D. R, Walker, B. R., Morrison, G. R., Hyland, M. T., Averz, J. C., Maden, J. L and Bartram, D. C. (1989). Yield response to lime of wheat and barley on acidic soils in north-eastern Victoria. *Aust. J. Exp. Agric*, 209-214.

Crawford, T. W., Singh, U. and Breman, H. (2008). *Solving agricultural problems related to soil acidity in central Africa's great lakes region.* Alabama: International center for soil fertility and agriculture development.

Cregan, D. D., Hirth, J. R. and Conyers, M. K. (1989). Amelioration of soil acidity by liming and other amendemnts. In A. Robson, *Soil acidity and plant growth* (pp. 206-264). Sydney: Academic press.

David, W., Adrian, C. and Carl, W. (2011). *Soil pH.* Colorado, USA: Colorado State University.

Fageria, N. (1989b). Effect of phosphorus on growth, yield and nutrient accumulation in the common bean. *Trop. Agric*, 249-255.

Fageria, N. (2001a). Effect of liming on upland rice, common bean, corn and soybean production in cerrado soil. *Pesq. Agropec. Bras*, 1419-1424.

Fageria, N. K, Baligar, V. C. (2008). Ameliorating Soil Acidity of Tropical Oxisols by Liming For Sustainable Crop Production. In E. Inc, & D. L. SPARKS (Ed.), *Advances in Agronomy* (Vol. 99, pp. 345-389). Brazil: Academic Press.

Fageria, N. K and Stone L. F. (2004). Yield of common bean in no-tillage system with application of lime and zinc. *Pesq. Agropec. Braas*, 73-78.

Fageria, N. K. and Baligar V. C. (2004). *Ameliorating soil acidity of tropical oxisols by liming for sustainable crop production* (Vol. 99). (L. Donald, Ed.) Elsevier Inc. Academic press.

Fageria, N. K., Baligar, V.C. and Edwards, D. G. (1990). Soil plant nutrient relationship at low pH stress. In B. V. Duncan, *Crops as enhancers of nutrient use* (pp. 475-507). California: Academic press.

FAOSTAT. (2008). *World potato*. Retrieved from Africa and international year of potato: www.potato2008.0rg/en/world/index.html

Folscher, W. J., Barnard, R. O. , Bornaman, J. J. and Van Vuuren, J. A. J. (1986). Growth of wheat with heavy lime application. *Trop. agric*, 133-136.

Foth, H. D and Ellis, B. G. (1996). *Soil fertility* (2 ed.). Boca: Lewis Publishers.

Fox, R. H. (1979). Soil pH, aluminium saturation and corn grain yield. *Soil science*, 330-335.

Franzel, S., Paul, K.B., Yates, B. and Voth, D. E. (1985). *Preliminary diagnostic survey of five communes of Ruhengeri Prefecture, Rwanda.* Fayetteville,Arkansas, USA: University of Arkansas.

Garrison, S. (1989). *The chemistry of soils.* Oxford, UK: Oxford university press.

Gavalk., R., Horneck, D., Millar, O. and Kotuby, J. (2003). *Soil, Plant and water reference methods for western region* (2 ed.). Oregon: Oregon state University.

Gee, G.W. and Bauder. (1986). Particle size analysis. In A. Klute, & A. Klute (Ed.), *Methods of soil analysis part 1* (2 ed., pp. 383-412). Madison, Wisconsin: Soil sciince of America.

Giller, Y. and Brogniez, D. (1991). *Reference document on fertilizer and calcite amendment in scope of policy definition of agriculture inputs in Rwanda.* Kigali, Rwanda: Ministry of Agriculture.

Goossens, F. (2002). *Potato marketing in Rwanda.* Montgomery: Abt associates Inc.

Habyarimana, E. (1989). *Effects of limes on irish potato grown in acidic soils of high altitude of Gikongoro.* Butare, Rwanda: National university of Rwanda.

Hakim, N., Agustian, Syafriman and Soepardi, G. (1989). Effect of lime, fertilizers and crop residues on yield and nutrient uptake of upland rice, soybean and maize in intercropping system. In J. Heide, *Nutrient management for food crop production in tropical farming system* (pp. 349-360). The Netherlands: Wangenigen University.

Hardy, D. H., Raper, C. D. and Miner, G. S . (1990). Chemical restrictions of root in ultisol subsoils lessened by longterm management. *Soil Sci. Soc. Am. J,* 1657-1660.

Harelimana, B. (1990). *Comparative study of burned lime and travertin application in acidic soils of high altitude of Gikongoro.* Butare, Rwanda: National University of Rwanda.

Hartmann, M. (1993). *Possibilities and limits of boron improvement to the degraded soils by liming and application of colcanic ash in Rwanda.* Mainz, Germany: Geographical Intitute of J.Gutenberg University.

Havlin, J. L., Beaton, J. D., Tisdale, S. L and Nelson, W. L. (2005). *Soil fertility and fertilizers: An introduction to nutrient managemnt* (7 ed.). New Jersey: Pearson prentice hall.

Haynes, R. J. (1984). Lime and phosphate in the soil–plant system. *Adv. Agron*, 249–315.

Haynes, R. J. and Ludecke, T. E. (1981). Effect of lime and phosphorus application on concentration of available nutrients and on P, Al, Mn uptake by 2 pasture legumes in acidic soil. *Plant soil*, 117-128.

Hazelton, P. A. and Murphy, B. W. (2007). *Interpreting soil test results: What do all numbers mean?* Collingwood, Australia: CSIRO Publishing.

Hesse, J. (1971). *A textbook of soil chemical analysis.* London: John Murray.

Hester, J. B. (1936). Results from lime experiment with potatoes for 1936. *Am. Pot. J*, 39-40.

Huang, J., Fisher, P. R, and Argo, W. R. (2007). HortScience. *American Society for*, 1268-1273.

IITA. (1979). *Selected methods for soil and plant analysis.* Ibadan, Nigeria: IITA manual services.

Kaitibie, S., Epplin, F. M. , Krenzer, E. G. and Zhang, H. (2002). Economics of lime and phosphorus application for dual purpose winter wheat production in low pH soils. *Agron.J*, 1139-1145.

Kamprath, E. (1970). Exchangeable Al as criterion for liming leached minal soils. *Soil Sci. Soc. Amer*, 252-254.

Kanzikwera, C.R.,Tenywa J.S. ,Osiru D.S. , Adipala E. and Bhagsari A.S. (2001). Interactive effect on nitrogen and potassium on flowering and berry set in true potato seed mother plants. *African Crop Sciences Journal*, 109-125.

Kariuki, S. K., Zhang, H. , Schroder, J.L. , Edwards, J.E., Payton, M. ,Carver, B.F. ,Raun, W.R. and Krenzer, E.G. (2007). Hard red winter wheat cultivar responses to a pH and aluminium concentration gradient. *Agron. J*, 88-98.

Kayitare, L. (1989). *Potential increase of yield and economic utilization of mineral fertilizers in Rwanda.* Kigali, Rwanda: MINAGRI.

Kayonga, J. and Goud, B. (1989). Experiment for soil fertility improvement in crete Zaire-Nil. In MINAGRI, *Soil fertility improvement trials in Crete Zaire-Nil* (pp. 131-144). Kigali, Rwanda: MINAGRI.

Kemperl, J. and Maček, J. (2009). Precipitation of calcium carbonate from hydrated lime of variable reactivity, granulation and optical properties. *International journal for mineral processing*, 84-85.

Khandakhar, S. M. A. T, Rahman, M. M. , Uddin, M. J., Khan, S. A. K. U. and Quddus, K.G. (2004). Effect of lime and potassium on potato yield in acidic soil. *Pakistan Journal of Biological sciences*, 380-383.

Kiiya, W. W., Mwoga, S.W. , Obura, R.K. and Musandu, A.O. (2006). Soil acidity ameriolation as a method of sheep sorrel (rumex acetosella) weed management in Potato (solanum tuberosum L.) in cool highlands of the north Rift, Kenya. *KARI Biannual scientific conference.* Nairobi: KARI.

Kiraly, Z. (1976). Plant disease resistance as influenced by biochemical effects on nutrients in fertilizers. *fertiliezer use and plant health* (pp. 33-46). Bern, swetzerland: International Potash Intitute.

Larry, O. (2000). *Agricultural limestone neutralizing value, Plant and soil sciences.* Mississippi, USA: Mississippi State University.

Magdoff, F. R and Bartlett, R. J. (1985). Soil pH buffering revisited. *Soil Sci.Soc. Am. J*, 145-148.

Maheshwari, D. (2006). *Soil acidity.* Sandip patil: Department of Landscape architecture , CEPT University.

Marcus, M. A. (2009). *Fertilizers, Agronomic handbook.* Virginia, USA: Virgina Tech University.

Marschaner, H. (1995). *Mineral Nutrition of higher plants* (2 ed.). New York: Academic Press.

Mathew, P. K and Rao, S. N. (1997). Effect of lime on cation exchange capacity of maritina clay. *Journal of Geotechnical and geoenvironmental engineering*, 183-185.

McBride, M. B. (1994). *Environmental chemistry of soils.* New York: Oxford University Press.

McCauley, A., Jones, C. and Jacobsen, J. (2009). *Soil pH and organic matter, nutrinets managements module 8,.* Bozeman, USA: Montana State University.

McFarland, M. L. (2001). *Managing soil acidity.* Texas: Texas agricultural experiment station.

Mercy, O. A and Ezekiel, A. A. (2007). Lime effectiveness of some fertilizers in tropical acid alfisol. *Journal of cental European agriculture, 8*, 17-24.

Millar, C. E., Turk, L.M. and Forth, H.D. (1958). *Fundamentals of soils sciences.* New York, USA: John Wiley& Sons.

MMCF(MINIPLAN, MINAGRI, CCE, FAO). (1993). *Report on national policy of agricultural inputs mission.* Kigali, Rwanda: Government printer.

Mukuralinda, A. (2007). *Influence of phosphorus resources on soil phosphorus dymaincs and crop productivity in Rwanda.* Kampala, Uganda: Makerere University.

Munyengabe, J. (1993). *Qualitative study of travertin deposits in Rwanda on productivity effects of acid soils.* Butare, Rwanda: National University of Rwanda, Agriculture Faculty.

Myers, J. A. (1988). Reductions in exchangeable Magnesium with liming acidic Ohio soils. *Soil Sci. Soc. Am. J*, 131-136.

Nabahungu, L. N. (2003). *Effects of limestone, Minjingu phosphate rock and green manure application on iimprovement of acidic soils in Tonga, Burate, Rwanda.* Morogoro, Tanzania: Sokoine University.

Naidu, R., Syers, J. K., Tillman, R. W. and Kirkman, J. H. (1990). Effect of liming and added phosphate on charge characteristics of acid soils. *Soil Sci. J,* 157-164.

NISR. (2009). *National census.* Kigali, Rwanda: National Statistical office of Rwanda.

Nurlaeny, N., Marschner, H. and George, E. (1996). Effects of liming and mycorrhizal colonization on soil phosphate depletion and phosphate uptake by maize (Zea Mays L.) and soybean (Glycine max L.) grown in two tropical acid soils. *Plant Soil*, 275-285.

Oates, K. M and Kamprath, E. J. (1983b). Soil acidity and liming: I Effect of the extracting solution cation and pH on the removal of aluminium from acid soils. *Soil Sci. Soc. Am. J*, 686-689.

Oates, K. M and Kamprath, E. J. (1983b). Soil acidity and liming. II. Evaluation using aluminium extracted by various chloride salts for detrmining lime requirements. *Soil Sci. Soc. Am. J*, 680-692.

Page, J. R., Miller, R. H., Keeney, D.R., Baker, D.E., Ellis, J. R and Rhoades, J.D. (1982). *Methods of soil analysis. II Chemical and microbiology properties* (2 ed.). Wisconsin, USA: Madison.

Peter, C., Quiline, K. and Hunter, M. (2006). *Liming materials.* USA: Nutrients Managements Spear program, Cornell University.

Piper, C. S. (1942). *Soil and plant analysis.* New York, USA: Int. Sci. Publ, Inc.

Payne, R.W., Harding, S. A., Murray, D. A., Soutar, D. M., Baird, D. B., Glaser, A. I., Welham, S. J., Gilmour, A. R., Thompson, R., Webster, R. (2011). *The guide to Genstat release 14, Part 2: Statistics*. VSN International, Hemel Hempstead, UK.

Regina, R and Regina, S. (2010). The influence of liming and organic fertilization on the changes of some agrochemical indicators and their relationship with crop weed incidence. *Agric Journal*, 3-14.

Rosemary, L. (1991). *Vegetable crops.* New York, USA: Department of plant pathology, Cornell University.

Ruganzu, V. (2009). *Potential of improvement of acid soils fertility by incorporation of natural fresh plant biomass combined with travertine in Rwanda.* Gembloux, Belgique: Agricultural University.

Rurangwa, E. (2013). Land tenure reform. The case study of Rwanda. Land Divided: Land and South African Society in 2013, in comparative perspective. University of Cape Town, Cape Town, South Africa.

Sanchez, P. (1976). *Properties and management of soils in tropics.* New York, USA: Wiley-Interscience.

Scott, B. J., Conyers, M. K., Fisher, R.and Lil, W. (1992). Particle size determines the effeciency of calcitic limestone in amending acidic soil. *Austraria journal od Agricultural Research*, 1175-1185.

Scott, B. J., Fisher, J. A. and Cullins, B. R. (2001). Alluminium torelance and lime increase wheat yield on the acidic soils of central and southern. *Aust. J. Exp. Agric*, 523-532.

SOFRECO. (2001). *Evaluation and classification of travertines deposits.* Kigali, Rwanda: Ministry of Industries and tourism

Soil Science of America. (1997). *Glossary of soil science terms.* Madison, USA: soil science society of America.

Soil Survey Division Staff. (1993). *Soil survey manual. US Dept. of agriculture handbook.* Washington, DC: US Govert. printing office.

Sparks, D. L. (2003). *Environmental soil chemistry* (2 ed.). California, USA: Academic press.

Stephen, P. C., Caroline, H. O. , Angel, J. , Carlo, L. and Julia, M. C. (2011). Diversity and activity of free-living nitrogen -fixing bacteria and total bacteria in organic and conventionally managed soils. *Appl. Environ. Microbiol*.

Stevens, R. J., Laughlin, R. L. and Malone, J. P. (1998). Soil pH affects process reducing nitrate to nitrous oxide and Di-nitrogen. *Soil Biol. Biochem*, 1119-1126.

Synder, C. S and Leep, R. H. (2007). Fertilization forages. *Science of grassland agriculture*, 355-379.

Tisdale, S. L., Nelson, W. L. , Beaton, J. D. and Havlin, J. L. (1993). *Soil acidity and basicity* (5 ed.). New York: Macmillan Publishing.

Treder, W and Cieslinski, G. (2005). Effect of silicon application on cadminium uptake and distributiion in starwberry plants grown on contaminated soils. *J. Plant nutr.*, 917-929.

Uchida, R and Hue, N. V. (2000). Soil acidity and liming. In S. J, & U. R, *Plant nutrient management in Hawaii soils, approaches for tropical and subtropical agriculture.* Manoa, Hawaii: College of tropical agriculture and human resources, University of Hawaii.

Van Straaten, P. (2002). *Rocks for crops: Agrominerals of sub-saharan Africa.* Nairobi, Kenya: ICRAF.

Verhaeghe, M. (1963). *Inventory of deposit of limestone, dolomite and travertine in Kivu, Rwanda and Burundi.* Ruhengeri, Rwanda: Ministry of agriculture and economic affairs, Geology service.

Wambeke, V. A. (1995). *Sols des tropiques- Proprietes et appreciation.* Wageningen, Pay-Bas: CTA.

Wouters, J. (1989). *Rapport des synthèses. Maitien et amélioration de la fertilité des sols du Burundi par la valorisatiSummary report of soil fertility conservation and improvement in Burundi through local.* Bujumbura, Burundi.: Faculty of Agriculture, University of Burund.

Zeller V., Perimenis, A., Giersdorf, J., Müller-Langer, F., Thrän, D., Valens, M. and Sievers, J. (2011). *The potential of sustainable liquid biofuel production in Rwanda: A study on the agricultural, technical and economic conditions and food security*. GIZ, Eschborn, Germany. p. 142.

Yamoah, C. F., Burleigh, J. R., Regas, J. L. and Mukaruziga, C. (1992). Correction of acid infertility in Rwandan oxisols with lime from an indigenous source for sustainable cropping. *Exploratory agriculture*, 417-424.

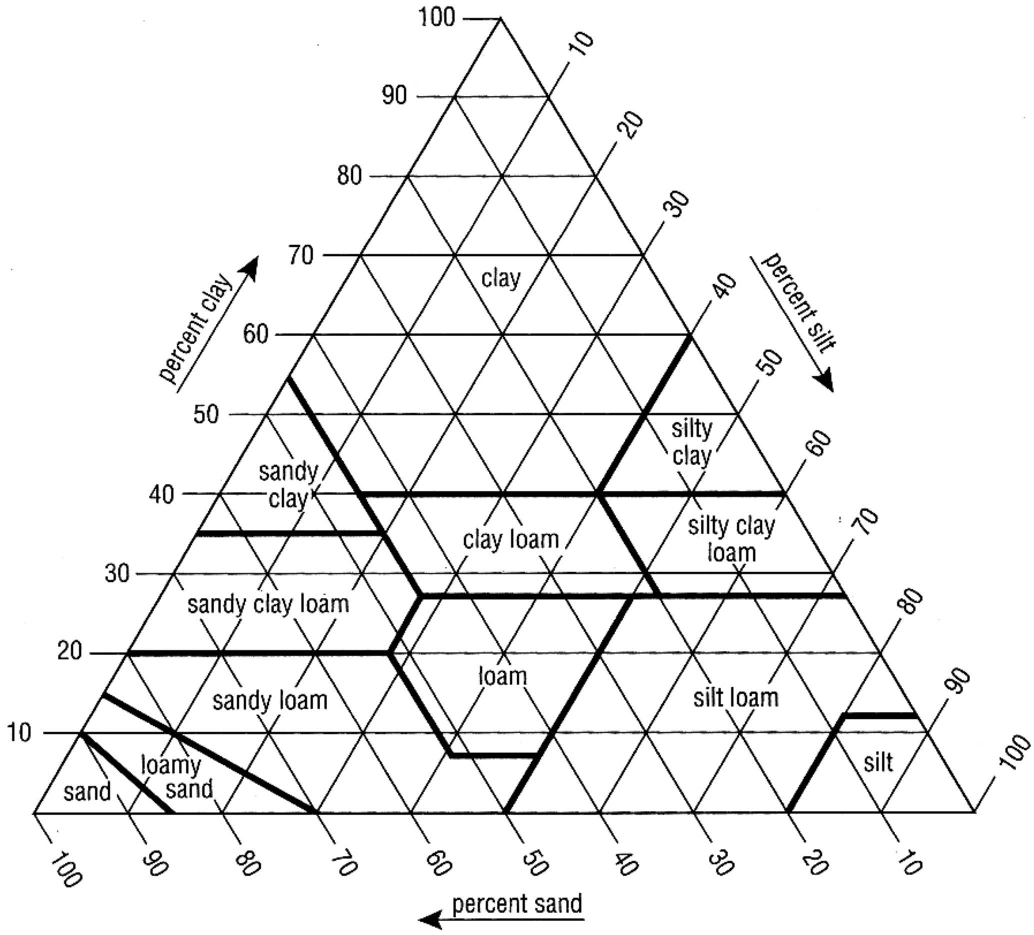
Yamoah, C., Burleigh, J. R. and Malcolm, M. R. (1990). Application of expert systems to the study of acid soils in Rwanda. *Agriculture, Ecosystems and Environment*, 203-218.

Yamoah, C., Ngong Ngueguin, M. C and Dias, D. K. W. (1996). reduction of P fertilizer requirement using lime and mucuna on high P-sorption soil of NW Cameroon. *African Crop Science Journal, 4,* 441-451.

APPENDICES

Appendice 1: colour of liming materials used in this study

Appendice 2:USDA textural class triangle



Appendice 3: Calculation of relative economic efficiency of local limes

Treatments	**Yield**	**Gross revenue**	**Transport cost kg^{-1}**	**Lime Cost kg^{-1}**	**Lime total cost**	**Total transport cost**	**Revenue**	**RAE**
Controls(0 t ha^{-1})	14.3	1,716,000	-	-	-	-	1,716,000	-
Agricultural lime 1.4t ha^{-1}	18.9	2,268,000	16	36	50,400	22,400	2,195,200	-
Agricultural lime 2.8t ha^{-1}	22.5	2,700,000	16	36	100,800	44,800	2,554,400	-
Agricultural lime 4.2t ha^{-1}	24.8	2,976,000	16	36	151,200	67,200	2,757,600	-
Karongi lime 1.4t ha^{-1}	17.9	2,148,000	28	6	11,400	53,200	2,083,400	76.67
Karongi lime 2.8t ha^{-1}	19.6	2,352,000	28	6	22,800	106,400	2,222,800	60.45
Karongi lime 4.2t ha^{-1}	19.2	2,304,000	28	6	34,200	159,600	2,110,200	37.85
Musanze lime 1.4t ha^{-1}	19.6	2,352,000	16	10	20,000	32,000	2,300,000	121.9
Musanze lime 2.8t ha^{-1}	22.2	2,664,000	16	10	40,000	64,000	2,560,000	100.7
Musanze lime 4.2t ha^{-1}	24.9	2,988,000	16	10	60,000	96,000	2,832,000	107.1
Rusizi lime 1.4t ha^{-1}	18.1	2,172,000	32	8	11,200	51,200	2,109,600	82.14
Rusizi lime 2.8t ha^{-1}	21.1	2,532,000	32	8	22,400	102,400	2,407,200	82.44
Rusizi lime 4.2t ha^{-1}	21.9	2,628,000	32	8	33,600	153,600	2,440,800	69.59

Price of 1kg (potato) =120 Rwfs

Exchange rate: 1USD = 650 Rwfs