EVALUATION OF LIME IN AMELIORATING SOIL ACIDITY FOR IMPROVED YIELDS OF INTERCROPPED SUGARCANE AND SOYBEAN IN WESTERN KENYA

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EXTENDED ABSTRACT

Farmers in Western Kenya contribute significantly to the Kenyan economy through food and cash crop production such as sugarcane. However, the acidic nature of the soil reduces the yields due to soil fertility problems. Acidity is further accelerated by the long term sugarcane monoculture and long term use of acidifying fertilizers. Cropping systems such as intercropped sugarcane referred to crop diversification is currently advocated and practiced by smallholder farmers. The productivity of this system is under threat due to the soil fertility problems associated with acidity. Liming offers the opportunity to ameliorate soil acidity, increase nutrient availability, nutrients content and yields of intercropped sugarcane. However, liming costs are prohibitive due to the large quantities required, coupled with the lime broadcast method of application. Various lime placement methods, including lime rates and nitrogen rates under sugarcane monoculture and soybean intercropped were investigated. The overall objective was to determine the best lime placement method for ameliorating soil acidity, increase soil nutrient availability, nutrients content by sugarcane and yields. The findings are presented in three chapters. Chapter two findings were on the effects of cropping systems (intercropped sugarcane with soybean; monoculture sugarcane), lime placement methods [broadcasted, shallow banded (0 – 15 cm) and deep banded (15 – 30 cm)] and lime rates (0, 1 and 2 t ha^{-1}) on soil pH, soil nutrient and sugarcane nutrient content. Lime rate at 2 t ha^{-1} significantly ($P \leq 0.05$) increased soil pH from 5.5 to 6.4 in water. Increased lime rate led to decreased levels of manganese from 203 to 172 mg kg^{-1} and iron from 147 to 129 mg kg^{-1}. Lime deep banded to 15 – 30 cm soil depth increased soil pH to the highest level of 6.20 and highest available phosphorus to 23.91 mg kg^{-1}. Intercropping system (IC) led to a lower soil pH level (5.94) but higher soil organic carbon (1.41 %) as compared to monoculture system which led to a higher soil pH (6.20) and lower soil organic carbon (1.21 %). Intercropped sugarcane (IC) led to higher content of sugarcane leaf calcium (0.44 %) and Mn (76.96 mg kg^{-1}) compared to sugarcane monoculture which recorded 0.38 % sugarcane leaf Ca and 64.93 mg kg^{-1} sugarcane leaf Mn. Broadcasted lime led to high content of sugarcane leaf nitrogen (0.47 %) and phosphorus (0.08 %). Lime shallow banded led to highest content of sugarcane leaf Ca (0.44 %) and Zinc (17.93 mg kg^{-1}). To reduce soil acidity for acidic Cambisols of Kibos in Kisumu, lime rate at 2 t ha^{-1} is recommended. Also lime broadcasting (L-BC) is preferred to ameliorate acidity at 0 – 15 cm depth while banded lime shallow and banded lime deep are preferred to reduce sub soil acidity. It was found that that, use of lime placement methods depends on the soil acidity stratification with depth which therefore needs further investigation. Chapter three presents results on the effects of cropping systems, lime placement methods and lime rates on sugarcane yields and quality. Intercropped sugarcane led to higher sugarcane yields (136 TCH) than the monoculture sugarcane (133 TCH). No significant effect was observed for ratoon crop harvest. Shallow banded lime gave the highest sugarcane quality of 15.09 pol % cane and 13.83 commercial cane sugar (CCS) while lime broadcasted gave the least at 14.59 pol % cane and 13.29 CCS. There was significant ($P \leq 0.05$) reduction of yield and quality (pol % and brix % juice) from plant crop to ratoon crop cycle both under sugarcane monoculture and also intercropped sugarcane. Under monoculture, sugarcane yield was reduced from 133 TCH in plant crop to 116.6 TCH in ratoon crop. Pol % juice was reduced from 19.47 % in plant crop harvest to 17.57 % in ratoon one harvest. It was found that, liming plays a limited role on the direct effect on sugarcane yield, but a significant and direct role on amelioration of acidity and nutrient transformations. Liming should therefore be integrated with other cropping and nutrient management strategies for increased yields. Results in chapter four were on the effects of lime placement methods, lime rates and nitrogen rates (0, 50 and 100 kg N ha^{-1}) on soil pH, soil nutrient availability, leaf nutrient content, yield and quality of sugarcane. Lime rates significantly affected soil pH at both 0 – 15 cm and 15 – 30 cm depths. Lime rate at 2 t ha^{-1} led to the highest soil pH of 6.34 and 5.23 for 0 – 15 cm soil depth and 15 – 30 cm soil depth respectively. Lime placement methods (LPM) and nitrogen rates (NR) did not affect soil acidity. Some soil chemical properties, specifically, soil available Ca, Mn and Zn and also soil organic carbon were significantly ($P \leq 0.05$) affected by the lime rates but not the lime placement methods. Lime rate at 2 t ha^{-1} led to highest soil available Ca at 23.74 cmol (+) kg^{-1} but least soil extractable Mn (178 mg kg^{-1}), Zn (1.44 mg kg^{-1}) and soil OC (1.30 %). Lime placement methods affected content of sugarcane leaf K, Ca, Mn and Zn. Lime shallow banded led to the highest sugarcane leaf K (0.57 %), leaf Ca (0.68 %), leaf Mn (60 mg kg^{-1}) and leaf Zn (18.4 mg kg^{-1}). Lime rate at 2 t ha^{-1} using the broadcasting placement method or lime shallow banding (0 – 15 cm depth) is recommended for Cambisols of Kibos, Kisumu County, Kenya. It is further recommended that routine soil and plant analysis be carried out for judicious soil and crop management.

DECLARATION

I, JACOB OMONDI OMOLLO, do hereby declare to the Senate of Sokoine University of Agriculture that the work that is reported in this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any institution.

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DEDICATION

To God Almighty, my Lord Ebenezer. To my late Mother Teresia Omolo, your support is immeasurable and incomparable. To my spouse Leah Nanjala, your love keeps me going. To our daughter, Shammah and son Juan, the reason to work and share the fruits of my labour.

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LIST OF ACRONYMS AND ABBREVIATIONS

Al	Aluminium
Al^{3+}	Aluminium ion
BC	Broadcasted
Ca	Calcium
Ca^{2+}	Calcium ion
$CaCO_3$	Calcium carbonate
CaO	Calcium Oxide
Cane	Sugarcane
CEC	Cation Exchange Capacity
cm	Centimeter
cmol (+)	centimole (+)
CO_2	Carbon dioxide
CS	Cropping systems
Cu	Copper
DB	Deep banded
DTPA	Diethylenetriaminepentaacetic acid
et al	and others
Fe	Iron
g	gram
H^+	Hydrogen ion
H_2O	water
H_2SO_4	Sulphuric acid
ha	hectare
HCl	Hydrochloric acid
IC	Intercropped Cane

K	Potassium
KALRO	Kenya Agricultural and Livestock Research Organization
KESREF	Kenya Sugar Research Foundation
$K_2Cr_2O_7$	Potassium dichromate
KCl	Potassium chloride
kg	kilogram
l	litre
L	Lime
LPM	Lime placement methods
L-BC	Lime broadcasted
L-SB	Lime shallow banded
L-DB	Lime deep banded
LR	Lime rates
M	Molarity
m^2	meter square
MC	Monocropping
me	milliequivalent
Mg	Magnesium
mg	milligram
ml	millilitre
mls	millilitres
mm	millimeter
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Na	Sodium
$Na_4P_2O_7$	Sodium Hexametaphosphate

NaOH	Sodium hydroxide
NH_4	Ammonium
NH_4AC	Ammonium acetate
NR	Nitrogen rates
^oC	Degrees centigrade
^oE	Degrees East
OH^-	Hydroxyl ion
^oS	Degrees south
$P = 0.05$	Probability level of 0.05
P	Phosphorus
P_2O_2	Phosphorus Pentaoxide
pH	Measure of acidity
ppm	Parts per million
SB	Shallow banded
SRI	Sugar Research Institute
SUA	Sokoine University of Agriculture
t	tonne
TCH	Tonnes Cane per Hectare
TSP	Triple superphosphate
Vol.	Volume
Zn	Zinc

CHAPTER ONE

1.0 INTRODUCTION

1.1 Sugarcane Production in Kenya

Sugarcane is an economic important crop in Kenya. Sugarcane is the primary raw material for processing into sugar and co – products, hence key to the Kenyan sugar industry. The industry ensures food security, improves livelihoods and provides sustainable livelihoods for millions of Kenyans, mostly to the small scale sugarcane growers (KESREF, 2009). There are currently over 200 000 farmers involved in sugarcane production in the country.

Sugarcane is commonly cultivated in the western part of Kenya, namely in the counties of Kisumu, Nandi, Kakamega, Bungoma, Homabay, Transmara and Migori. Cultivation is done on the nucleus and out – growers' lands which are managed by sugar milling factories and contracted farmers, respectively. Catchment area for sugarcane production and processing is based on the sugar miller zone and also the regional geographical location. For example, Nyando sugar zone boasts of four sugar milling factories, namely Kibos, Chemelil, Muhoroni, and Soin. The various sugarcane production areas in Kenya have varied climatic and biophysical (soils and land topography) conditions which influence sugarcane performance. These conditions have been broadly categorised as agro-ecological zones (AEZ's) as studied by Jaetzold *et al*. (1982; 2007) in the farm management handbook of Kenya.

Mature sugarcane is harvested and supplied to the respective sugar miller factory for processing into sugar and by – products. Therefore, the yield of sugarcane as tonnes per hectare is critical to production. In addition, the quality of the sugarcane is paramount to processing so as to get high sugar content per sugarcane processed. In each sugar miller factory zone or geographical sugar zone, the bulk of the sugarcane is produced by the out - grower farmers. Sugarcane cultivation is undertaken by the miller companies in their land, referred to as nucleus, and also by the small, medium and large scale farmers in their land referred to as out - growers. The sugarcane contributed by the miller companies is about 10 % while 90 % is from the out - grower farmers (Wawire *et al.*, 2006).

1.1.1 Sugarcane yield trends

Sugarcane production in Kenya has witnessed a declining trend. According to Jamoza *et al.* (2013), the average cane yield was 64 t ha^{-1} against the potential of at least 100 t ha^{-1} under rain-fed conditions in Kenya. Most farmers still apply old technologies on their farms. Sugarcane yield potential in the zone is 100 tonnes cane per hectare under rain fed conditions and 120 tonnes cane per hectare under irrigation (Wawire *et al.*, 2006; Omollo and Abayo, 2011; Amolo *et al.*, 2014). One of the causes of the yield decline is decline soil fertility resulting from depletion of the essential plant nutrients such as nitrogen (N), potassium (K) and phosphorus (P) with low rates of replenishment rates (Wawire *et al.*, 2006).

1.1.2 Indices for expressing sugarcane quality

The quality of sugarcane is critical with regard to processing into sugar and co – products. The quality of sugarcane is assessed using a number of measurements, namely: pol % in juice, pol % cane; brix % juice, brix % cane, fibre %, purity and commercial cane sugar (CCS), (BSES, 1991; STASM, 1991). Brix % in cane refers to the total soluble solids content present in the juice and corrected to more accurately represent those of the total juice in cane.

Brix % in cane = Brix in juice x 100 – [fibre % + 3] / 100. …………….[Equation No. 1]

Pol % in juice refers to the sucrose content present in the juice expressed in %. Pol is derived from the name of the machine that measures the sucrose content, a polarimeter. Pol % in cane refers to the sucrose content present in the juice expressed in % and corrected to more accurately represent those of the sucrose in cane.

Pol % cane = Pol in juice x [100 – (fibre % + 5] / 100 …………………[Equation No. 2]

Fibre % cane refers to amount of fibre in the cane expressed in %. Sampled sugarcane stalks are cut and shredded through a cutter grinder. The ground samples are placed in a fibre machine and washed to remove brix (soluble solids) and fine dirt. The sample is then dried in an oven. The final weight divided by initial weight provide the fibre % as shown in the formula:

Fibre % = [final weight / original weight] x 100. …………………………[Equation No. 3]

Purity % refers to the measure of the level of sucrose present in cane relative to the total level of soluble solids:

Purity = [pol in cane / brix in cane] x 100…………………………………[Equation No. 4]

Purity along with sucrose aids in determining maturity of sugarcane. Generally, sugarcane crop is considered fit for harvest (mature / ripen) if it has attained a minimum of 16 % sucrose and 85 % purity. Commercial cane sugar (CCS) refers to the total recoverable sugar % (sucrose) in the cane.

CCS (tons ha^{-1}) = [(yield (tons ha^{-1}) x sugar recovery (%)] / 100. ……......[Equation No. 5]

Sugar recovery (%) = [S – 0.4 (B – S)] x 0.73 where, S = sucrose % in juice and B = corrected brix (%)

1.2 Sugarcane Production Systems

1.2.1 Sugarcane monoculture

Mono – cropping is the agricultural practice of growing a single crop year after year on the same land. Historically, sugarcane is cultivated as monoculture, especially in large scale farms and nucleus farms.

1.2.2 Sugarcane intercropping

Intercropping system involves growing of more than one crop in field. Inter-cropping of sugarcane may refer to either growing alternative crops between crops of sugarcane, or between the rows of existing sugarcane fields (Irwine, 2004). Sugarcane intercropping, also considered as crop diversification, is practiced on small - holder farms of less than 2 ha in western Kenya (Wawire *et al*., 2006; KESREF, 2009). The small - holder farmers, also referred to as out - grower farmers, practice sugarcane intercropping with annual crops both for food security and household income (Wawire *et al*., 2006).

A study by Amolo (2003) on sugarcane - common bean intercrop and also groundnuts intercrop revealed high income with intercrop than sole cropping. This intercrop technology was documented for application by the sugarcane growers (KESREF, 2010). The benefits of sugarcane soybean intercropping are diverse crops yield, increased income, nutrition and also biological nitrogen fixation (BNF) which cut costs on the use of N fertilizers and therefore reduce soil N mining (Chianu *et al*., 2008).

1.3 Soil Fertility Problems and Sugarcane Production in Kenya

Soils of sugarcane growing areas of Kenya

The major soil types in western Kenya are Acrisols and Cambisols (Jaetzold *et al*., 2007). Acrisols are acidic soils with pH in water less than 5.0, low base status, with base saturation of the B horizon is less than 50 %, strongly leached but less weathered than Ferralsols, and the base saturation of the B horizon is less than 50 %. Cambisols are inherently less weathered than most of the other soils of the humid tropics. It has a Cambic B horizon and the layers are differentiated and characterised by their relatively young age (Jaetzold *et al*., 2007). Cambisols in the sugarcane growing areas of western Kenya are acidic, with a pH as low as 5.5 due to acidification caused by long term use of ammonium - based fertilizers, namely diammonium phosphate (DAP) and urea (Amolo *et al*., 2011). Soil acidification is further exacerbated by continuous sugarcane monoculture through removal of basic cations and leaching (Omollo and Abayo, 2011). The acid soils cause soil fertility problems such as Aluminium (Al) and Manganese (Mn) Toxicity, Calcium (Ca) and Magnesium (Mg) Deficiency and Low Molybdenum (Mo) and Phosphorus (P) availability, which are major constraints to crop production.

1.4 Soil Acidification

Bolan *et al*. (2003) stated that soil acidification is a natural process, which can either be accelerated by the activity of plants, animals and humans or/and can be impeded by sound management practices. Processes of acid generation can be categorised broadly under two groups, namely: occurring under natural ecosystems and under managed ecosystems. Under managed ecosystems, generation of H^+ and hydroxyl ion (OH^-) under this ecosystem arises due to the biogeochemical cycling of carbon (C), nitrogen (N) and sulphur (S) as given in Table 1.1 (Bolan *et al*., 2003).

The processes involved in the generation of H^+ and OH^- ions during C, N and S cycling in soils can be grouped into two main categories: plant - induced uptake and assimilation of C, N and S; and soil – induced (the transformations especially oxidation of C, N and S in soils) (Bolan and Hedley, 2001; Adriano, 2001 as cited in Bolan *et al*., 2003).

Table 1.1: Proton generation and consumption processes in acid precipitation, pyrite oxidation and C, N and S biogeochemical cycles

Cycle	Process	Reaction equation	H^+(mol$_c$ mol^{-1})
Carbon	Dissolution of carbon dioxide	$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO^-_3$	+ 1
	Synthesis of organic acid	Organic C $\rightarrow$ RCOOH $\rightarrow$ $RCOO^- + H^+$	+ 1
Nitrogen	N fixation	$2N_2 + 2H_2O + 4R{\cdot}OH \rightarrow 4R{\cdot}NH_2 + 3O_2$	0
	Mineralization of organic N	$RNH_2 + H^+ + H_2O \rightarrow R{\cdot}OH + NH_4^+$	- 1
	Urea hydrolysis	$(NH_2)_2CO + 3H_2O \rightarrow 2NH_4^+ + 2OH^- + CO_2$	- 1
	Ammonium assimilation	$NH_4^+ + R{\cdot}OH \rightarrow R{\cdot}NH_2 + H_2O + H^+$	+ 1
	Ammonia volatilization	$NH_4^+ + OH- \rightarrow NH_3\uparrow + H_2O$	+ 1
	Nitrification	$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$	+ 2
	Nitrate assimilation	$NO_3^- + 8H^+ + 8e^- \rightarrow NH_3 + 2H_2O + OH^-$	- 1
	Denitrification	$4NO_3^- + 4H^+ \rightarrow 2N_2 + 5O_2 + 2H_2O$	- 1
Sulfur	Mineralization of organic S	2Organic S $+ 3O_2 + 2H_2O \rightarrow 2SO_4^{2-} + 4H^+$	+ 2
	Assimilation of sulfate	$SO_4^{2-} + 8H^+ + 8e^- \rightarrow SH_2 + 2H_2O + 2OH^-$	- 2
	Oxidation of S°	$2S^O + 2H_2O + 3O_2 \rightarrow 2SO_4^{2-} + 4H^+$	+ 2

Source: Bolan *et al*. (2003).

Also, regular ammonium based fertilizer use is one of the major contributors of soil acidification under managed ecosystems. In the case of plant induced processes, reactions that cause acid generation are carbon assimilation (Felle, 1988), uptake and assimilation of nitrogen (Bolan *et al.*, 1991; Marschner, 1995) and uptake and assimilation of sulphur (Saggar *et al.*, 1998). For soil induced processes, the reactions involve decomposition of organic matter, transformation of nitrogen and also transformation of sulphur.

Fertilizer use in managed ecosystems used for agricultural production is a major contributor to soil acidification. Bolan *et al.* (2003) reviewed mechanisms involved in the acidifying effects of different fertilizers, specifically N, phosphate and sulphate fertilizers. The nutrient contents and the acidifying effects of the most common fertilizers used in agricultural production is presented in Table 1.2.

1.5 Effect of Soil Acidity on Nutrient Transformation in Soils

Soil pH has a profound influence on the quantity of nutrients in the soil solution. According to Adriano (2001), the pH can be viewed as the master variable of all the driving factors because it can affect the surface charge and subsequent adsorption of solutes by variable charge soil components, such as layer silicate clays, organic matter, and oxides of Fe and Al. In addition to the effect on the sorption of metal cations and anions in soils, it also influences metal speciation, complexation of metals with organic matter, precipitation/dissolution reactions, redox reactions, mobility and leaching, dispersion of colloids, and the eventual bioavailability of trace metals.

Table 1.2: Nutrient content and acidity equivalent of various fertilizers

		Nutrient content (% w/w)				
Fertilizer	Chemical formula	N	P	K	S	Acidity equivalent [a]
Ammonium sulfate	$(NH_4)_2SO_4$	21	0	0	24	110
Ammonium chloride	NH_4Cl	26	0	0	0	93
Ammonium nitrate	NH_4NO_3	33	0	0	0	60
Diammonium phosphate	$(NH_4)_2HPO_4$	18	20	0	0	74
Monoammonium phosphate	$NH_4H_2PO_4$	11	21	0	0	55
Urea	$CONH_2CO$	46	0	0	0	79
Potassium nitrate	KNO_3	14	0	39	0	- 23
Calcium nitrate	$Ca(NO_3)_2$	14	0	0	0	- 50

Source: Bolan *et al*. (2003).
[a]Acidity equivalent is the number of parts by weight of pure lime (Calcium Carbonate) required to neutralize the acidity caused by 100 parts of the fertilizer. Negative values indicate the liming value (kg $CaCO_3$ / 100 kg) of the fertilizer.

Soil solution pH is one of the major factors controlling surface properties of variable charge components (Sposito, 1984; Barrow, 1985; Sparks, 1986). pH affects the surface charge through the supply of H^+ for adsorption onto the metal oxides and the dissociation of the functional groups in the soil organic matter. An increase in pH increases the net negative charge (often referred to as cation exchange capacity or CEC) and a decrease in pH increases the net positive charge (often referred to as anion exchange capacity or AEC) (Singh and Uehara, 1986 cited in Bolan *et al*., 2003).

1.5.1 Nitrogen

Acidity, by virtue of influencing the type, number and activity of microorganisms, regulates the rate of organic matter decomposition, thereby reducing the number of simple organic molecules available for further decomposition and eventually rendering N and other constituent elements (P and S) soluble (Alexander, 1977). Acidity has deleterious effect on the symbiotic relationship between rhizobia and legumes, and generally in soils with pH below 6, poor nodulation and N fixation result. Several physiological reasons have been attributed to this phenomenon, including: (i) inhibition of infection of legume roots by nodule bacteria, thereby decreasing nodule formation; (ii) inhibition of nitrogenase enzyme activity in the nodule due to modification of the nitrogenase iron protein; (iii) decrease in bacterial membrane potential and the inhibition of the leghaemoglobin and (iv) decrease in the supply of photosynthate to the rhizobia due to the poor supply of major nutrients, such as P. The inhibitory effect of acidity on biological N_2 fixation has also been attributed to the poor supply of Mo and Ca which are essential for N_2 fixation. When nutrient deficiencies, especially Ca and Mo, are overcome in acid soils, biological N_2 fixation can be improved (Unkovich *et al*., 1996).

1.5.2 Phosphorus

A decrease in soil pH initially increases the concentration of Fe and Al ions in soil solution, thereby increasing the adsorption/ precipitation of P (Haynes, 1984). Phosphorus deficiency symptoms noted in acid soils may often be accounted for by immobilization of phosphorus within the root tissue as well as fixation of phosphorus by iron and aluminium compounds either through precipitation or by surface chemisorption (Pearson and Adams, 1967).

1.5.3 Potassium

Under acid conditions, weathering liberates K from micaceous and K feldspar minerals, thus enhancing it to enter the soluble and exchangeable pools (Barshad and Kishk, 1970). However, in variable charge soils, increasing acidity decreases CEC, reducing the ability of the soil to retain K, resulting in more soil solution K. This solution K would then be prone to leaching (Blue and Ferrer, 1986; Alibrahim *et al*., 1988).

1.5.4 Calcium

Poor growth of plants under acid soils is common (Pearson and Adams, 1967) and this might be due to calcium deficiency. It has been reported that a soil solution calcium concentration of 0.4 cmol (+) kg^{-1} resulted in calcium deficiency in tobacco (Abruna *et al.*, 1970). Adams and Moore (1983) observed that calcium deficiency occurred in cotton when soil solution calcium activity was < 0.27 µM and calcium saturation was < 17 %. Working with soils under sisal in Tanga, Nandra (1973) suggested that liming should be considered when pH in water (1:2.5) was below 6.0 and calcium level below 2.0 cmol (+) kg^{-1}. In a similar observation, Foster (1970) reported that groundnuts responded to lime when the soil exchangeable calcium was below 6 cmol (+) kg^{-1}. Cotton, sweet potatoes, beans, and other non-cereal crops responded to lime only if exchangeable calcium level was below 6 cmol (+) kg^{-1} and soil pH below 5.25. Among the cereals tested, only maize and sorghum showed response to lime at one site that had a particularly low exchangeable calcium level (< 2.5 cmol (+) kg^{-1} (Nyambo, 1986).

One of the major consequences of acidification is the decline in basic cations, such as Ca and Mg, leading to deficiency of these cations for plant growth. In acid 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). Furthermore at low pH the bioavailability of Ca is retarded by high concentrations of Al.

1.5.5 Magnesium

With increasing soil acidification, low amounts of Mg remain in exchangeable form due to reduction in variable charge, and more is present in solution and liable to leaching losses. Also, since Mg is a poor competitor with Al and Ca for the exchange sites, it tends to accumulate in the solution phase and is therefore more prone to leaching (Edmeades *et al.*, 1985; Myers *et al.*, 1988).

1.6 Amelioration of Soil Acidity through Liming

Liming offers the opportunity to ameliorate soil acidity, improve nutrient availability and crop yields (van Straaten, 2002; Baligar and Fageria, 2008; Okalebo *et al.*, 2009; Rao and Reddy, 2010). Despite the benefits of liming, the costs are prohibitive due to the "broadcast" method of lime application and corresponding large quantities. Okalebo *et al.* (2009) conducted field trials on lime use for maize - groundnut production and revealed increased soil pH to a range of 5.8 - 6.5 at lime rate of 2 t ha^{-1}. Mbakaya *et al.* (2010) demonstrated integrated lime use with inorganic fertilizer on maize yields in acid soils of western Kenya with increased yield from 2.6 to 3.6 t ha^{-1} Therefore, studies on lime use in Kenya have centered on the lime rate on maize production, with limited work on lime use efficiency (Nekesa, 2007). Traditionally, liming is the most common practice used to overcome the impact of soil acidification. However, an integrated approach involving liming, cultural practices and plant tolerance will probably be necessary, particularly where the acidification potential is high and its effect likely to extend into the subsoil. The hydrolysis of the basic cations in lime produces OH^- ions which neutralize H^+ ions, thereby decreasing the activity and bioavailability of Al and Mn. But liming also increases the solubility of Mo and P, thereby increasing their availability. Lime provides the basic nutrient cations (Ca and Mg), and also reduces the solubility of heavy metals, thereby minimizing their bioavailability and mobility in soils (Baligar and Fageria, 2008).

1.6.1 Effects of liming on soil chemical properties

Liming influences the transformation and uptake of nutrients and heavy metals by plants through its direct effect on the neutralization of soil acidity and its indirect effect on the physical, chemical and biological characteristics of soils (Bolan *et al*., 2003).

1.6.1.1 Nitrogen

Liming has often been shown to enhance the decomposition of organic matter, thereby releasing inorganic plant nutrients such as N, S and P to soil solution. Liming affects both the chemical and microbial transformations of N in soils. In general, NH_4^+ – N is nitrified more rapidly on addition of lime due to an increase in the activity of microorganisms involved in nitrification (Lyngstad, 1992; Puttanna *et al*., 1999). The efficiency of nitrification inhibitors decreases with the addition of lime.

1.6.1.2 Phosphorus

A reason commonly given for liming-induced improvement in plant growth in acid soils was to increase P availability. It is well established that, in strongly acid soils, Al toxicity can have a substantial inhibitory effect on the uptake and translocation of P (Chen and Barber, 1990). In soils high in exchangeable and soluble Al, liming may increase plant P uptake by decreasing Al, rather than by increasing P availability *per se*. This may be due to improved root growth where Al toxicity is alleviated, allowing a greater volume of soil to be explored (Friesen *et al*., 1980).

1.6.1.3 Potassium

Effects of lime on soil K availability to plants are not well documented however. In theory, a number of processes that control the concentration of K in the soil solution could be influenced by liming. Liming could alter the equilibrium between soil solution K and exchangeable K due to increases in CEC and removal of Al from exchange sites or because of competition for exchange sites with lime derived Ca (Bolan *et al.*, 2003).

1.6.1.4 Calcium and Magnesium

Liming materials supply Ca and Mg to soil and one of the primary purposes of liming is to overcome the deficiency of basic cations. An increase in pH through liming increases the net negative charge, thereby increasing the adsorption of cations, whereas an increase in Ca in soil solution through liming is likely to decrease the adsorption of other cations (Bolan *et al.*, 2003). Therefore, the resultant effect of liming on the adsorption of cations depends largely on the concentration of Ca in soil solution.

Plants derive their nutrients including the cations (Ca, Mg, and K) directly from the soil solution. The concentrations of Ca, Mg, and K in the soil solution are determined primarily by cation exchange equilibrium (Heald, 1965; Curtin and Smillie, 1995). Addition of lime can alter the solution concentrations of these cations as a consequence of: (a) the input of Ca (and Mg in the case of dolomitic lime), and (b) pH-induced changes in the extent and nature of the cation exchange complex, which may shift the equilibrium between solution and exchangeable cations.

Addition of lime usually increases the contribution of organic matter to CEC (Helling *et al.*, 1964; Curtin *et al.*, 1998). As organic and mineral exchange sites differ considerably in their affinity or selectivity for cations (Baes and Bloom, 1988), changes in the relative proportions of organic and mineral sites may have some effect on the distribution of cations between the exchange and solution phases of soil. Several studies have demonstrated that organic matter exhibits a preference for Ca over Mg.

Negative charge sites activated when soils are limed are mostly occupied by Ca, with minimal effects on the levels of exchangeable Mg (Hochman *et al.*, 1992). However, there have been frequent reports of decreases in exchangeable Mg following the use of calcitic limestone (Myers *et al*., 1988; Riggs *et al*., 1995). This phenomenon has been associated mainly with highly weathered soils (Oxisols and Ultisols), but it has also been observed in less weathered soils in Great Britain (Riggs *et al*., 1995).

1.6.1.5 Iron

With the exception of Mo, plant availability of most other micro - nutrients decreases with liming mainly due to decrease in the concentration of these elements in soil solution. For example, most problems with Fe nutrition are encountered when pH is raised by liming, resulting in a sufficient depression of Fe solubility to limit uptake in crops (Marschner, 1995). This phenomenon is often referred to as “lime-induced iron chlorosis”. The effect of soil pH greater than 6 in lowering free metal ion activities in soils has been attributed to the increase in pH - dependent surface charge on oxides of Fe, Al, and Mn (Stahl and James, 1991), and chelation by organic matter. Fe is involved in N_2 fixation, photosynthesis, electron transfer, respiratory enzyme systems as a part of cytochrome and haemoglobin and in other enzyme systems. Fe deficiency in plants is mainly a result of soil conditions that reduce its availability to plants. As soil pH increases, the concentration of Fe in the soil solution decreases, with a minimum at pH 7.4 to 8.5. Organic matter improves Fe availability by combining with Fe, reducing chemical fixation or precipitation, thereby resulting in more Fe in the soil solution available for plant uptake.

Iron exists in the soil solution as either the ferrous (Fe^{2+}) or ferric (Fe^{3+}) cation, the actual oxidation state being determined by soil conditions.

1.6.1.6 Zinc

Zinc is necessary for chlorophyll synthesis and carbohydrate formation. Zinc is a metal component of several enzyme systems that function as electron transfer mechanisms and in protein synthesis and degradation. At pH above 7.0, the bioavailability of Zn to crops is substantially reduced. Severe Zn deficiencies are often associated with alkaline and calcareous soils. In these soils, acidification of root zone may prove an efficient method to increase the bioavailability of Zn to plants (Fenn *et al*., 1990). The effect of pH on the activity of Zn in solution in naturally acid soils is found to decrease with increasing pH. The gradual decrease in Zn activity with increasing pH is attributed to increasing CEC (Shuman, 1986). Similarly, Stahl and James (1991) observed that increasing surface charge due to liming increased Zn retention. In general, both the CEC and the total amount of Zn removed from soil solution increased with liming. Zinc is a metal component of several enzyme systems that function in electron transfer mechanisms and in protein synthesis and degradation. Apart from soil pH, Zn availability is affected by soil texture, soil phosphorus, and weather conditions (Voss, 1998). Zinc availability to plants decreases as soil pH increases and may become deficient in soils with a pH above 6.5. Liming soil to pH above 6.0 or 6.5 leads to reduction or elimination of Zn toxicity. Zinc exists in the soil solution as the zinc (Zn^{2+}) cation. High soil phosphorus levels can induce Zn deficiency in sensitive crops (Voss, 1998).

1.6.1.7 Copper (Cu)

Strong complexation of Cu by soil organic matter is believed to be an important factor in explaining why Cu deficiencies are not as prevalent as Zn deficiencies in limed soils, even though the two cations show similar diminution in solubility with increasing pH (Naidu *et al.*, 2008). Precipitation of Cu contaminated industrial waste is usually achieved using lime or sodium hydroxide (caustic). Precipitation as cupric oxide, which is very effective between pH 9 and 10.3 using lime seems to offer distinct advantages with respect to cost and handling (Naidu *et al.*, 2008).

Cu is involved in the activation of several enzyme systems. Cu plays a role in cell wall formation and protein synthesis. Deficiency of Cu causes build up of soluble N compounds. Cu exists in soil solution as cupric (Cu^{2+}) cation. Strong complexation of Cu by soil organic matter is believed to be an important factor in explaining why Cu deficiencies are not as prevalent as Zn deficiencies in limed soils, even though the two cations show similar diminution in solubility with increasing pH. Precipitation of Cu contaminated industrial waste is usually achieved using lime or sodium hydroxide (caustic soda). Precipitation as cupric oxide, which is very effective between pH 9 and 10.3 using lime seems to offer distinct advantages with respect to cost and handling.

The available Cu is held on the cation exchange complex in soils. Cu availability is mainly affected by OM and soil pH. As OM increases, Cu availability decreases. Increasing the soil pH by liming increases the amount of Cu held by clay and organic matter, decreasing Cu availability (Schulte and Kelling, 1999). Soils with a pH above 7.5 are more likely to be Cu deficient (Schulte and Kelling, 1999).

1.6.1.8 Molybdenum

Unlike most other trace elements, bioavailability of Mo in soils is greatest under alkaline pH than under acidic condition. Liming acid soils often helps to correct Mo deficiency; liming may substitute for Mo fertilization by releasing Mo from soils into forms readily bioavailable for plant uptake. Conversely, plant response to application of Mo under field conditions is more effective on acid soils (Adriano, 2001). However, liming could only increase the amount of plant available Mo on soils which have a reserve of Mo.

1.6.2 Effects of liming on biological properties

Liming has been shown to provide optimum conditions for a number of biological activities that include N_2 fixation, and mineralization of N, P and S in soils. The enhanced mineralization of these nutrient ions is likely to cause an increase in their concentration in soil solution for plant uptake and for leaching (Lyngstad, 1992; Arnold *et al*., 1994; Neale *et al*., 1997). Nitrogen fixing bacteria in legume plants require Ca, hence liming is likely to enhance N_2 fixation (Muchovej *et al*., 1986). Liming is often recommended for the successful colonization of earthworms in pasture soils. The lime-induced increase in earthworm activity may influence the soil structure and macro porosity through the release of polysaccharide and the burrowing activity of earthworms (Springett and Syers, 1984). Liming has been shown to cause short-term increases in microbial biomass and soil enzyme activity (Haynes and Swift, 1988). Increased microbial activity and the subsequent production of extracellular polysaccharides which act as a binding agent can increase soil aggregate stability.

1.7 Lime requirements of soils

Lime requirement is defined as the amount of liming material, as calcium carbonate or its equivalent, required to change a volume of soil to a specific state with respect to pH or soluble Al content (Soil Science Society of America, 1997). 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. The amount of lime required to produce maximum economic yields of crops grown on acid soils is determined by soil properties, liming material quality, management practices, cropping systems, crop species or genotypes within species, calcium and magnesium interaction with other nutrients, and economic considerations (Fageria and Santos, 2008).

1.7.1 Quality of liming material

The quality of liming material is very important in correcting soil acidity. Chemical analysis of the liming material gives its composition. Two important characteristics that determine lime material quality are its neutralizing power or reactivity and fineness. The chemical effectiveness of agricultural limestone is measured by its $CaCO_3$ equivalence as shown in Table 1.3. If neutralizing value is lower than $CaCO_3$, a higher quantity of liming material is required, and the vice a versa. The neutralizing power or value of a liming material is defined as the acid-neutralizing capacity of the material by weight in relation to $CaCO_3$.

Table 1.3: Nutrient content and acidity equivalent of various liming materials

Commercial name	Chemical formula	Neutralizing value (%)	Characteristics
Dolomitic lime	$CaMg(CO_3)_2$	95 - 109	Contains 78 – 120 g kg^{-1} of Mg and 180 – 210 g kg^{-1} of Ca
Calcitic lime	$CaCO_3$	100	Contains 284 – 320 g kg^{-1} of Ca
Dolomite lime	$MgCO_3$	100 - 120	Contains 36 – 72 g kg^{-1} of Mg
Burned lime	CaO	179	Fast reacting and difficult to handle
Slaked lime	$Ca(OH)_2$	136	Fast reacting and difficult to handle
Basic slag	$CaSiO_3$	86	Byproduct of pig-iron industry, also contains 1 – 7 % P
Wood ash	Variable	30 - 70	Caustic and water soluble

Source: Brady and Weil (2008)

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. A 60 - mesh sieve, which is the standard for comparisons of lime fineness and efficiency, the rating of 100 % is assigned (Caudle, 1991).

A range of liming materials are available, which vary in their ability to neutralize the acidity. These include calcite ($CaCO_3$), burnt lime (CaO), slaked lime ($Ca(OH)_2$), dolomite ($CaMg(CO_3)_2$) and slag ($CaSiO_3$). The acid neutralizing value of liming materials is expressed in terms of calcium carbonate equivalent (CCE), defined as the acid neutralizing capacity of a liming material expressed as a weight percentage of pure $CaCO_3$ (Table 1.3). A neutralizing value of 100 is assigned to pure $CaCO_3$ (Brady and Weil, 2008). The amount of liming material required to rectify soil acidity depends on the neutralizing value of the liming material and pH buffering capacity of the soil.

1.7.2 Other factors affecting quantity of lime required

Soil texture determines the buffering capacity of a soil, which refers to the ability of the solid phase soil materials to resist changes in ion concentrations in the solution phase. For liming purposes, the resistance of the soil solution to changes in pH is a main component of soil buffer power. Oxisols require large amount of liming materials to raise soil pH to a desired level for maximum crop yields. For example, to raise a pH from 5.3 to 6.5 in Oxisols, a lime rate of about 7 Mg ha^{-1} is needed (Fageria and Baligar, 2005). Soil fertility is defined as the quantity of nutrient present in the soil. High fertility soils in terms of exchangeable Ca^{2+}, Mg^{2+} and K^+ require less lime than those with lower soil fertility. When Ca^{2+}, Mg^{2+}, and K^+ contents are high, a lower lime rate is required, because the higher levels of these basic cations in the soil, translates to higher base saturation and higher pH.

Organic manures are products from the processing of animal or vegetable substances that contain reasonable amount of plant nutrients to be of value as fertilizers. Organic matter increases a soil's ability to hold and make available essential plant nutrients and to resist the natural tendency of soil to become acidic (Cole *et al*., 1987). Furthermore, addition of organic manures to acid soils has been shown to increase soil pH, decrease Al saturation, and thereby improve conditions for plant growth (Alter and Mitchell, 1992; Reis and Rodella, 2002; Wong and Swift, 2003).

Additional benefits of organic matter addition to acid soils are improving nutrient cycling and availability to plants through direct additions as well as through modification in soils' physical and biological properties. A complementary use of organic manures and chemical fertilizers has proven to be the best soil fertility management strategy in the tropics (Makinde and Agboola, 2002; Fageria and Baligar, 2005). Enhanced soil organic matter increases soil aggregation and water-holding capacity, provides source of nutrients, and reduces P fixation, toxicities of Al and Mn, and leaching of nutrients (Baligar and Fageria, 1999).

1.7.3 Criteria to determine liming material quantity

Use of adequate lime rate to correct soil acidity and production of maximum yield of a crop species is an important consideration for economic and ecological reasons. The quantity of liming material required is determined on the basis of soil pH, base saturation, and aluminium saturation adjustment at appropriate levels. However, soil pH is the mostly used criterion to determine the liming material quantity and also evaluate the soil pH changes upon liming.

1.7.4 Soil pH

Soil pH or hydrogen ion (H^+) activity is the most common acidity index used in soil testing program for assessing lime requirements of crops grown on acid soils. Weaver *et al.* (2004) reported that soil pH buffering capacity, since it varies spatially within crop production fields, may be used to define sampling zones to assess lime requirement, or for modelling changes in soil pH when acid-forming fertilizers or manures are added to a field. Soil pH is determined by means of a glass electrode or other suitable electrode or indicator at a specified soil to solution ratio in a specified solution, usually distilled water, 0.01 M $CaCl_2$, or 1 M KCl (Soil Science Society of America, 1997). In soil testing laboratories in Brazil, a soil to solution ratio of 1:2.5 is commonly used to determine soil pH (EMBRAPA, 1997).

The pH measured in the soil solution represents the active acidity of the soil. Hydrogen and aluminium ions adsorbed by the soil, as well as other soil constituents that generate hydrogen ions, constitute the reserve acidity. The active acidity is neutralized by the addition of lime where more hydrogen ions from the reserve pool go into solution. This results in the resistance of soil to changes in the pH of the soil solution, which is referred to as `buffering capacity. The pH of most agricultural soils is in the range of 4.0–9.0 (Fageria *et al.*, 1990, 1997). Soil acidity is classified into several groups based on soil pH. Slightly acid soils have a pH range of 6.0 – 6.4, moderately acid soils pH range from 5.0 to 5.9, strongly acid soils pH from 4.5 to 4.9, and extremely acid soils have a pH range below 4.5 (Fageria and Gheyi, 1999). These acidity classifications are arbitrary, and care should be taken when defining adequate pH for crop yields, particularly because the extractant used could make a difference. Soil pH in water is higher than that in $CaCl_2$ solution.

Soil pH measurements not only indicate the acidity level of a soil but can also be used as an initial basis for the prediction of the chemical behaviour of soils, particularly in relation to nutrient availability and the presence of toxic elements. Most plant-essential nutrients in soil reach maximal or near - maximal availability in the pH range 6.0 – 7.0, and decrease both above and below this range (McLean, 1973).

1.8 Methods and Depth of Lime Application

Methods, frequency, depth, and timing of liming are important practices in improving liming efficiency and crop yields on acid soils. The required amount liming material is applied to bring about the desired chemical changes in acid soils. Hence, the best method is applying it as broadcast as uniformly as possible and mixing thoroughly through the soil plow layer. Lime broadcasting machines are available for uniform application of liming materials.

Liming material should be mixed thoroughly in the soil as deeply as possible to improve crop-rooting systems in acid soils as reported by Fageria and Baligar (2005). However, with currently available machinery, it is generally mixed to a depth of 20 - 30 cm (Fageria and Baligar (2005). More mechanical power and cost in terms of labour and energy for a depth greater than 30 cm require Timing of lime application is important in achieving desirable results. Lime should be applied as far in advance as possible of crop planting to allow it to react with soil colloids and to bring about significant changes in soil chemical properties. Brown *et al.* (2008) found that broadcast lime increased pH in the surface 15 cm, although reductions in Al^{3+} activity [(Al^{3+})] occurred only in the 0 to 5 cm layer.

Brown *et al.* (2008) reported no increase in soil pH at 5 – 10 cm depth where lime was placed. However, lower pH such as 4.6, 5.1 and 5.0 were observed at 0 – 5 cm depth in plots that received elemental Sulphur broadcasted, Nitrogen fertilizer banded (control) and lime banded respectively.

In their study cited above, Brown *et al*. (2008) suggested that alternative application strategies such as placement of lime in a band beneath the row at seeding may allow lower rates of lime to be used and thereby offset economic constraints posed by high application rates; however, the effects of this practice on soil pH and crop yield have not been extensively studied. In one year of research, subsurface banded lime at the rate of 220 kg ha^{-1} was shown to effectively reduce soil acidity in the surface 10 cm at an eastern Washington location, but no grain yield response was observed (Wildey, 2003). Caires *et al*. (2005) evaluated the downward movement of surface applied lime in a no till system and effect on grain yield. Results showed that surface applied lime alleviated soil acidity below the point of placement and increased the cumulative grain yield of the crops. The acidity variables (pH, Al and basic cations) were significant at 0 – 5 cm and 5 – 10 cm soil depth from one year onward (Caires *et al*., 2005; Caires *et al*., 2006).

Lime has low solubility and therefore its efficiency in liming calls for unbiased application in soil surface and incorporation in soil profile and ensures lime will reach higher contact with the soil particles (Rosa *et al*., 2015). To ensure lime efficiency, Rosa *et al*. (2015) assessed the effect of lime management under no till system and its effect on millet cover crop and soybean performance. Result showed that, lime was better incorporated in 10 – 20 cm and 20 – 30 cm soil depth when treatment “Lime at 2.7 t ha^{-1} surface applied and incorporated with intermediate disk harrow followed by levelling disk harrow” and treatment “Lime at 2.7 t ha^{-1} surface applied and incorporated with chisel plough, followed by intermediate disk harrow and levelling disk harrow” were used. Decreased yield of millet and soybean was recorded in plots where lime was not incorporated (Rosa *et al*., 2015).

1.9 Problem Statement and Justification

Liming is considered as a management practice to reduce the soil acidity and therefore one of the soil fertility management practices that are knowledge - based and adapted to local conditions to optimize fertilizer and organic resource use efficiency and crop productivity (AGRA, 2009). Liming using calcitic limestone offers the opportunity to ameliorate soil acidity, improve nutrient availability and yields (Okalebo *et al*., 2009). In Kenya, Calcitic limestone is mined from Koru, Kisumu County, located within western Kenya (van Straaten, 2002). Liming acid soils decreases toxic levels of Al and Mn, increase availability of P, Ca, Mg and Mo and also increase microbial activity of nitrogen fixing bacteria (Rao and Reddy, 2010). Okalebo *et al*. (2009) found that lime at 2 t ha^{-1} combined with phosphorus at 26 kg P ha^{-1} and nitrogen at 75 kg N ha^{-1} raised the soil pH to the range of 5.8 – 6.5, available P to above 10 mg P ha^{-1} and also resulted in significant maize yield of 6 t ha^{-1}. Mbakaya *et al*. (2010) recorded increased yield of 3.6 t ha^{-1} in lime treatments compared to inorganic fertilizer treatments which recorded 2.6 t ha^{-1} maize yield.

Studies on lime use in Kenya have centered on the lime rate with limited work on lime use efficiency (Nekesa, 2007; Okalebo *et al*., 2009). Lime is an input cost to soil fertility management and therefore its judicious use is paramount. Lime placement is considered a strategy that can increase lime use efficiency. Gonzalez-Erico *et al*. (1979) cited in Kamprath (1984) studied lime placement and found that incorporation of lime to a depth of 30 cm resulted in higher grain yields than when lime was incorporated only in the top 15 cm. Caires *et al*. (2005) found that surface application of lime at 4 t ha^{-1} under no till system significantly reduced acidity problem (pH, Al and basic cations) at different depths 0 – 5 cm and 5 – 10 cm within one year onward and also at 10 – 20 cm from 2.5 years onwards.

There exist knowledge gap in our understanding of lime placement and efficient amelioration of soil acidity for enhanced biological nitrogen fixation, nitrogen use efficiency and performance of sugarcane intercrops The hypothesis of the proposed study is that localized lime use is advantageous to broadcast in efficiently ameliorating soil acidity to enhance biological nitrogen fixation, nitrogen use efficiency and performance of sugarcane - soybean intercrops.

1.10 Research Objectives

1.10.1 Overall objective

To determine the best lime placement method in ameliorating soil acidity for balanced nutrient availability and performance of intercropped sugarcane and soybean in acid Cambisols of Kibos, Kisumu County, Kenya.

1.10.2 Specific objectives

1. To determine the effects of cropping systems, lime placement methods and lime rates on soil acidity, soil nutrients availability and nutrients content by sugarcane.

2. To determine the effects of lime placement methods, lime rates and nitrogen rates on soil acidity, soil nutrients availability and nutrients content by sugarcane.

3. To examine the sugarcane yield and quality response to cropping systems, liming and nitrogen fertilizer application.

1.11 Organization of the Thesis

The dissertation is organized into six chapters. Chapter 1, which presents a general introduction with background information and literature review on soil acidity problems, liming as a management strategy to ameliorate the acidity and its implied effect on performance of intercropped sugarcane and soybeans in western Kenya. Chapter 2 deals with the effects of cropping systems and agricultural lime on soil properties and nutrient content of sugarcane on acidified soils. The effects of cropping systems, lime placement methods and rates on sugarcane yields and quality under acidified soils of Kibos are presented in Chapter 3. Chapter 4 addresses the effects of liming and nitrogen rates on soil acidity, nutrient content and yields of intercropped sugarcane under acid soils of Kibos. Chapter 5 gives a general discussion and finally, chapter 6 provides general conclusions and recommendations.

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CHAPTER TWO

2.0 EFFECTS OF CROPPING SYSTEMS AND AGRICULTURAL LIME ON SOIL PROPERTIES AND NUTRIENT CONTENT OF SUGARCANE ON ACIDIFIED SOILS OF KISUMU COUNTY, KENYA

Abstract

Acid soils cause soil fertility problems such as Al and Mn toxicity, Ca, Mg, N deficiency and P fixation. These are constraints to high crop yields. Historically, liming is the common management practice used to neutralize soil acidity and to overcome the problems associated with soil acidification. A field experiment was conducted to investigate the effects of cropping systems, lime placement methods and lime rates on some soil chemical properties and nutrient uptake by sugarcane during the plant crop and ratoon one cycle under acidified Cambisols of Kibos, Kisumu, Kenya. A Split - split plot in randomized complete block arrangement was employed. The factors and respective levels (in parenthesis were): main plot; two cropping systems (sugarcane monoculture [MC] and intercropped sugarcane and soybeans [IC]). The sub – plots were three lime placement methods (lime broadcasted [L-BC], lime shallow banded, 0 – 15 cm [L-SB] and lime deep banded, 15 – 30 cm (L-DB] and the sub - sub plots were three lime rates (0, 1 and 2 t ha^{-1}). Lime rate of 2 t ha^{-1} significantly ($P \leq 0.05$) increased soil pH to 6.4 and 5.2 as determined in water and 1 N KCl, respectively compared to 1 t ha^{-1} and control (0 t ha^{-1}). Increased lime rate led to decreased levels of manganese, iron, and copper hence confirms the inverse relationship between soil pH and these micronutrients. Lime deep banded (L-DB) increased soil pH and available phosphorus for soil depth 15 – 30 cm compared to lime shallow banded (L-SB) and lime broadcasted (L-BC). Intercropped sugarcane and soybeans (IC) led to increased soil acidity and soil organic carbon (SOC)

than did sugarcane monoculture (MC). For nutrient content of sugarcane leaves, IC system led to increased Ca and Mn compared to MC. Lime broadcasted (L-BC) caused high nitrogen and phosphorus content of sugarcane leaves and lime shallow banded resulted in increased Ca and Zn content of sugarcane to optimum levels. In view of the findings, the lime rate of 2 t ha^{-1} is recommended for use to ameliorate soil acidity for acidified Cambisols of Kibos, Kisumu County, Kenya. Lime broadcasted (L-BC) is preferred to ameliorate acidity at top depth (0 – 15 cm) while lime banded both (L-SB) and L-DB) is preferred to reduce sub - soil acidity.

***Keywords*:** Soil pH; lime rates, lime placements, cropping, nutrient content

2.1 Introduction

Acidified soils are a major constraint to crop production. In western Kenya, soil acidity is an economic and natural resource threat (Okalebo *et al*., 2009). Soil acidity causes soil fertility problems such as Aluminium (Al) and Manganese (Mn) toxicity, Calcium (Ca) and Magnesium (Mg) deficiency and low Molybdenum (Mo) and Phosphorus (P) availability (Kamprath, 1984; Kanyanjua *et al*., 2002; Bolan *et al*., 2003). Bolan *et al*. (2003) highlighted the detrimental effects of soil acidity to plants and soil organisms. Activities of soil organisms are reduced leading to the inhibition of biological nitrogen fixation (BNF) by legumes and decomposition of organic matter. Low pH may also result in the deficiency of Ca and Mg in soils (Sumner *et al*., 1991). Soil acidification is a natural process but it does also occur under managed ecosystems. Bolan *et al*. (2003) stated that regular fertilizer use is one of the major causes of soil acidification under managed ecosystems. Fertilizer – caused soil acidification occurs due to long term use of acidifying fertilizer such as urea and diammonium phosphate coupled with continuous monoculture.

Soil acidity affects availability of the macronutrients and micronutrients. Soils that are adequately limed are high in Ca. Very acid soils (soil pH less than 5.0) and soils that have received very excessive amounts of potassium and/or magnesium are conducive to Ca deficiency (Sumner and Noble, 2003; Brady and Weil, 2008). For Mg, acid soils, especially sands, frequently contain low levels of Mg. Soils of neutral or high pH usually contain adequate Mg. Mg deficiency in soils arises when the lime materials used are low in Mg, e.g. calcitic limestone. Ca and Mg deficiency, if it persists, leads to low yields since these nutrients play critical role in plant growth. Ca is a component of every cell wall and is involved in cell elongation and cell division. Mg is an essential part of chlorophyll molecule. It also activates many enzymes and aids in the formation of sugars, oils, and fats.

Soil pH is the most important factor influencing the availability of most micronutrients. As soil pH increases, the availability of iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn) decreases. This is attributed to the cropping systems e.g. long term/ continual cropping have removed large amounts of the micronutrients, limited or lack of use of animal manure for crop production and use of high analysis fertilizers that lack micronutrients. As soil pH increases, the concentration of Fe in the soil solution decreases, with a minimum at pH 7.4 to 8.5. Mn availability to plants decreases as soil pH increases and may become deficient in soils with a pH above 6.5. Conversely, Mn availability increases as soil pH decreases and may become toxic in soils with pH below 5.5. The amount of soluble Mn increases 100 fold for each unit decrease in soil pH, e.g. pH 5.0 down to 4.0 (Voss, 1998).

Zinc availability to plants also decreases as soil pH increases and may become deficient in soils with a pH above 6.5 (Voss, 1998). Liming soil to pH above 6.0 or 6.5 leads to reduction or elimination of Zn toxicity. The available Cu is held on the cation exchange complex in soils (McCauley, 2009). Increasing the soil pH by liming increases the amount of Cu held by clay and organic matter, decreasing Cu availability. Soils with a pH above 7.5 are more likely to be Cu deficient (Msaky and Calvet, 1990 cited in Bolan *et al*., 2003).

Liming is considered as a management practice to reduce the soil acidity (AGRA, 2009). Most plants grow well at a pH range of 5.5 – 6.5 and liming is aimed to maintain the pH at this range. The benefits of liming include: enhanced soil physical, chemical and biological conditions. The indirect benefits include mobilization of plant nutrients, immobilization of toxic heavy metals, and improvements in soil structure. Liming also causes optimal conditions that enhance biological activities like N_2 fixation and mineralization of N, P and S in soils (Haynes and Naidu, 1998; Bolan *et al*., 1991).

In Kenya, the common sugarcane production practice is continuous sugarcane monoculture and use of acidifying fertilizers such as urea and diammonium phosphate (Amolo *et al*., 2011). These fertilizers are favoured due to their high levels of nutrient element per weight compared to other nutrient fertilizer sources. The advantage of these fertilizers means their use will be continued. This therefore calls for integrated use of these fertilizers with other soil improvement strategies that will mitigate against soil acidification, improve soil fertility and sugarcane nutrient uptake.

However, the cost of lime is prohibitive due to large amounts required. Alternative application strategies such as placement of lime in a band may allow lower rates of lime to be used and thereby offset economic constraints posed by high application rates. Liming, integrated with appropriate cropping systems may also lead to improved soil pH but also structure for sustained crop yields. Benefits of intercropping are: yield advantages of diverse crops, income, nutrition and also nitrogen (N_2) fixation which can cut costs on the use of N fertilizers. Farmers benefit from biological nitrogen fixation and therefore reduce soil N mining, which is estimated at 22 kg Nha^{-1} for Sub Saharan Africa (Chianu *et al*., 2008).

This study investigated whether lime use and intercropped sugarcane and soybeans leads to amelioration of soil pH, soil nutrient status and nutrient content in sugarcane leaves. Also, the study determined the best lime rate, placement methods for improved soil pH, soil fertility and sugarcane nutrition for plant crop and ratoon one crop cycle.

2.2 Materials and Methods

2.2.1 Study site

The field experiment was conducted at field 6, experimental plots of Kibos (35^{o}13 E, 0^{o}06 S), KALRO – Sugar Research Institute, Kisumu County, Kenya. The site elevation is 1268 m above sea level. The area is in agro-ecological zone (AEZ) LM 2, which is a marginal sugarcane zone and is sub humid. The soil type in field 6 is Eutric Cambisol (FAO, 2006), with the following soil properties: dark reddish brown friable sandy clay loam underlain by gravely red loam to light clay. The soil is well drained and has good physical properties and is slightly acid (Jaetzold *et al*., 2007).

The weather data during the experiment period (2012 to 2014) is shown in Figures 2.1, 2.2 and 2.3. The total annual rainfall was 1714 mm, 1544 mm and 1497 mm in 2012, 2013 and 2014, respectively (Figure 2.1).

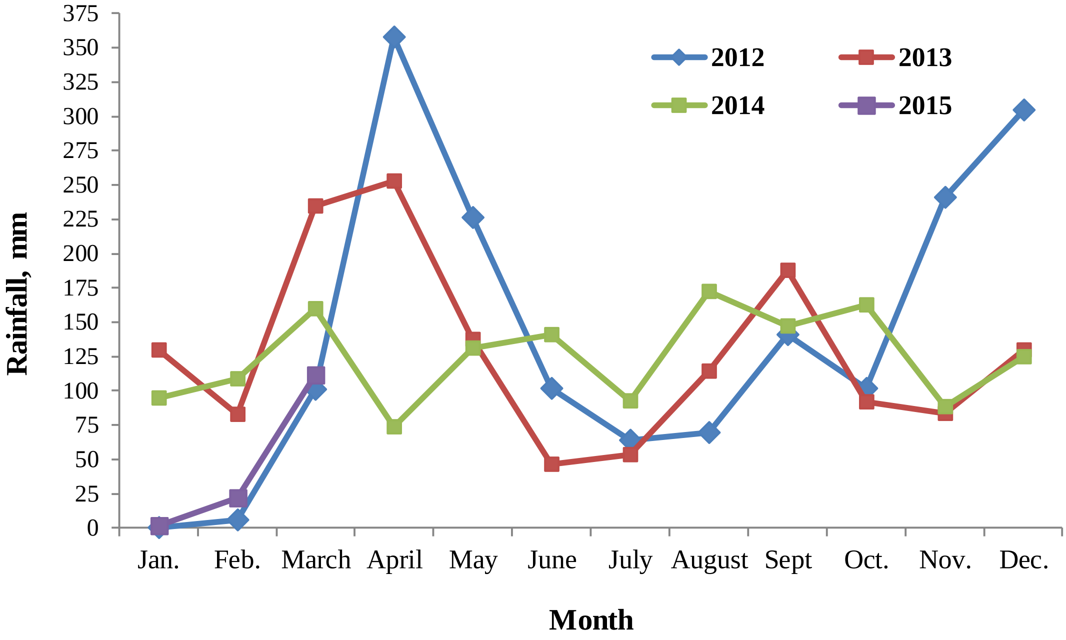

Figure 2.1: Precipitation data for the study site during the period of experiment (January 2012 to March 2015)

The study area experiences bimodal rainfall characterized by two rainy seasons per year known as long and short rains. Long rains during 2012 to 2014 were from March to May while short rains were in September to October annually. This bimodal rainfall pattern reflects the pattern for the lake regions in Kenya (Jaetzold *et al.*, 2007). Rainfall amounts are higher during long rains than short rain periods. The mean maximum temperature was 30^{o} C while the minimum temperature ranged from 16^{o}C to 17^{o} C (Figure 2.2). The mean temperature was 23^{o} C. Relative humidity (% RH) was recorded at 9 AM (0900 hours) and 3 PM (1500 hours) in 2012, 2013 and 2014 (Figure 2.3). Relative humidity at 9 AM was higher than at 3 PM for all the years. Annual RH at 9 AM was 71 %, 70 % and 72 % for 2012, 2013 and 2014, respectively, while it was 47 %, 49 % and 50 % at 3 PM for 2012, 2013 and 2014, respectively.

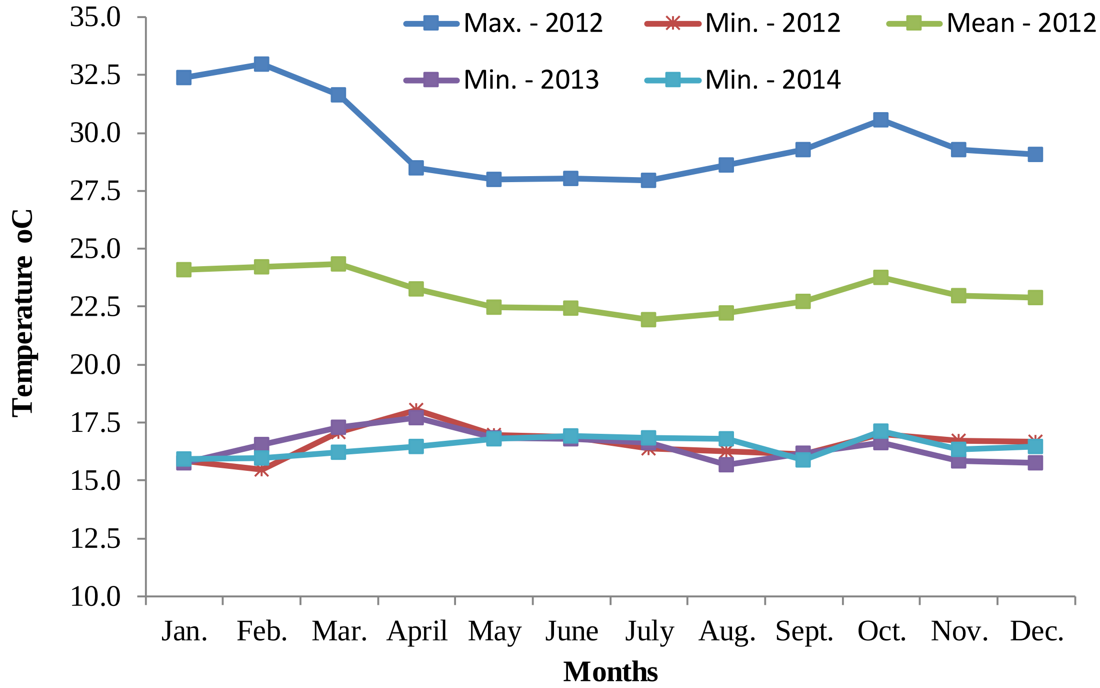

Figure 2.2: Temperature data for the study site during the period of experiment (2012 to 2014)

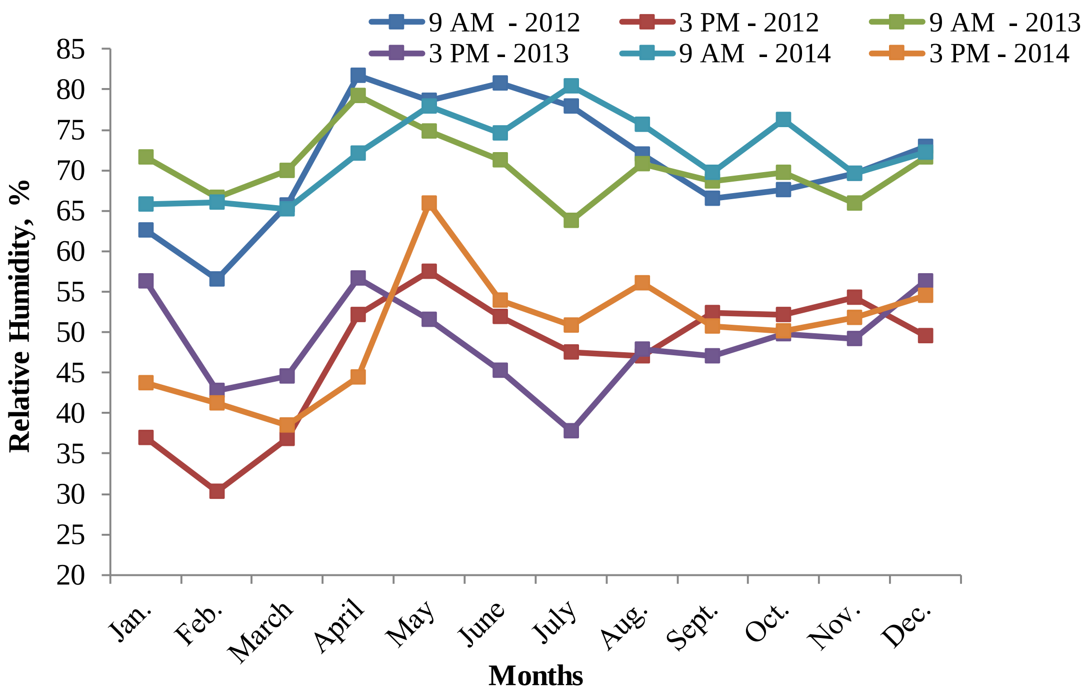

Figure 2.3: Relative humidity for the study site during the period of experiment (2012 to 2014)

Soil chemical properties prior to establishment of field experiment

Soil testing for the study site was carried out prior to establishment of the field experiment. An area of about 0.5 ha was sampled. Diagonal sampling pattern was used and sampling points randomly selected. Soil auger was used to collect soil at 0 – 15 cm depth and also 15 – 30 cm depth. The soil samples per depth across sampling points were composited and about a kg of soil was packaged in well labelled brown paper bags. They were later dried, ground using pestle and mortar and sieved through a 2 mm sieve for chemical analysis. The soils were analysed for selected chemical properties using recommended methods as given in Table 2.1.

Generally, the magnitudes of the results for 0 – 15 cm soil depth were higher as compared to 15 – 30 cm soil depth except extractable copper which showed the reverse. The soil results were rated according to Landon (1991); Estefan *et al*. (2013) and IUSS (2015). For 0 – 15 cm soil depth, the soil reaction was slightly acid (in water) and very strongly acid (in KCl). For 15 – 30 cm depth, soil reaction was medium acid (in water) and very strongly acid (in KCl). Organic carbon was medium and low for 0 – 15 cm and 15 – 30 cm soil depths respectively. Total nitrogen was low at both depths. Available P was high at 0 – 15 cm and medium for 15 – 30 cm. The high P levels depicted residual P attributed to high and continual use of phosphorus fertilizer at planting, e.g. diammonium phosphate in the field for sugarcane production prior to establishment of field experiment. The micro – elements copper, zinc, iron and manganese were sufficient, above the critical levels.

2.2.2 Field experiment

The field experiment was established in 2012 and managed up to 2014. The field research period coincided with the sugarcane crop cycle, namely the plant crop (0 – 18 months after planting sugarcane setts) and the ratoon one crop cycle (0 – 16 months after ratoon emergence).

Table 2.1: Some chemical properties of the soils of the study site

Soil properties	Method of analysis	0 – 15 cm depth	Rating	15 – 30 cm depth	Rating
pH (H_20)	1: 2.5 soil / water. Potentiometrically	6.19	Slightly acid	5.93	Medium acid
pH (KCl)	1 : 2.5 soil / 1 N KCl. Potentiometrically	5.04	Very strongly acid	4.73	Very strongly acid
Org. C (%)	Dichromate Wet Oxidation	1.30	Medium	1.23	Low
O.M (%)	Convert using factor 1.72 x Org, C	2.24	Medium	2.11	Medium
Total N (%)	Kjeldhal Method	0.10	Low	0.1	Low
Avail. P (mg kg^{-1})	Bray 1	20.52	High	11.91	Medium
Ex. Cu mg kg^{-1}	Extracted using DTPA and measured using AAS	1.53	High	1.60	High
Ex. Zn mg kg^{-1}	DTPA	1.79	High	1.52	High
Ex. Fe mg kg^{-1}	DTPA	147.9	High	137.2	High
Ex. Mn mg kg^{-1}	DTPA	206.2	High	193.7	High

DTPA – diethylenetriaminepentaacetic acid; AAS – Atomic absorption spectrophotometer. Ratings are according to Landon (1991), Estefan (2013), IUSS (2015)

Soybean was intercropped and managed during the stage when sugarcane was young (the period for sugarcane germination stage is usually between 0 – 60 days after planting) and sugarcane tillering stage (this period is usually between 2^{nd} month and 7^{th} month after planting).

The experiment unit was a plot which measured [5 m x 5 rows each 1.2 m apart] referred to as gross plot. Data was collected in the net plots which are the three inner rows with the one row in each side referred to as guard rows. The sugarcane variety used was KEN 83 – 737, which is of medium maturity at 0 – 18 months and 0 – 16 months for plant crop and ratoon crop cycle, respectively. Soybean variety SB 19 was used as intercrop which was sowed in between sugarcane rows. The soybean was inoculated with a rhizobial (Biofix ®) inoculant.

The experimental design for the field experiment was the split – split plot arranged in randomized complete blocks. The main plot was cropping system (CS) with two levels, namely sugarcane monoculture (MC) and intercropped sugarcane (IC). The sub – plots were lime placement methods (LPM) with three levels namely; lime broadcasted (L-BC), lime shallow banded (L-SB) at 0 – 15 cm soil depth and lime deep banded (L-DB) at 15 – 30 cm soil depth. The sub – sub plots were lime rates with three levels namely 0, 1 and 2 tonnes ha^{-1}. This gave a total of 18 treatments which were then replicated three times to give a total of 54 plots. Agricultural lime (20% CaO) mined in Koru, Kisumu County, was used as the liming material. The raw limestone is carbonanite which is volcanic in origin. The lime treatments were applied prior to planting of sugarcane setts. Sugarcane setts were treated with imidacloprid (confidor ®) at 200g / L to control termite attack. Termite mounds within the vicinity of the field experiment sites were identified and drenched with confidor. Similarly, the sugarcane planting furrows were drenched using confidor. After 30 to 45 days after planting sugarcane, germination of sugarcane was started. This time, soybean was sowed as intercrop, in between the sugarcane rows. Soybean was inoculated with rhizobial (biofix ®) inoculant. The sugarcane was managed for 18 months and harvested as the plant crop. It was also managed for the ratoon one crop for 16 months and harvested. Ratoon crop establishment involved alignment of the sugarcane trash in between sugarcane rows following green sugarcane harvest of plant crop cycle. Soybean intercrop was managed for 6 months and the pods harvested upon maturity. The above ground soybean biomass residue was then incorporated into the soil during manual weed control using a hoe. Soil sampling per plot was carried out after harvest of sugarcane plant crop and soon after trash alignment. Sugarcane leaf sampling for plant tissue tests was carried out at 18^{th} month of the plant crop cycle, and also during the ratoon crop cycle at 9^{th} and 12^{th} month after sugarcane ratoon emergence.

2.2.3 Soil analysis during the field experiment

2.2.3.1 Soil sampling at post-harvest of sugarcane

Soil was sampled in each of the treatment plots. In every plot, a diagonal pattern was used to mark the sampling points. Soil auger was then used to collect soil sample at depth 0 – 15 cm (top soil) and 15 – 30 cm (sub soil). Soils sampled were then composited per depth for each treatment. About 0.5 kg of soil was then packed and the package well labelled.

2.2.3.2 Soil analysis

Soil samples were air - dried, ground using pestle and mortar and sieved using a 2 mm sieve to remove debris. The parameters analysed were soil pH, total nitrogen (N), extractable phosphorus, organic carbon, exchangeable bases (sodium, calcium, magnesium and potassium), cation exchange capacity and also micro – nutrients, i.e. manganese, iron, zinc and copper. Soil pH was determined in water and also 1 N KCl at the ratio of 1 soil: 2.5 extractant. About 10 g of soil was transferred into 100 ml plastic bottle followed by 25 ml of the extractant. The mixture was shaken for 30 minutes, allowed to settle for 5 minutes and the supernatant solution read using an electrode pH meter (MacLean, 1982; Moberg, 2001). Total N was determined by the Kjedahl method (Bremner and Mulvaney, 1982) whereby one gram of soil was put in a digestion tube, followed by addition of 10 ml 98 % H_2SO_4 and a scoop of mixed catalyst which contained 100 g potassium sulphate, 10 g copper sulphate and 1.55 g selenium powder. This mixture was then digested in a digestion block for 1 hour at 360^o C. The digest was then distilled after adding 40 %

NaOH, and the distillate collected over 4 % boric acid, followed by titration with 0.05 N H_2SO_4. The titre value was used to compute total N. The Wakley - Black Method was used to determine soil organic carbon (OC) (Moberg, 2001). One gram of finely ground soil was put in a conical flask. Ten ml of $K_2Cr_2O_7$ solution, 10 ml phosphoric acid (85 % H_3PO_4) solution and 20 ml of 98 % H_2SO_4 were added. The mixture was swirled to mix, left for 30 minutes, cooled and then titrated. Diphylemine indicator was added and mixture titrated using ferrous sulfate. Organic carbon was then computed using amount of dichromate used in the oxidation.

Extractable P was determined using the Bray 1 method (Moberg, 2001). Five grams of soil was put in 50 ml plastic bottle followed by 25 ml of extraction solution. The mixture was hand shaken for one minute and then filtered. Five ml of the filtrate was then transferred into a 50 ml volumetric flask. About 30 ml distilled water was added followed by 10 ml of the phospho - molybdate reagent. The mixture in the volumetric flask was then made to the mark using distilled water and was allowed to settle for about 30 minutes for colour development. The absorbance was measured by spectrophotometer at 884 nm wavelength (Moberg, 2001).

Soil cation exchange capacity (CEC) and exchangeable bases were determined by ammonium acetate saturation at pH 7.0 (Rhoades, 1982; Moberg, 2001). Five grams of soil was placed in 100 ml plastic bottle followed by 35 ml of 1 M ammonium acetate buffered at pH 7. This mixture was shaken for half an hour and left overnight. The suspension was filtered into 100 ml volumetric flask which was then used to determine exchangeable Ca, Mg, K and Na. The remaining soil was washed with 80 % ethanol and leached with 1 M KCl and then filled into 100 ml volumetric flask. The leachate was transferred into a Kjeldtex distillation tube, 10 ml of 40 % NaOH added, the distillate collected over 4 % boric acid and thereafter titred using 0.1 N H_2SO_4 (Moberg 2001). The titre value from titration was used to calculate CEC. The ammonium acetate leachate was used to determine exchangeable Ca and Mg using an atomic absorption spectrophotometer while for exchangeable K and Na the flame photometer was used.

Extractable Fe, Mn, Zn and Cu were determined after extraction using the DTPA extractant. Fifteen grams of soil was placed in 100 ml plastic bottles followed by addition of 40 ml of DTPA. The mixture was then shaken for 2 hours and filtered into 50 ml plastic bottles. The filtrate was used to determine Fe, Mn, Zn and Cu at respective wavelengths using an atomic absorption spectrophotometer (Moberg, 2001).

2.2.4 Plant tissue analysis

As already mentioned, sugarcane leaf was sampled at 18^{th} month of sugarcane age after planting for the plant crop cycle and also at 9^{th} and 12^{th} months of the ratoon one crop. The sampling unit was sugarcane stool. Four sugarcane shoot were randomly selected within the net plots and marked. Third dew lap leaf from the tip was chosen and cut using scateur. The leaves were then placed in brown bags and well labelled. The leaves sampled were then taken to the laboratory.

In the laboratory, the leaf samples were gently cleaned using distilled water and debris / dirt removed. Using a sharp knife, the leaf midrib was removed, leaving only the leaf sheath. This was then placed in brown bags which were then placed in the oven to dry at $72^{o}C$ to constant weight. The dried leaf samples were ground to fine texture using a plant mill. The ground leaf samples were subjected to dry ashing and also wet digestion. For dry ashing, 0.5 grams of the leaf samples was weighed in crucibles. The crucibles were then placed in a muffle furnace and heated for 3 hours at 600^{o}C. Ten ml of 6 N HCl and 10 ml of distilled water were added into the crucible to dissolve the ash, and the solution was filtered using Whatman number 42 filter paper. The amount of filtrate collected was then put into 25 ml volumetric flask and then topped up to mark using distilled water. The extract following dry ashing was used for determining Mn, Fe, Zn and Cu using respective wavelengths in an atomic adsorption spectrophotometer (AAS). One ml of extract was diluted and used for determining Ca and Mg in AAS and for K using a flame photometer.

The amount of P in the extract was determined using the ascorbic acid molybdate blue method. Total N in the plant samples was determined by the Kjedahl method. One gram of the plant samples was put in digestion tube, followed by addition of 10 ml 98 % H_2SO_4 and a scoop of mixed catalyst. This mixture was then digested in a digestion block for one hour and at 360^{o} C. The digest was then distilled after adding 25 ml of 40 % NaOH followed by titration with 0.05 N H_2SO_4 and boric acid indicator. The titre value was used to compute total N.

2.2.5 Statistical analysis

Data on soil chemical properties, nutrient content of sugarcane leaves as affected by the treatments were subjected to analysis of variance using the GENSTAT software (GENSTAT, 2011). A 2 x 3 x 3 general treatment structure in randomized blocks was used to analyse the data. Main plot effects and respective interactions on treatments were also analysed (GENSTAT, 2011). Comparison of means test was carried out using the least significance difference (LSD) at the 5 % probability level.

2.3 Results and Discussions

2.3.1 Effects of cropping systems, lime placement methods and lime rates on soil chemical properties

Effects of lime rates on some soil chemical properties

Findings from this study show that some soil chemical properties were significantly affected by cropping systems (CS), lime placement methods (LPM), lime rates (LR) and respective interactions as shown in Tables 2.2, 2.3, 2.4, 2.5 and 2.6. Lime rates significantly increased the soil pH (in water and KCl) for both 0 – 15 cm and 15 – 30 cm depth (Tables 2.2 and 2.3). Plots limed at 2 t ha^{-1} recorded highest soil pH compared to plots limed at 1 t ha^{-1} and control plots (not limed, 0 t ha^{-1}) (Table 2.3). Lime rates significantly decreased soil extractable Mn for top depth, 0 – 15 cm (Tables 2.4 and 2.5). Highest amount of extractable Mn was recorded in control (non limed plots) while lowest amount was recorded in plots limed at 1 t ha^{-1} and 2 t ha^{-1} (Table 2.5).

Table 2.2: F – test probabilities of the effects of cropping systems (CS), lime placement methods (LPM) and lime rates on soil pH, organic carbon, total nitrogen and extractable phosphorus for 0 – 15 cm (top) and 15 – 30 cm (sub) soil depth

	F – Test probabilities									
	Soil pH (in H_2O		Soil pH (in KCl)		OC		Total N		Extractable P	
	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub
CS	NS	**< 0.001**	**< 0.001**	**0.003**	**0.026**	**0.008**	NS	NS	NS	NS
LPM	NS	**< 0.001**	NS	**0.003**	NS	**0.039**	NS	NS	**0.039**	**0.003**
LR	**0.013**	**< 0.001**	**0.004**	**0.002**	NS	NS	NS	NS	NS	NS
CS x LPM	NS	NS	**< 0.001**	NS	NS	**0.01**	NS	**0.013**	NS	**0.014**
CS x LR	NS	NS	NS	NS	**0.011**	Ns	NS	NS	NS	NS
LPM x LR	NS	NS	NS	**0.021**	NS	NS	NS	NS	NS	NS
CS x LP x LR	NS	NS	**0.002**	NS	NS	NS	NS	NS	NS	NS
CV (%)	3.2	2.7	4.5	5.2	21.3	21.1	13.4	12.9	35.7	26.8

Significant effect at $P \leq 0.05$; CS – cropping systems; LPM – lime placement methods; LR – lime rates; OC – organic carbon; N – nitrogen; P – phosphorus

Table 2.3: Effects of cropping systems (CS), lime placement methods (LPM) and lime rates (LR) on soil pH, organic carbon, total nitrogen and extractable phosphorus for 0 – 15 cm depth (top soil) and 15 – 30 cm depth (sub soil)

		Soil pH (in Water)		Soil pH (in 1N KCl)		OC (%)		total N (%)		Extractable P (mg / kg)	
Factors	Levels	Top	Sub	Top	Sub	Top	Sub	Top	Sub	Top	Sub
CS	MC	6.33	6.20a	5.19a	4.99a	1.53a	1.218b	0.10	0.102	20.30	12.48
	IC	6.17	5.94b	4.95b	4.77b	1.75b	1.416a	0.11	0.105	18.76	13.23
	LSD (P ≤ 0.05)	NS	0.09	0.131	0.141	0.192	0.193	NS	NS	NS	NS
LPM											
	L-BC	6.21	5.94c	5.02	4.74b	1.6	1.409a	0.10	0.104	18.26b	14.3a
	L-DB	6.29	6.20a	5.08	5.05a	1.7	1.353a	0.11	0.104	23.91a	14.04a
	L-SB	6.25	6.07b	5.12	4.86b	1.6	1.189b	0.10	0.103	16.41b	10.22b
	LSD (P ≤ 0.05)	NS	0.159	NS	0.172	NS	0.154	NS	NS	5.38	3.08
LR (t ha^{-1})	0	6.20ab	5.93c	5.04b	4.73c	1.6	1.226	0.10	0.104	20.52	11.91
	1	6.11b	6.07b	4.96b	4.85b	1.7	1.318	0.11	0.105	17.53	12.25
	2	6.37a	6.21a	5.22a	4.99a	1.6	1.407	0.11	0.103	20.54	14.4
	LSD (P ≤ 0.05)	0.137	0.091	0.156	0.118	NS	NS	NS	NS	NS	NS
	CV (%)	3.2	2.7	4.5	5.2	21.3	21.1	13.4	12.9	35.7	26.8

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level of significance Key: NS – not significant at (P = 0.05); CV – coefficient of variation; MC – Sugarcane monoculture; IC – Intercropped sugarcane; L-BC – lime broadcasted; L-DB – lime deep banded; L-SB – lime shallow banded.

Table 2.4: F – test probabilities of the effects of cropping systems (CS), lime placement methods (LPM) and lime rates on soil extractable manganese, iron, zinc and copper 0 – 15 cm and 15 – 30 cm soil depth

	F – Test probabilities							
	Extractable Mn		Extractable Fe		Extractable Zn		Extractable Cu	
	Top	Sub	Top	Sub	Top	Sub	Top	Sub
CS	**0.018**	**< 0.001**	**0.025**	**0.004**	NS	**< 0.001**	**0.026**	**0.008**
LPM	NS	NS	NS	**0.003**	NS	NS	NS	**0.039**
LR	**0.012**	NS	NS	NS	NS	NS	NS	NS
CS x LPM	NS	**0.049**	NS	**0.007**	NS	**0.041**	NS	**0.010**
CS x LR	NS	NS	NS	NS	NS	NS	**0.011**	NS
LPM x LR	NS	NS	NS	NS	NS	NS	NS	NS
CS x LPM x LR	NS	NS	NS	NS	NS	NS	NS	NS
CV (%)	16	9.9	20	18.5	13.4	11.7	10.4	11

Significant effect at P ≤ 0.05; CS – cropping systems; LPM – lime placement methods; LR – lime rates; Mn – Manganese; Fe – Iron; Zn – Zinc; Cu - Copper

Table 2.5: Effects of cropping systems (CS), lime placement methods (LPM) and lime rates (LR) on soil extractable manganese (Mn), iron (Fe), zinc (Zn) and copper (Cu) for 0 – 15 cm depth (top soil) and 15 – 30 cm depth (sub soil)

		Extractable Mn mg kg^{-1}		Extractable Fe mg kg^{-1}		Extractable Zn, mg kg^{-1}		Extractable Cu, mg kg^{-1}	
Factors	Levels	Top	Sub	Top	Sub	Top	Sub	Top	Sub
CS	MC	172.6b	171.2b	121.7 b	121.7 b	1.72	1.43 b	1.53b	1.22b
	IC	196.5a	200.4a	142.5 a	137.7 a	1.82	1.62 a	1.75a	1.42a
	LSD ($P \leq 0.05$)	17.9	12.5	19.9	13.18	NS	0.114	0.192	0.142
LPM	L-BC	185.1	195.5a	137.30	145.3a	1.73	1.552	1.60	1.41a
	L-DB	175.2	177.8b	134.50	112.3b	1.873	1.497	1.67	1.36ab
	L-SB	193.4	184.0ab	124.5	125.0b	1.694	1.519	1.64	1.19b
	LSD ($P \leq 0.05$)	NS	15.4	NS	18.8	NS	NS	NS	0.107
LR (t ha^{-1})	0	203.2a	193.7	147.9a	137.2	1.796	1.524	1.61	1.602
	1	175.4b	188.0	118.4b	126.8	1.729	1.509	1.67	1.634
	2	172.1b	185.2	129.9ab	125.0	1.773	1.535	1.63	1.57
	LSD ($P \leq 0.05$)	21.9	NS	18.22	NS	NS	NS	NS	NS
	CV (%)	17.6	12.2	24	21,9	16.3	15.1	21.3	18.9

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level of significance. Key: NS – not significant at (P = 0.05); CV – coefficient of variation; MC – Sugarcane monoculture; IC – Intercropped sugarcane; L-BC – lime broadcasted; L-DB – lime deep banded; L-SB – lime shallow banded.

The amounts of exchangeable Ca at both 0 – 15 and 15 – 30 cm soil depth increased with increase in lime rates. Lime rate, 2 t ha^{-1} gave the highest exchangeable Ca at both depths while the least was where there was no lime (Table 2.7). Lime rate 2 t ha^{-1} led to highest soil pH and exchangeable Ca but lowest extractable Mn (Tables 2.6 and 2.7).

Table 2.6. F – test probabilities for the effects of CS, LPM and LR on exchangeable bases at 0 – 15 and 15 – 30 cm soil depths

	F – test probabilities							
	Top, 0 – 15 cm				**Sub, 15 – 30 cm**			
Treatments	**Mg**	**Ca**	**K**	**Na**	**Mg**	**Ca**	**K**	**Na**
CS	0.146	0.633	0.415	0.102	0.750	0.599	0.674	0.137
LPM	0.324	0.866	0.633	0.184	0.195	**0.106**	0.850	0.448
LR	0.192	**0.004**	0.872	0.059	0.200	**0.015**	0.328	0.550
CS x LPM	**0.032**	0.846	0.794	0.161	0.885	0.915	0.100	0.142
CS x LR	0.846	0.324	0.132	0.985	0.374	0.687	0.467	0.749
LPM x LR	0.121	0.142	0.092	0.269	0.434	< **0.001**	0.589	0.793
CS x LPM x LR	0.276	0.790	0.835	0.125	0.284	0.215	0.463	0.508

Significant effect at $P \leq 0.05$; CS – cropping systems; LPM – lime placement methods; LR – lime rates

Table 2.7: Effects of lime rates on soil exchangeable calcium

Lime rates, t / ha	0 – 15 cm soil depth Exc. Ca., cmol (+) / kg soil	15 – 30 cm soil depth Exc. Ca., cmol (+) / kg soil
0	19.37b	20.38b
1	20.49b	22.63a
2	23.92a	23.65a
LSD ($P \leq 0.05$)	2.69	2.09
CV %	18.7	13.9

Means in the same column followed by the same letter (s) are not significantly different at 0.05 level of significance. Key: Exc. – exchangeable, Ca – calcium, CV – coefficient of variation

Several studies in Kenya reported that agricultural lime (21 % CaO) led to increased soil pH and exchangeable Ca (Nekesa *et al*., 2007; Osundwa *et al*., 2013 and Kisinyo, 2016). Bolan *et al*. (2003) stated that liming enhances the chemical, physical and biological characteristics of soil. Hence the chemical characteristics, soil pH and exchangeable Ca of the study site were enhanced. The reaction of the lime in acidic soil is that lime dissolves in the soil, and Ca moves to the surface of the soil particles (exchange sites) to replace the acidity (H^+ and/or Al^{+++}). The acidity reacts with the carbonate (CO_3) to form carbon dioxide (CO_2) and water (H_2O). The result is a soil with higher pH or less acidic and more exchangeable Ca (Brady and Weil, 2008).

The primary purpose of liming acid soils is to overcome the chemical problems associated with acidity for example high Mn level (Bolan *et al*., 2003). Liming an acid soil is suggested as the best method to attain and maintain a suitable pH for the growth of a variety of crops. The benefits of liming include improved nitrogen fixation and availability of essential nutrients (Ca, P, Mo) and decreasing the solubility of toxic elements Al and Mn (Haynes and Ludeke, 1981).

Other soil chemical properties that were not significantly affected by liming in this study were total N, soil extractable P, soil extractable Mg, soil extractable K, and soil extractable Na, soil extractable Fe, Zn and Cu. The results are contrary to the study by

Bolan *et al.* (2003) who found that increased liming increased mineralization / nitrification. It is therefore expected that plots that received lime should have indicated increased soil total N. Liming has often been shown to enhance microbial populations and the decomposition of organic matter, thereby releasing inorganic plant nutrients such as N, S and P to soil solution. Unless these nutrients are actively taken up plants they are liable for leaching losses. The possible lack of significant difference between the cropping systems, lime placement methods and lime rates on total soil nitrogen may have been a result of the leaching of the soil nitrates (Bolan *et al.*, 2003). Lime rates did not significantly affect soil extractable P (Tables 2.2 and 2.3). The reason could be the adequate level of available P in the soil prior to establishment of the experiment (Table 2.1).

Effects of lime placement methods on soil chemical properties for 0 – 15 cm and 15 – 30 cm depth

Lime placement methods significantly affected soil pH (in water), soil pH (1 N KCl), soil OC, exchangeable Ca, extractable Fe and Cu for 15 – 30 cm depth (Tables 2.2, 2.4 and 2.6. Plots that were deep banded with lime (L-DB) recorded highest soil pH, exchangeable Ca and extractable P for the 15 – 30 cm depth. Plots broadcasted with lime (L-BC) recorded the highest soil OC, extractable Fe and Cu for 15 – 30 cm depth. Lime deep banded (L-DB) plots showed highest exchangeable Ca, while the least was in plots which were lime broadcasted (L-BC) as given in Table 2.8.

Similar results of lime placement were reported on studies of lime management in soybean no – tillage system in Brazil (Rosa *et al*., 2015). Rosa *et al.* (2015) determined the effect of lime incorporated at different depths namely, on the soil surface, at 0 – 15 cm depth and at 0 – 30 cm using tractor drawn implements such as chisel ploughs and disc harrows.

Table 2.8: Effects of lime placement methods on exchangeable calcium

Lime placement methods	15 - 30 cm soil depth Exc. Ca., cmol (+) / kg soil
Lime broadcasted (L-BC)	20.87b
Lime shallow banded (L-SB)	21.88ab
Lime deep banded (L-DB)	23.91a
LSD ($P \leq 0.05$)	2.09
CV %	13.9

Means in the same column followed by the same letter (s) are not significantly different at 0.05 level of significance. Key: Exc. – exchangeable, Ca – calcium, CV – coefficient of variation

Weirich *et al*. (2000) noted that deeper incorporation raises the pH value of the sub – soils to acceptable levels for improved yields. The results of this study are in agreement to those of Rosa *et al*. (2015) who concluded that lime incorporated within 0 – 15 cm soil depth and also within 0 – 30 cm soil depth plough resulted in increased soil pH and improved chemical condition which then led to higher soybean yields. Freiria *et al*. (2008) cited in Rosa *et al*. (2015) noted that lime applied on the surface (broadcasted) increased exchangeable Ca and Mg in the 0 – 15 cm depth, while lime incorporated in 0 – 20 cm depth led to increased Ca and Mg down to the 30 cm depth.

Effects of cropping systems on soil chemical properties for 0 – 15 cm and 15 – 30 cm depth

Cropping systems (CS) significantly affected the soil pH, soil OC, extractable Mn, Fe and Cu for 0 – 15 cm and 15 – 30 cm depth (Tables 2.2 and 2.4). Plots under sugarcane monocrop recorded highest soil pH and also soil OC for 0 – 15 cm compared to plots under intercropped sugarcane and soybeans (Table 2.3). Plots under intercropped sugarcane and soybean recorded highest soil extractable Mn, Fe, Cu for both 0 – 15 cm and 15 – 30 cm. For 15 – 30 cm, extractable Zn was recorded in plots intercropped with sugarcane and soybeans (Table 2.5).

The low pH under IC than MC is related to the decomposition of the soybean residues which were incorporated. Decomposition of organic matter and transformation of N are some of the soil induced processes that contribute to acid generation in soils (Bolan *et al*., 2003). Decomposing plant litter rich in organic compounds but low in basic cations lead to production of organic acids by soil microorganism (Uren, 2001). Soybean residues are rich in organic compounds hence explain the possible reason for low soil pH under sugarcane intercropped (IC) than sugarcane monoculture (MC) system.

The high soil extractable Mn, Fe, Zn and Cu under IC is linked to the low pH recorded under IC system. These micronutrients tend to be more soluble and available under acid conditions. Generally, the solubility and phyto - availability of metals are inversely related to soil pH. Several studies reported increased levels of soluble Mn with decrease in soil pH (Sumner *et al*., 1991; Patra and Mohanty, 1994). Bolan *et al*. (2003) stated that Zinc (Zn) activity increases rapidly with decreasing pH. The pH - dependent increased solubility of Zn in soils is governed by a complex mixture of mechanisms including adsorption on sesquioxides, co - precipitation with Al, and complexation with organic matter at lower pH (Stahl and James, 1991) that lead to increased solubility from the insoluble reservoir.

2.3.2 Interaction effects of cropping systems, lime placement methods and lime rates on some soil chemical properties

Effects of CS x LPM on soil pH (In 1 N KCl) for 0 – 15 cm soil depth

There was a significant ($P < 0.001$) interaction effect between cropping systems and lime placement method on soil pH (Table 2.2 and Figure 2.4). This result indicates that the change in soil pH with regard to cropping system and lime placement methods varies at different magnitudes. The findings imply that, use of one lime placement method to a given cropping system will not show similar result to a different cropping system. Therefore each cropping system should have a respective lime placement method.

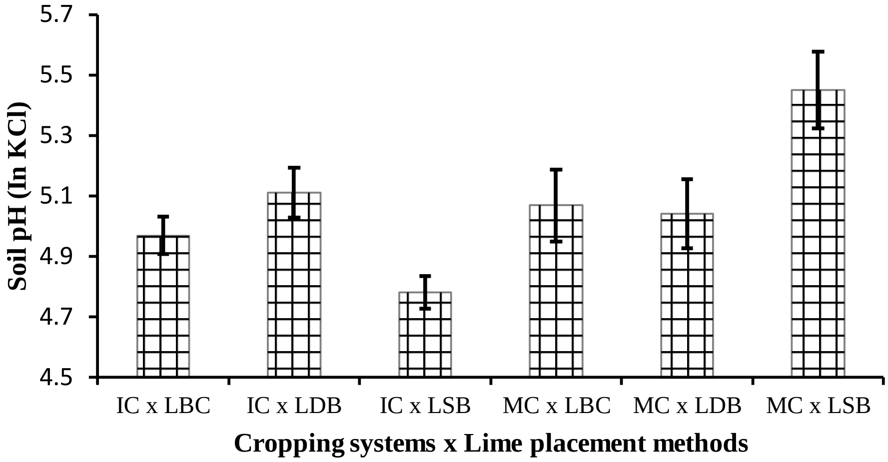

Figure 2.4: Interaction CS x LPM on soil pH for 0 – 15 cm depth

Effects of CS x LPM on soil OC and total N for 15 – 30 cm soil depth

There was a significant interaction effect between cropping systems and lime placement method on soil OC and total N at (P = 0.01) and (P = 0.013) respectively (Table 2.2 and Figure 2.5). This result shows that, variation in soil OC and total N as influenced by cropping system type and lime placement method differs based on the combination. Under IC plots, soil N increased in the following pattern, LSB > LDB > LBC. While under MC plots, soil N and soil OC decreased in the following pattern, LSB < LDB < LBC (Figure 2.5). The findings signify that a given lime placement method to a given cropping system will not show similar result to a different cropping system. Therefore each cropping system should have varied suitable lime placement method so as to benefit on soil OC and total N.

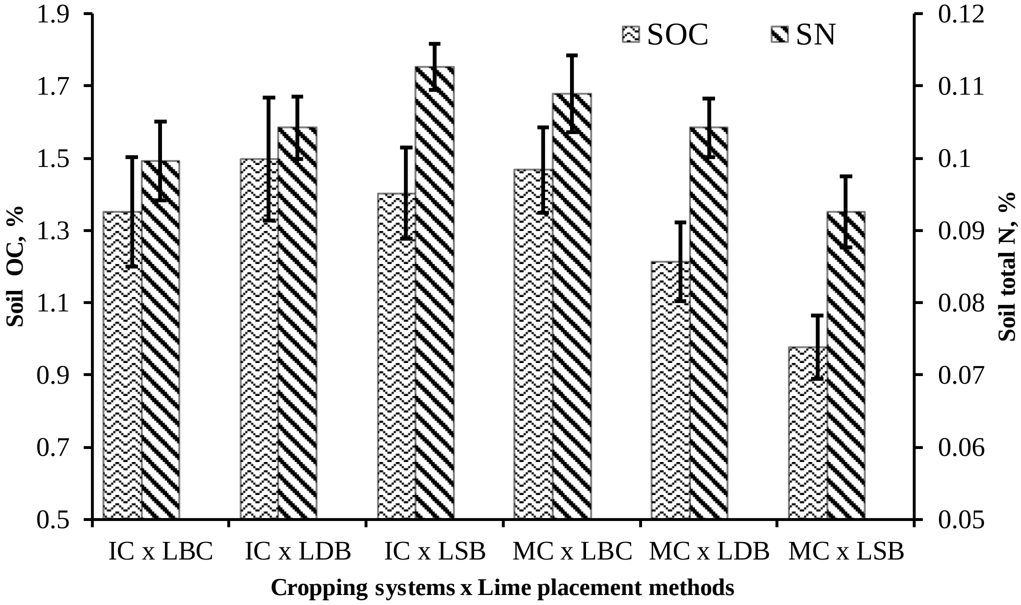

Figure 2.5: Interaction CS x LPM on soil organic carbon (SOC) and soil total N (SN) for 15 – 30 cm depth

Effects of CS x LPM on soil exchangeable Mg for 0 – 15 cm soil depth

There was a significant (P = 0.032) interaction effect between cropping systems and lime placement method on soil extractable Mg (Table 2.6 and Figure 2.6). The CS x LPM indicated that, the change in soil exchangeable Mg based on the cropping system and the lime placement methods do no vary at the same magnitude. The results imply that it is important to consider lime placement methods for either sugarcane monocrop or intercropped sugarcane and soybeans.

Effects of CS x LPM on soil extractable Manganese for 15 – 30 cm depth

There was a significant (P = 0.007) interaction effect between cropping systems and lime placement methods on soil extractable Mn (Table 2.4 and Figure 2.7). Under sugarcane monoculture (MC) system, amount of Mn decreased in the following pattern of lime placement methods, LSB < LDB < LBC (Figure 2.7).

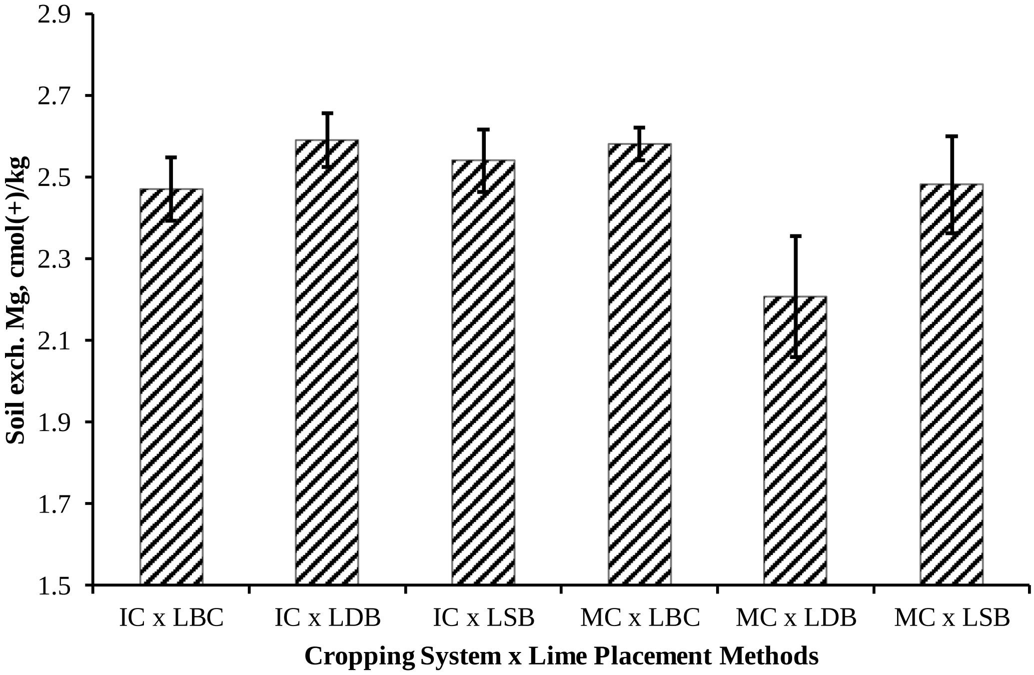

Figure 2.6: Interaction CS x LPM on soil exchangeable Mg for 0 – 15 cm depth

This, unlike under IC where soil Mn amount declined in plots broadcasted with lime (LBC) to plots LDB and then rose in plots LSB (Figure 2.7). Cropping systems (CS) influenced much on the soil Mn in the interaction. Therefore, different lime placement method (LPM) should be used for each of the cropping systems (CS).

Effects of CS x LR on soil OC for 0 – 15 cm depth

There was a significant (P = 0.01) interaction effect between cropping systems and lime rates on soil OC for 0 – 15 cm depth (Table 2.2 and Figure 2.8). This result indicates that difference in soil OC as affected by CS and LR differs based on the interaction. Under MC, soil OC decreased with increase in lime rates. While under IC, soil OC increased with increase in lime rates (Figure 2.8). This shows that in each cropping system, different lime rates should be used because the reaction of the lime rates varies.

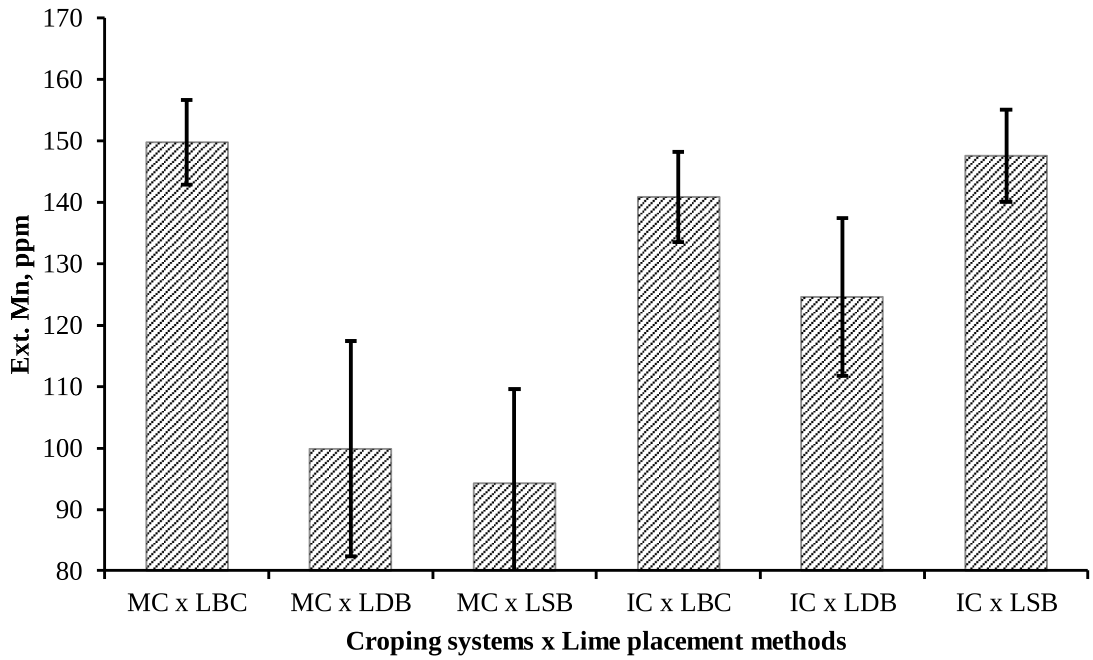

Figure 2.7: Interaction CS x LPM effect on soil extractable Mn for 15 – 30 cm depth

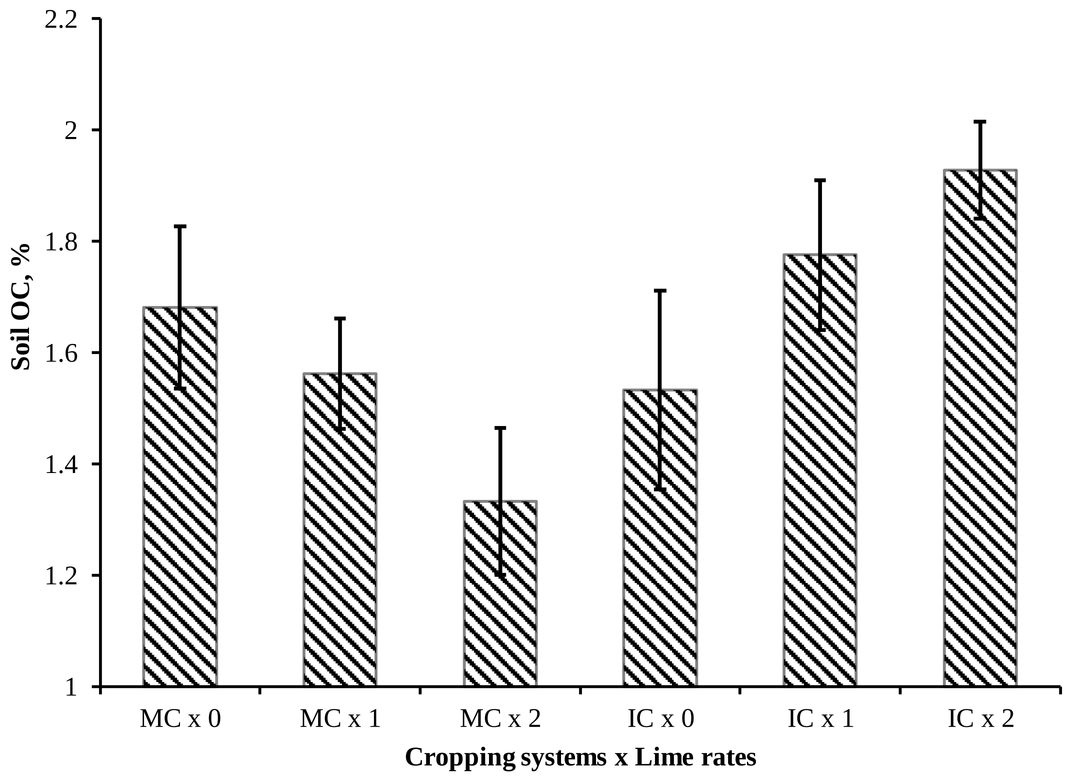

Figure 2.8: Effects of CS x LR on soil OC for 0 – 15 cm depth

Effects of LPM x LR on soil pH (In 1 N KCl) for 15 – 30 cm

There was a significant (P = 0.021) interaction effect between lime placement methods and lime rates on soil pH (in KCl) for 15 – 30 cm depth (Table 2.2 and Figure 2.9). There was increase in soil pH with increased lime where lime was banded deep banded (LDB) and also where lime was banded shallow (LSB) (Figure 2.9).

Effects of LPM x LR on soil exchangeable Ca for 15 – 30 cm depth

There was a significant (P < 0.001) interaction effect between lime placement methods (LPM) and lime rates (LR) on exchangeable Ca (Table 2.6 and Figure 2.10). Plots that had the combination LDB x 2 t ha^{-1} showed the highest soil exchangeable Ca (Figure 2.10). This indicates that variation in soil exchangeable Ca is affected by varied lime placement methods and also varied lime rates. Therefore, different lime rates should be determined for different lime placement methods.

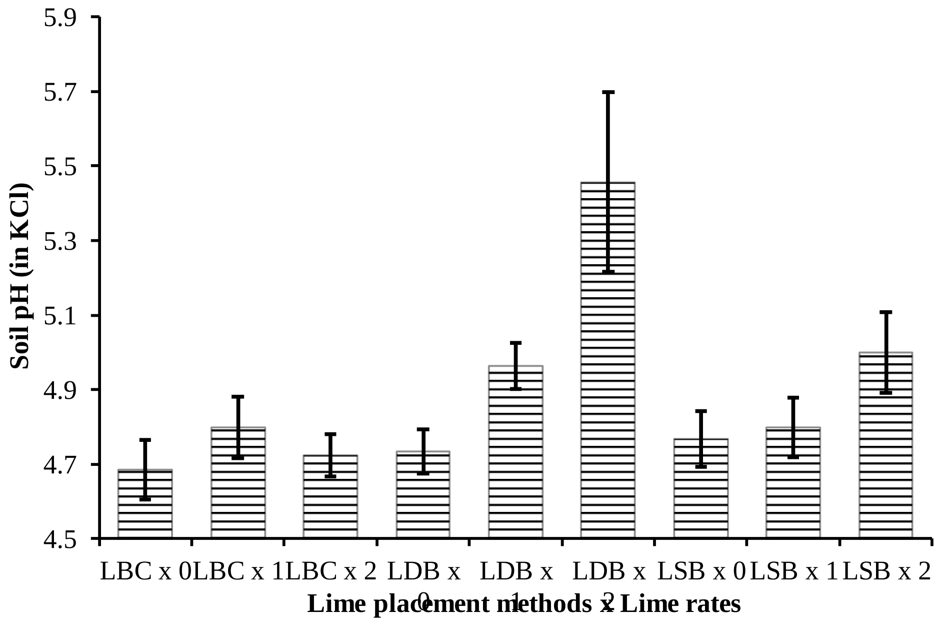

Figure 2.9: Effects of LPM x LR on soil pH for 15 – 30 cm

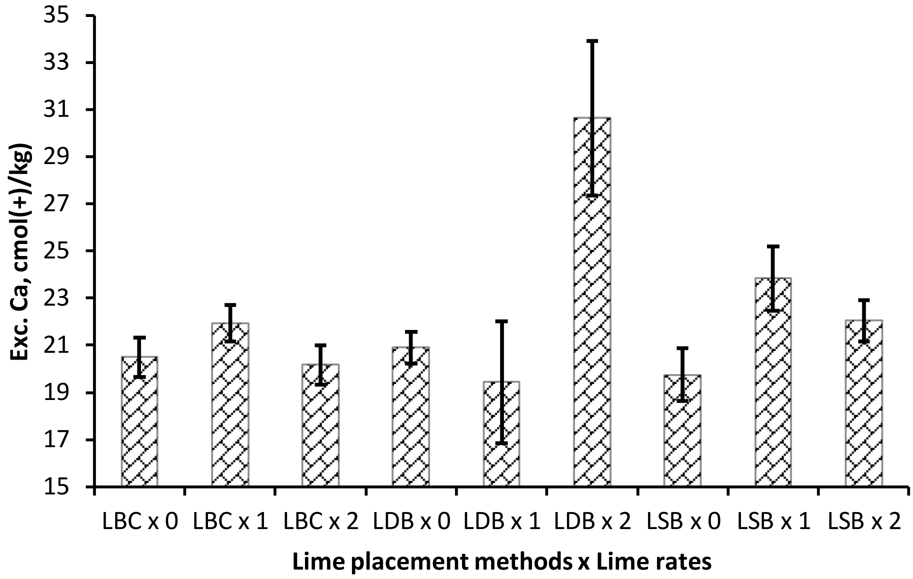

Figure 2.10: Effects of LPM x LR on exchangeable Ca for 15 – 30 cm depth

2.3.3 Effects of cropping systems (CS), lime placement methods (LPM) and lime rates (LR) on sugarcane nutrients content at plant crop and ratoon one cycles

The macronutrients tested for sugarcane leaves were total nitrogen (N), total phosphorus (P), total potassium (K), total calcium (Ca) and total magnesium (Mg) as shown in Tables 2.9, 2.10, 2.11 and 2.12. The micronutrients were total manganese (Mn) and total zinc (Zn) as shown in Tables 2.11 and 2.12.

Cropping systems significantly influenced sugarcane total Ca (P = 0.04) and total Mn (P = 0.05) for plant crop cycle at the 18^{th} month after planting (Table 2.9 and 2.12). Sugarcane under intercropped system (IC) recorded higher total Ca (0.44 %) and total Mn (76.96 mg kg^{-1}) compared to sugarcane under MC which was 0.38 % and 64.93 mg kg^{-1} for total Ca and total Mn, respectively. The total Ca recorded was in the optimum range (0.2 – 0.45 %). Likewise for total Mn was in the optimum range (20 – 100 mg kg^{-1}). The critical ranges are classified according to Calcino *et al.* (2000) and McCray *et al.* (2013).

Lime placement methods significantly affected the sugarcane total N for plant crop cycle at 18th month after planting (MAP). Sugarcane under plots that lime was broadcasted (L-BC) showed highest total N (0.47 %) compared to those under plots that lime was shallow - banded (L-SB) or deep - banded (L-DB), which was 0.41 % and 0.40 %, respectively (Table 2.10). However, the levels of total N were below the critical value (< 1.80 %). Lime placement methods significantly affected the sugarcane total P for plant crop cycle at 18th MAP (Table 2.9). Sugarcane under plots that were L-BC recorded the highest P (0.08 %) compared sugarcane under L-SB and L-DB, which was 0.06 % and 0.06 %, respectively (Table 2.10).

Lime placement methods significantly affected the sugarcane total Ca for plant crop cycle at 18th MAP (Table 2.9 and 2.12). Sugarcane under plots that were L-SB recorded the highest Ca (0.44 %) compared to sugarcane under L-BC and L-BD, which was 0.37 % and 0.42 %, respectively. The levels of total Ca was at optimum range (0.20 – 0.45 % Ca) as shown in Table 2.12. Sugarcane under plots that were L-SB recorded the highest Zn (17.93 mg kg^{-1}) compared to sugarcane under L-BD and also under L-BC which was 16.95 ppm and 13.03 mg kg^{-1}, respectively (Table 2.12). In terms of levels, sugarcane total Zn at 17.93 mg kg^{-1} was within optimum range (17 – 32 mg kg^{-1}), those at 16.95 mg kg^{-1} was between critical value (> 15 mg kg^{-1}) and optimum range, those at 13.03 mg kg^{-1} were below the critical Zn value (< 15 mg kg^{-1}) according to Calcino *et al.* (2000) and McCray *et al.* (2013).

Table 2.9: F – test probabilities for the effects of cropping systems (CS), lime placement methods (LPM) and lime rates (LR) on total Nitrogen (N), total Phosphorus (P) , total potassium (K) and total calcium (Ca) content in sugarcane leaves at plant crop cycle and ratoon one cycle

		F test probabilities											
		Total N			**Total P**			**Total K**			**Total Ca**		
SOV	**d.f.**	**PC**	**R1, 9 MAR**	**R1, 12 MAR**	**PC**	**R1, 9 MAR**	**R1, 12 MAR**	**PC**	**R1, 9 MAR**	**R1, 12 MAR**	**PC**	**R1, 9 MAR**	**R1, 12 MAR**
CS	1	0.110	0.669	0.114	0.942	0.944	0.721	0.458	0.138	0.774	**0.003**	0.187	0.750
LPM	2	**0.015**	0.828	0.177	< **0.001**	0.134	0.969	0.518	0.538	0.460	**0.021**	0.159	0.366
LR	2	0.109	0.521	0.293	0.127	0.238	0.140	0.773	0.824	0.153	0.641	0.163	0.334
CS x LPM	2	0.340	0.828	0.716	0.904	0.951	0.986	0.165	0.366	0.659	0.278	0.242	0.811
CS x LR	2	0.344	0.815	**0.038**	0.979	0.671	0.727	0.616	0.242	0.730	0.941	0.637	0.312
LPM x LR	4	0.144	0.669	0.461	0.058	0.169	0.508	0.795	0.279	0.196	0.525	0.601	0.276
CS x LPM x LR	4	0.153	0.049	0.732	0.787	0.224	0.743	0.669	0.039	0.389	0.868	0.619	0.513

Significant effect at $P \leq 0.05$; CS – cropping systems; LPM – lime placement methods; LR – lime rates; PC – plant crop cycle; R 1 – ratoon one crop cycle; MaP – months after planting sugarcane setts; MaR – months after ratoon one emergence; d.f. – degrees freedom;

Table 2.10: Effects of cropping systems, lime placement methods and rates on sugarcane uptake of nitrogen, phosphorus and potassium at plant crop and ratoon one cycles

		Total nitrogen (% N)			Total phosphorus (% P)			Total potassium (% K)		
Factors	Levels / Stage	PC – 18th MaP	R 1 – 9th MaR	R 1 – 12th MaR	PC – 18th MaP	R 1 – 9th MaR	R 1 – 12th MaR	PC – 18th MaP	R 1 – 9th MaR	R 1 – 12th MaR
Cropping systems (CS)	MC	0.42	1.17	1.13a	0.07	0.13	0.13	0.58	0.62	0.61
	IC	0.45	1.16	1.09b	0.07	0.13	0.13	0.63	0.56	0.60
	LSD ($P \leq 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS
Lime placement Methods (LPM)	L-BC	0.47a	1.17	1.08	0.08a	0.13	0.13	0.55	0.57	0.62
	L-DB	0.40b	1.18	1.12	0.06b	0.13	0.13	0.61	0.62	0.63
	L-SB	0.41b	1.16	1.13	0.06b	0.14	0.13	0.66	0.58	0.58
	LSD ($P \leq 0.05$)	0.04	NS	NS	0.02	NS	NS	NS	NS	NS
Lime rates (LR) – t ha^{-1}	0	0.43	1.17	1.12	0.06	0.14	0.12	0.58	0.59	0.61
	1	0.46	1.15	1.13	0.07	0.13	0.14	0.64	0.57	0.56
	2	0.41	1.19	1.08	0.06	0.13	0.13	0.59	0.60	0.65
	LSD ($P \leq 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS
	CS x LR	NS	NS	NS	NS	NS	NS	NS	NS	NS
	LPM x LR	NS	NS	NS	**0.04**	NS	NS	NS	NS	NS
	CS x LPM x LR)	NS	NS	NS	NS	NS	NS	NS	**0.04**	NS
	CV (%)	16.1	8.3	8.3	25.9	11.8	19.3	41.3	22.8	20.2

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level. Key: NS – not significant at ($P = 0.05$); CV – coefficient of variation; MC – Sugarcane monoculture; IC – Intercropped sugarcane; L-BC – lime broadcasted; L-DB – lime deep banded; L-SB – lime shallow banded. PC – plant crop cycle; R 1 – ratoon one crop cycle; MaP – months after planting sugarcane setts; MaR – months after ratoon one emergence

Table 2.11: F – test probabilities for the effects of cropping systems (CS), lime placement methods (LPM) and lime rates (LR) on total Magnesium (Mg), total Manganese (Mn) and total Zinc (Zn) content in sugarcane leaves at plant crop cycle and ratoon one cycle

		F test probabilities								
		Total magnesium			**Total manganese**			**Total zinc**		
SOV	**d.f.**	**PC**	**R1, 9 MAR**	**R1, 12 MAR**	**PC**	**R1, 9 MAR**	**R1, 12 MAR**	**PC**	**R1, 9 MAR**	**R1, 12 MAR**
CS	1	0.077	0.419	0.336	**0.004**	0.419	0.479	0.600	0.896	0.941
LPM	2	0.714	0.739	0.967	0.465	0.626	0.106	0.719	0.063	0.395
LR	2	0.561	0.225	0.728	0.183	0.317	0.666	0.378	0.097	0.332
CS x LPM	2	0.442	0.309	0.543	0.413	0.904	0.546	0.335	0.344	0.263
CS x LR	2	0.624	0.876	0.559	0.918	0.696	**0.003**	0.927	0.917	0.965
LPM x LR	4	0.626	0.449	0.455	0.845	0.647	0.964	0.792	0.692	0.078
CS x LPM x LR	4	0.413	0.154	0.085	0.127	0.817	0.204	0.129	0.807	0.349

Significant effect at $P \leq 0.05$; CS – cropping systems; LPM – lime placement methods; LR – lime rates; PC – plant crop cycle; R 1 – ratoon one crop cycle; MaP – months after planting sugarcane setts; MaR – months after ratoon one emergence; d.f. – degrees freedom;

Table 2.12: Effects of cropping systems, lime placement methods and rates on sugarcane uptake of calcium, magnesium, manganese and zinc at plant crop and ratoon one cycles

		Total Calcium (% Ca)			Total magnesium (% Mg)			Total manganese (mg kg^{-1} Mn)			Total zinc (mg kg^{-1} Zn)		
Factors	Levels	PC - 18	R 1 - 9	R 1 - 12	PC - 18	R 1 - 9	R 1 - 12	PC - 18	R 1 - 9	R 1 - 12	PC – 18	R 1 - 9	R 1 - 12
CS	MC	0.38b	0.39	0.41	0.07	0.13	0.17	64.93b	44.30	50.56	3.22	16.08	13.17
	IC	0.44a	0.43	0.42	0.08	0.15	0.15	76.96a	47.02	48.55	3.67	15.86	12.94
	LSD ($P \leq 0.05$)	0.05	NS	NS	NS	NS	NS	11.43	NS	NS	NS	NS	NS
LPM	L-BC	0.37b	0.44	0.43	0.07	0.13	0.17	67.44	45.13	52.09	3.50	13.03b	10.22
	L-DB	0.42a	0.37	0.45	0.07	0.15	0.16	72.72	47.86	51.34	3.00	16.95a	13.61
	L-SB	0.44a	0.42	0.37	0.07	0.14	0.16	72.67	43.99	45.23	3.83	17.93a	15.34
	LSD ($P \leq 0.05$)	0.03	NS	NS	NS	NS	NS	NS	NS	NS	NS	1.53	NS
LR	0 t ha^{-1}	0.40	0.40	0.46	0.07	0.12	0.16	76.22	49.16	51.29	3.11	18.14	11.71
	1 t ha^{-1}	0.42	0.38	0.39	0.07	0.16	0.18	68.17	43.04	49.12	2.94	16.32	11.13
	2 t ha^{-1}	0.40	0.45	0.39	0.07	0.14	0.16	68.44	44.78	48.25	4.28	13.45	16.32
	LSD ($P \leq 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	CV (%)	19.3	28.8	39.6	20.8	43.3	63.9	20.6	29.4	20.7	90.7	43.8	82.1

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level of significance.
Key: NS – not significant at ($P = 0.05$); CV – coefficient of variation; MC – Sugarcane monoculture; IC – Intercropped sugarcane;
L-BC – lime broadcasted; L-DB – lime deep banded; L-SB – lime shallow banded.

There was no significant effect of lime rates on the nutrients content in sugarcane leaves during the plant crop cycle and also ratoon one cycle. The leaf nutrient status was assessed based on the treatments, crop cycle and age at time of leaf sampling. Time of leaf sampling, especially for purposes of fertilizer recommendations, should be carried out during the actively growing stage of sugarcane, hereby referred to the grand growth stage (Calcino *et al*., 2000; McCray and Mylavarapu, 2013).

The four sugarcane growth stages are germination and establishment phase; tillering phase; grand growth phase and ripening and maturation phase (Meyer and Clowes, 2011; Rossler *et al*., 2013). Germination denotes activation and subsequent sprouting of the vegetative bud from the planted sugarcane setts (sugarcane vegetative planting material). Tillering involves physiological process of repeated under ground branching from compact nodal joints of the primary shoot. Grand growth involves actual sugarcane formation and elongation and thus yield build up. Finally, Ripening and maturation phase entails sugar synthesis and rapid accumulation of sugar takes place while the vegetative growth is reduced.

Nitrogen is one of the main building blocks of proteins. Nitrogen is responsible for growth and expansion of green leaves and is essential for photosynthesis and sugar production (Calcino *et al*., 2000). The sugarcane leaf total N across the treatments, crop cycle and age was very low, regarded as below the critical N level (< 1.80 %). At plant crop cycle and 18^{th} month, the sugarcane leaf N content ranged from mean of 0.41 to 0.47 % (Table 2.10). However, at ratoon crop cycle at 9^{th} and 12^{th}, sugarcane leaf N range was (1.15 to 1.17 %) and (1.08 to 1.13 %) respectively (Table 2.10). It appears the low total N is attributed to the time the leaves were sampled. Schroeder (2000) stated sugarcane crop age as one of the factors influencing leaf analysis and nutrient content. Bishop (1965) cited in Schroeder (2000) reported that leaf N decreased markedly from a mean of 2.70 % at 1st month to 1.85 % in the 4th month and further decreased to 1.67 % in the 9th month.

Phosphorus is essential for the formation of a strong and vigorous root system and plays a role in photosynthesis and many other biochemical processes such as cell division and cell growth (Calcino *et al*., 2000; Meyer, 2011). The sugarcane leaf P content was very low regarded as below the critical leaf P level (< 0.18 %). At plant crop cycle and 18th month, the sugarcane leaf P content ranged from mean of 0.02 to 0.07 % (Table 2.10). The ratoon crop cycle at 9th and 12th, sugarcane leaf P range was (0.13 to 0.14 %) and (0.12 to 0.13 %) respectively (Table 2.10).

Potassium is involved in chlorophyll development, helps the plant use other nutrients and water more efficiently and controls the movement of sugars in the plant. The sugarcane leaf K content was very low regarded as below the critical leaf K level (< 1.11 %). At plant crop cycle and 18th month, the sugarcane leaf potassium content ranged from mean of 0.55 to 0.64 % (Table 2.10). The ratoon crop cycle at 9th and 12th, sugarcane leaf K range was (0.56 to 0.62 %) and (0.56 to 0.65 %) respectively (Table 2.10).

Calcium is essential for the growth and development of the spindle, leaves and roots. Calcium comprises part of the cell walls, thus strengthening the plant. The sugarcane leaf Ca content was adequate regarded as above the critical leaf Ca level (> 0.2 %). At plant crop cycle and 18th month, the sugarcane leaf Ca content ranged from mean of 0.37 to 0.44 % (Table 2.12). The ratoon crop cycle at 9th and 12th, sugarcane leaf Ca range was (0.37 to 0.45 %) and (0.37 to 0.46 %) respectively (Table 2.12).

Magnesium is an essential constituent of chlorophyll where photosynthesis takes place to underpin sugar production and other growth processes (Meyer, 2011). At plant crop cycle aged 18th month, the sugarcane leaf Mg content was very low regarded as below the critical leaf Mg (< 1.13 %). However, at ratoon one crop cycle aged 9th and 12th month, Mg content was adequate regarded as above 1.13 % Mg critical level (Table 2.12). The range of leaf Mg content for ratoon was 0.12 to 0.16 % while for plant crop cycle was 0.07 to 0.08 % as shown in Table 2.12.

Manganese is involved in photosynthesis, chlorophyll production, and the formation of organic compounds, especially enzyme systems (Calcino *et al.*, 2000; Meyer, 2011). The sugarcane leaf Mn content was adequate regarded as above the critical leaf Mn level (> 15 mg kg^{-1}). At plant crop cycle and 18th month, the sugarcane leaf Mn content ranged from mean of 64.93 to 76.96 mg kg^{-1} (Table 2.13). The ratoon crop cycle at 9th and 12th, sugarcane leaf Mn range was (43.04 to 49.16 mg kg^{-1}) and (48.25 to 52.09 mg kg^{-1}) respectively (Table 2.12).

Zinc is involved in chlorophyll formation, the regulation of plant growth and development, and the efficient use of water (Calcino *et al.*, 2000; Meyer, 2011). At plant crop cycle aged 18th month, the sugarcane leaf Zn content was very low regarded as below the critical leaf Zn (< 10 mg kg^{-1}) (Table 2.12). However, at ratoon one crop cycle aged 9th and 12th month, Mg content was adequate regarded as above 10 mg kg^{-1} Zn critical level. The range of leaf Zn content for ratoon was 3.00 to 4.28 mg kg^{-1} while for plant crop cycle was 11.30 to 17.93 mg kg^{-1} (Table 2.12).

2.3.4 Effects of interactions of the main factors on nutrient content of sugarcane leaves

Influence of the interactions of the main factors on nutrient content of sugarcane during plant crop and ratoon one cycle is given in Tables 2.9, 2.10, 2.11 and 2.12. There was significant interaction (P = 0.01) between CS and LR on total Mn in sugarcane leaves during ratoon one cycle at 12th month after ratoon one emergence (Table 2.11 and Figure 2.11). Under MC, total Mn in leaves increased with increase in lime rate. While under IC, total Mn decreased with increase in lime rates (Figure 2.11). There was significant interaction (P = 0.038) between CS and LR on total N in sugarcane leaves during ratoon one cycle at 12th month after ratoon one emergence (Table 2.09 and Figure 2.12). Under MC, total N in leaves was high when lime rate used was 1 t ha^{-1}. While under IC, total N in sugarcane leaves decreased with increase in lime rate (Figure 2.12).

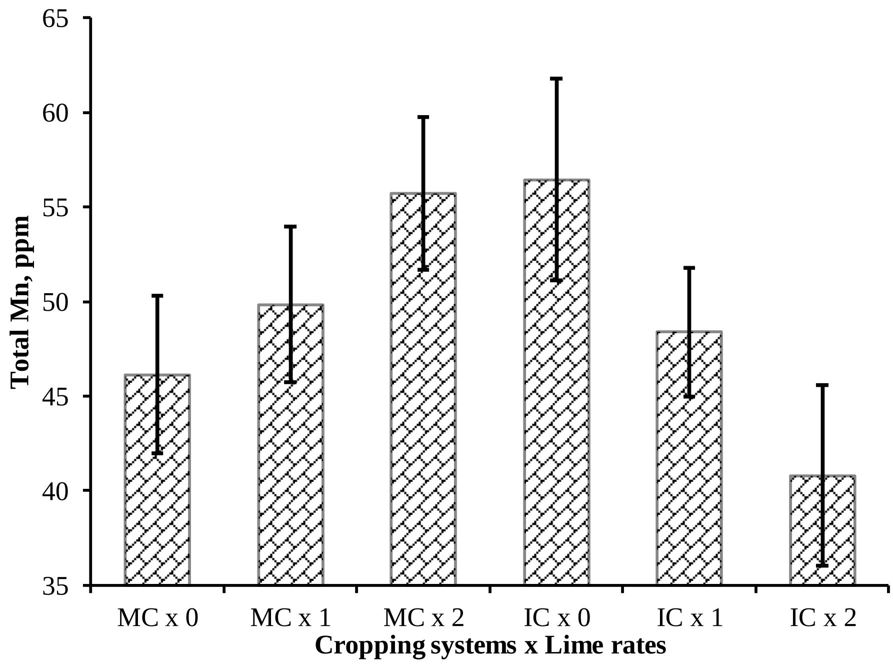

Figure 2.11: Effects of CS x LR on Mn content in sugarcane leaves

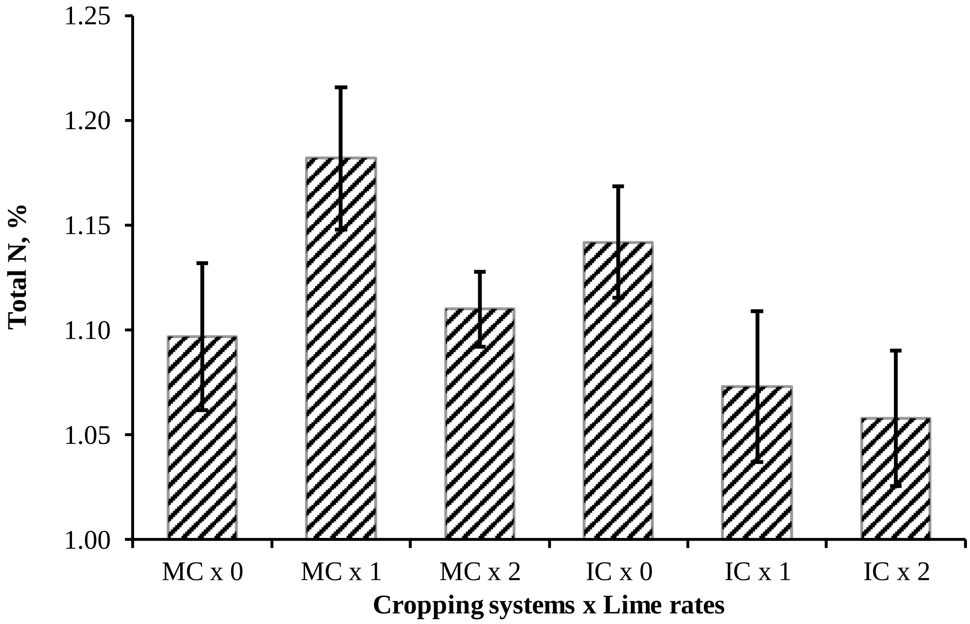

Figure 2.12: Effects of CS x LR on total N in sugarcane leaves

2.5 Conclusions

Liming has the potential to reduce toxicity caused by high levels of the micronutrients. Lime placement methods seemed to affect soil properties although variedly. The study shows that, sub soil acidity is best limed when lime is deep banded as a lime placement method is employed. The increased acidity under intercropped system is a result of the reaction during decomposition of soil organic carbon / soil organic matter generated from sugarcane and soybean residues. The increase in Ca and Mn content of sugarcane leaves is attributed to decomposition of soybean residues which then produced calcium. In view of the findings of increased N, P, Ca and Zn with liming, lime rate 2 tons ha^{-1} is recommended for use to ameliorate soil acidity for acidified Cambisols soils of Kibos, Kisumu County, Kenya. Also, lime placement methods should take into consideration the soil pH stratification with depth. Lime banded should only be employed when sub soil acidity is identified. Lime broadcasted, still remains the preferred lime placement method to ameliorate soil pH within plough depth 0 – 15 cm when acidity is identified.

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CHAPTER THREE

3.0 EFFECTS OF CROPPING SYSTEMS, LIME PLACEMENT METHODS AND RATES ON SUGARCANE YIELDS AND QUALITY UNDER ACIDIFIED SOILS OF KIBOS, KENYA

Abstract

This field study was conducted to investigate whether appropriate lime placement methods, lime rates and intercropped sugarcane with soybeans leads to amelioration of soil pH hence increased yields and quality of sugarcane for plant and ratoon one crop cycles. Cambisols of the study site at Kibos, Kisumu County are acidified due to long term use of acidifying fertilizers and continuous sugarcane monoculture. Acidified soils are a constraint to crop production due to imbalance in availability of essential plant nutrients. Appropriate cropping systems and liming are therefore advocated. The field experiment design was split - split plot in randomized complete block arrangements was employed. The factors and respective levels (in parenthesis were): the main plots were two cropping systems namely, sugarcane monoculture [MC] and intercropped sugarcane and soybeans [IC]). The sub – plots were three lime placement methods (lime broadcasted [L-BC], lime shallow banded, 0 – 15 cm [L-SB] and lime deep banded, 15 – 30 cm (L-DB] and the sub - sub plots ; lime rates (0, 1 and 2 t ha^{-1}). Intercropped sugarcane led to high sugarcane yields than the sugarcane monoculture for plant crop cycle. No significant effect was observed for ratoon crop harvest. Lime use caused changes on sugarcane quality [pol % cane and commercial cane sugar] for plant crop and that lime placement method [lime shallow banded] gave the highest reading while the least was for sugarcane under lime broadcasted. There was significant reduction of yield and quality (pol % and brix % juice) from plant crop to ratoon crop cycle. It is therefore concluded that liming plays a

limited role on the direct effect on sugarcane yield. Liming only plays a significant and direct role on amelioration of soil acidity and nutrient transformations. Liming should therefore be integrated with other cropping and nutrient management strategies for increased yields to be witnessed.

Keywords**:** Soil acidity, lime rates, lime placements, sugarcane yields

3.1 Introduction

Acidification of the soils of western Kenya threatens the productivity of economic crops such as sugarcane and annual legume crops such as soybeans. The acid soils cause soil fertility problems such as aluminium (Al) and manganese (Mn) toxicity, calcium (Ca) and magnesium (Mg) deficiency and low molybdenum (Mo) and phosphorus (P) availability which are constraints to crop production (Kanyanjua *et al*., 2002., Bolan *et al*., 2003). Inherently, the soils of western Kenya are acid. The major soil types in western Kenya are Acrisols and Cambisols (Jaetzold *et al*., 2007). Acrisols are acid soils at pH in water less than 5.0, low base status, strongly leached but less weathered than Ferralsols and base saturation of the B horizon is less than 50 %. Cambisols are inherently less weathered than most of the other soils of the humid tropics. It has a Cambic B horizon and the layers are differentiated and changing characteristically due to their relatively young age (Jaetzold *et al*., 2007).

Cropping systems such as mono – cropping and long term use of acidifying fertilizers accelerate soil acidity. However, Cambisols in the sugarcane growing areas of western Kenya are acidic, to a pH as low as 5.5, due to acidification caused by long term use of ammonium based fertilizers namely diammonium phosphate (DAP) and urea (Amolo *et al*., 2011).

Soil pH of 5.5 and below causes some nutrient unavailability for sugarcane and also soybeans used as intercrop. At this pH, P, Mg, Ca, K and Mo availability declines (Meyer, 2011). Studies have reported the optimum soil pH for sugarcane is 6.5 (FAO, 2015; Yara, 2015). The optimal pH for soybeans is 7.0 since it reduces the negative effects of low pH on nodulation and increases the efficiency of fertilizer use (Hungria and Vargas, 2000).

The soil acidification is further exacerbated by continuous sugarcane monoculture through plant removal and leaching of basic cations (Omollo and Abayo, 2011). Bolan *et al*. (2003) stated that fertilizer application in managed ecosystems used for agricultural production is a major contributor for soil acidification. Acidity equivalent of urea and DAP was 79 and 74, respectively. In comparison, elemental sulphur showed the highest acidity equivalent, at 310, followed by ammonium sulphate, at 110 acidity equivalent. Acidity equivalent is the number of parts by weight of pure lime (calcium carbonate) required to neutralize the acidity caused by 100 parts of the fertilizer.

Liming offers the opportunity to ameliorate soil acidity, improve nutrient availability and yields (van Straaten, 2002; Okalebo *et al.*, 2009; Rao and Reddy, 2010). Despite the benefits of liming, the costs are prohibitive due to the broadcast method of lime application and the corresponding large quantities required. Okalebo *et al*. (2009) conducted field trials on lime use for maize - groundnut production and observed increased soil pH to the range of 5.8 - 6.5 at lime rate of 2 t ha^{-1}. Mbakaya *et al*. (2010) demonstrated integrated lime use with inorganic fertilizer on maize yields in acid soils of western Kenya with increased yield from 2.6 to 3.6 t ha^{-1} Therefore, studies on lime use in Kenya have centered on the lime rate on maize production, with limited work on lime use efficiency (Nekesa, 2007). Brown *et al*. (2008) suggested that alternative application strategies such as placement of lime in a band beneath the row at seeding may allow lower rates of lime to be used and thereby offset economic constraints posed by high lime application rates. Wildey (2003) found out that subsurface banded lime at the rate of 220 kg ha^{-1} effectively reduced soil acidity in the surface 10 cm at an eastern Washington location, but no grain yield response was observed. Caires *et al.* (2006) found out that surface liming caused increases up to 66 % in the root growth (0 – 60 cm) and up to 140 % in the grain yield. Root density and grain yield were correlated positively with soil pH and exchangeable Ca^{2+}, and negatively with exchangeable Al^{3+} and Al^{3+} saturation in the surface and subsurface layers.

Rosa *et al.* (2015) concluded that lime management promoted chemical and physical changes in soil properties through the profile. The study found out that lime surface application and incorporation with intermediate disk harrow followed by levelling disk harrow, or lime surface application and incorporation with chisel plough, followed by intermediate disk harrow and levelling disk harrow led to better lime incorporation in the layer 10 - 20 cm and 20 - 30 cm. Also highest soybean yields of about 3330 kg ha^{-1} were recorded in plots that received lime surface application and incorporation with chisel plough, followed by intermediate disk harrow and levelling disk harrow. Rosa *et al.* (2015) utilized the lime rate at 2.7 ton ha^{-1} in the above study.

Lime is an input cost to soil fertility management and therefore its judicious use is paramount. Lime placement is considered a strategy that can increase lime use efficiency in crop production. Incorporation of lime to the depth of 30 cm resulted in higher grain yields than when lime was incorporated only in the top 15 cm (Kamprath, 1984). Caires *et al.* (2005) found that surface application of lime at 4 t ha^{-1} under no till system significantly reduced acidity problems (increased pH and decreased Al, and increased basic cations) at different depths of 0 – 5 cm and 5 – 10 cm within 1 year onward and also at 10 – 20 cm from 2.5 years. To increase yields and sustainability of soil production, site specific nutrient management is required. Therefore, a field experiment was established and the objective of the study was to evaluate the lime placement methods and lime rates on yields and quality of sugarcane under sugarcane mono crop and intercropped sugarcane and soybeans in acid soil of Kibos, Kenya.

3.2 Materials and Methods

3.2.1 Study site

The field experiment was conducted at field 6, experimental plots of Kibos (35^{o}13 E, 0^{o}06 S), under KALRO – Sugar Research Institute, Kisumu County, Kenya. The site elevation is 1268 m above sea level and the agro-ecological zone is LM 2 referred to sub humid, marginal sugarcane zone. The soil type in field 6 is Eutric Cambisols (FAO, 2006) characterized as dark reddish brown, friable sandy clay loam underlain by gravely red loam to light clay. Also, the soil is inherently well drained, has good physical properties and is slightly acid (Jaetzold *et al.*, 2007).

3.2.1.1 Weather data

The weather data during the experiment period (2012 to 2014) is shown in Figure 3.1. The total annual rainfall was 1714 mm, 1544 mm and 1497 mm in 2012, 2013 and 2014, respectively. The study area experiences bimodal rainfall characterized by two rainy seasons per year known as long and short rains. Long rains during 2012 to 2014 were in March to May while short rains were in September to October annually. This bimodal rainfall pattern reflects the pattern for lake regions in Kenya (Jaetzold *et al.*, 2007). The range for maximum and minimum temperatures was 28 – 33^{o}C and 21 – 24^{o}C, respectively, while the average temperature was 23^{o}C (Figure 3.1).

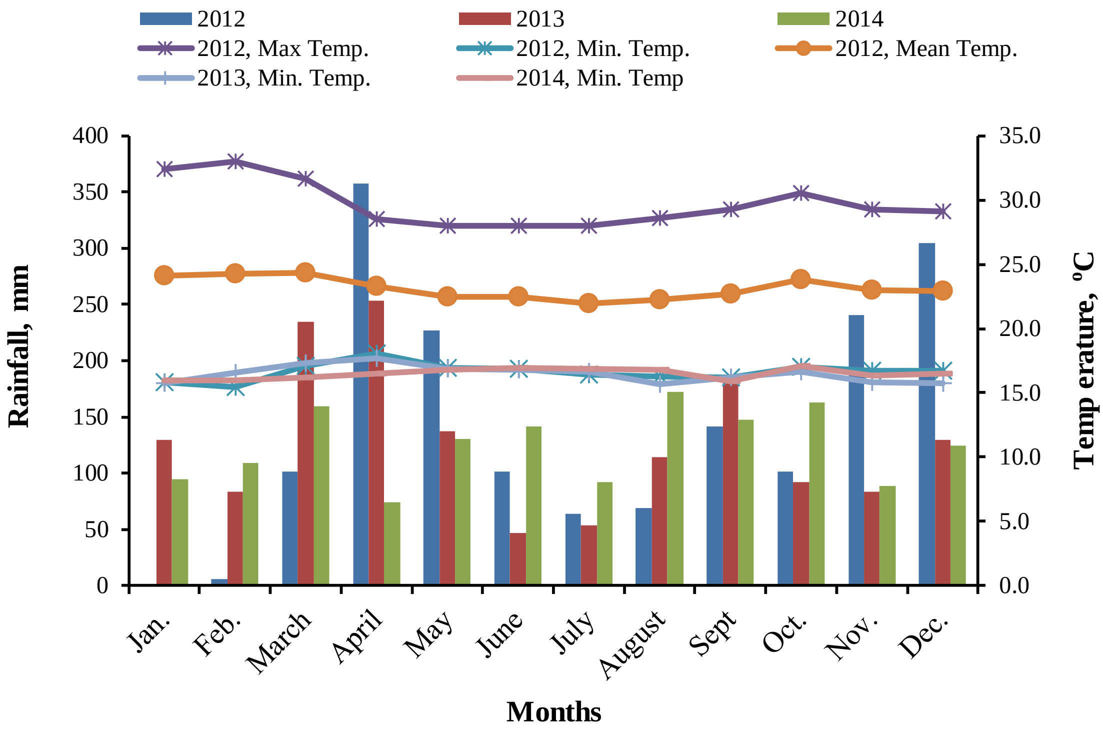

Figure 3.1: Rainfall and temperature for the study site during the period of field experiment

3.2.1.2 Soil chemical properties of the study site

Soil test for the study site was carried out prior to establishment of the field experiment. An area of about 0.5 ha was soil sampled. Diagonal sampling pattern was used and sampling points randomly selected. Soil auger was then used to collect soil at depth 0 – 15 cm and also 15 – 30 cm. The soil per depth and per sampling points was composited and about one kilogram of soil was packaged in a well labelled brown paper bag. The soil samples were then prepared for laboratory analysis. They were ground using a mortar and pestle, sieved and debris removed while the sieved soil was repacked for analysis. The soils were then analysed for some chemical properties using recommended methods as given in Table 2.1.

A summary of the soil chemical properties determined are the same as shown in Table 2.1. Records of the results for depth 0 – 15 cm were high compared to those for depth 15 – 30 cm except for extractable copper which showed the reverse. For the 0 – 15 cm soil depth, the soil reaction was slightly acid (in water) and very strongly acid (in KCl). For 15 – 30 cm, soil reaction was medium acid (in water) and very strongly acid (in KCl). Organic carbon was medium and low for the 0 – 15 cm and 15 – 30 cm, respectively. Total nitrogen was low at both depths. Available P was high at 0 – 15 cm and medium for 15 – 30 cm. This depicted residual P attributed to high and continual use of planting fertilizer e.g. diammonium phosphate in the field for sugarcane production prior to establishment of field experiment.

3.2.2 Experimental description

3.2.2.1 Experimental design

The experiment design was split – split plot in randomized complete block design. The main plot was cropping system (CS) with two levels namely sugarcane monoculture (MC) and intercropped sugarcane (IC). The sub plot was lime placement methods (LPM) with three levels namely; lime broadcasted (L-BC), lime shallow banded (L-SB) at 0 – 15 cm depth and lime deep banded (L-DB) at 15 – 30 cm depth. The sub – sub plot was lime rates with three levels namely 0, 1 and 2 t ha^{-1}. This gave a total of 18 treatments which were then replicated three times to give 54 plots.

3.2.2.2 Experiment management

The field experiment was established in 2012 and managed upto 2014. The field research period coincided with sugarcane crop cycle namely plant crop (0 – 18 months after planting sugarcane setts) and ratoon one crop cycle (0 – 16 months after ratoon emergence).

Soybean was intercropped and managed during the stage when sugarcane was young (the period for sugarcane germination stage is usually between 0 – 60 days after planting) and sugarcane tillering stage (this period is usually between 2^{nd} month and 7^{th} month after planting). The experiment unit was a plot which measured [5 m x 5 rows each 1.2 m apart] referred to as gross plot. Data was collected in the net plots described as the three inner rows with the one row in each side referred to guard rows. Sugarcane variety used was KEN 83 – 737, of medium maturity (0 – 18 months and 0 – 16 months for plant crop and ratoon crop cycle, respectively). Soybean variety SB 19 was used as intercrop which was sowed in between sugarcane rows. The soybean was inoculated with rhizobial (Biofix ®) inoculant.

Agricultural lime (20 % CaO) mined in Koru, Kisumu County was used as the liming material. The raw material limestone is carbonanite which is volcanic in origin. The lime as per treatment, was applied prior to planting of sugarcane setts. Lime placement methods used were broadcasting, banding at 0 – 15 cm and also 15 – 30 cm. Sugarcane setts were treated with the chemical imidacloprid (Confidor ®) at 200g / L to control termite attack. Termite mounds within the vicinity of the field experiment sites were identified and drenched with confidor. Similarly, the sugarcane planting furrows were drenched using confidor.

After 30 to 45 days after planting sugarcane, germination of sugarcane was started. This time, soybean was sown as an intercrop, in between the sugarcane rows. Soybean was inoculated with rhizobial (Biofix ®) inoculant. The sugarcane was managed for 18 months and harvested as plant crop. It was also managed for ratoon one crop for the following 16 months and harvested. Ratoon crop establishment involved alignment of the sugarcane trash in between sugarcane rows following green sugarcane harvest of the plant crop cycle. Soybean intercrop was managed for 6 months and the pods harvested upon maturity. The above ground soybean biomass residue was then incorporated into the soil during manual weed control using hoe. Weed control and other management practices were undertaken according to KESREF recommendations (KESREF, 2010).

3.2.3 Measured parameters

Sugarcane has four growth phases (Meyer and Clowes, 2011; Rossler, 2013). First, germination which starts from planting sugarcane setts to completion of germination of buds. It denotes activation and subsequent sprouting of the vegetative bud. Second, tillering refers to a physiological process of repeated underground branching from compact nodal joints of the primary shoot which then provides the crop with appropriate number of stalks required for a good yield. Third, grand growth refers to elongation of the sugarcane stalks and involves actual sugarcane formation. Fourth, ripening and maturation which involves sugar synthesis and rapid accumulation of sugar starting from the bottom to the top of the sugarcane stalk. To assess the effects of the treatments vis a vis the sugarcane growth stages, the parameters measured were as follows:

3.2.3.1 Sugarcane yield components

Sugarcane was harvested on the 18th month after planting for plant crop cycle and on the 16th month after ratoon one crop cycle. The mature sugarcane stalks were cut from the base and chopped at the end (breaking point) using a sharp disinfected knife. The yield parameters recorded were sugarcane stalk girth, height, population and weight. Girth is the diameter of the sugarcane stalk. The girth was measured using vernier callipers. The height of sugarcane stalk was measured using meter rule from the base of the stalk to the top of the stalk. The population of sugarcane stalks was determined by converting sugarcane stalks per net plot and converted to per ha basis to give total population. The weight of the sugarcane stalks per plot was measured using a weighing balance. The weight per net plot was then converted to per hectare basis to give tonnes cane per ha (TCH).

3.2.3.2 Sugarcane quality components

The quality traits of the harvested mature sugarcane were determined as pol % cane, brix % cane, fibre % cane and tons sugar hectare (BSES, 1991; STASM, 1991). The description of the sugarcane quality traits is as follows: Brix % in cane refers to the total soluble solids content present in the juice and corrected to more accurately represent those of the total juice in cane. Brix % in cane = Brix in juice x [100 – (fibre % + 3)] / 100. Pol % in juice refers to the sucrose content present in the juice expressed in %. Pol is derived from the name of the machine that measures the sucrose content, a polarimeter. Pol % in cane refers to the sucrose content present in the juice expressed in % and corrected to more accurately represent those of the sucrose in cane. Pol % cane = Pol in juice x [100 – (fibre % + 5)] / 100. Fibre % cane refers to amount of fibre in the cane expressed in %. Sampled sugarcane stalks were cut and shredded through a cutter grinder. The ground sample was placed in a fibre machine and washed to remove brix (soluble solids) and fine dirt. The sample was then dried in an oven. The final weight divided by initial weight provided fibre %. Fibre % = [final weight / original weight] x 100. Purity % refers to the measure of the level of sucrose present in cane relative to the total level of soluble solids. Purity along with sucrose aids in determining maturity of sugarcane. Purity = [pol in cane / brix in cane] x 100. Commercial cane sugar (CCS) refers to the total recoverable sugar % (sucrose) in the cane. CCS (tons ha^{-1}) = [(yield (tons ha^{-1}) x sugar recovery (%)] / 100. Sugar recovery (%) = [S – 0.4 (B – S)] x 0.73, where, S = sucrose % in juice and B = corrected brix (%).

3.2.4 Data processing and statistical analysis

Comparison of means was carried out using the least significance difference (LSD) at the 5 % probability level. Main plot effects and respective interactions on treatments were also analysed (GENSTAT, 2011), where comparison of means was carried out using the least significance difference (LSD) at the 5 % probability level.

3.3 Results and Discussion

3.3.1 Effects of cropping systems, lime placement methods and rates on sugarcane yield for plant crop cycle

Plant crop cycle is the period of growth of newly planted sugarcane (Ellis and Merry, 2004). Plant crop cycle starts when sugarcane is propagated vegetatively from setts referred to pieces of sugarcane stalk planted as three eyed bud stalks (Meyer and Clowes, 2011). F – Test probabilities for the effects of cropping systems (CS), lime placement methods (LPM) and lime rate (LR) on yield components for plant crop harvest is shown in Table 3.1. Only cropping systems significantly ($P = 0.004$) affected the weight (in tonnes per hectare, TCH) of sugarcane harvested (Table 3.2, Fig. 3.2). Other sugarcane yield components such as stalk girth, height and population were not affected by cropping systems, lime placement methods, lime rates or respective interactions ($P > 0.05$) as shown in Table 3.1.

Higher sugarcane weight referred to yield was recorded in plots that were intercropped with sugarcane and soybeans (Table 3.2). This is attributed to the benefits of intercropping system compared to sugarcane monoculture. Under intercropped system, the soybeans incorporated could have improved the soil fertility (Tang *et al.*, 2005). The improved soil fertility arises due to nutrient availability when the soybean residues decay, increase in the amount of humus leading to improved soil structure and also through nitrogen fixation by soybean roots (van Wolfswinkel, 2010). These results are consistent to findings by Li *et al.* (2012) who reported more sugarcane yield and dry weight biomass under sugarcane/soybean intercropping than in sugarcane monoculture. Soybean intercrop increases overall productivity per unit of land and enables sugarcane to more effectively utilize nutrients due to improved soil fertility as a result of intercropping (Tang *et al.*, 2005; He *et al.*, 2006).

Table 3.1: F – test probabilities for the effects of cropping systems, lime placement methods and rates on sugarcane yield components for plant crop harvest

	F – test probabilities			
	Sugarcane stalk parameters			Stalk weight parameters
Source of Variation	Girth	Height	Population	Tonnes Cane per Hectare, TCH
CS	0.951	0.296	0.509	**0.004**
LPM	0.369	0.701	0.865	0.969
LR	0.739	0.445	0.589	0.782
CS x LPM	0.922	0.217	0.919	0.987
CS x LR	0.761	0.236	0.380	0.130
LPM x LR	0.190	0.440	0.359	0.426
CS x LPM x LR	0.279	0.102	0.235	0.136
CV (%)	6.7	4.9	21.6	20.8

CS – cropping systems; LPM – lime placement methods; LR – lime rates; CV - coefficient of variation

Table 3.2: Effects of cropping systems on sugarcane yield for plant crop cycle

Cropping systems	Stalk weight (TCH) Tonnes cane per hectare
Monoculture sugarcane (MC)	133b
Intercropped sugarcane (IC)	136a
LSD ($P \leq 0.05$)	0.8
CV %	21

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level. Key: CV – coefficient of variation; MC – Sugarcane monoculture; IC – Intercropped sugarcane

Soybean fixes nitrogen and therefore, nitrogen requirement of sugarcane is met due to transfer of the symbiotically fixed N from the soybean legume crop residues to sugarcane, a non legume crop (Ledgard *et al.*, 1985). Other benefits of intercrop that lead to increased yield of companion have been reported.

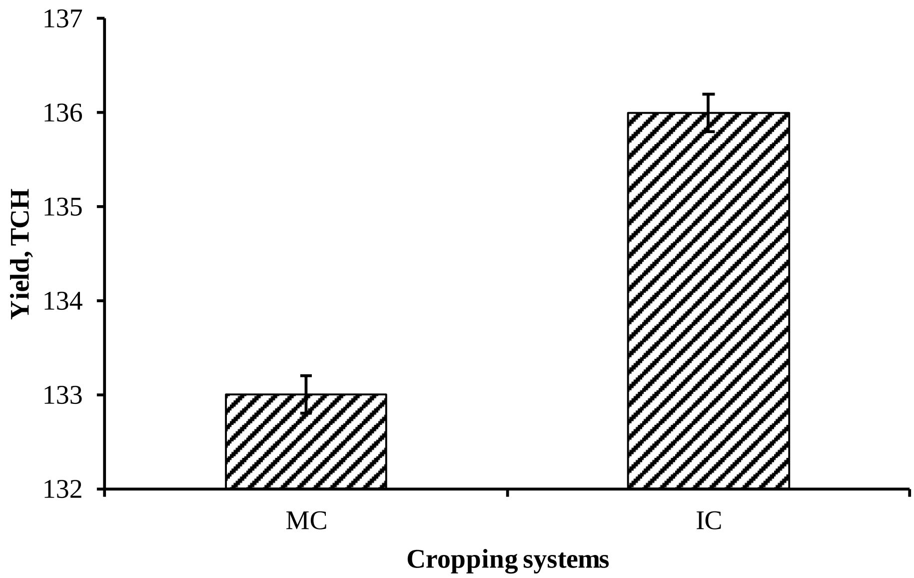

Figure 3.2: Effects of cropping systems on sugarcane yield for plant crop cycle

For example, organic matter content of sugarcane soil increased due to the companion crop (Yadav *et al.*, 1987). This then leads to increased microbial number, increased decomposition of organic residues which translates to increased cycling of nutrients (Dick, 1994). Application of lime did not affect the yield of sugarcane (Table 3.5). This finding is contrary to the findings of Mutonyi (2014). This may be attributed to use of lime treatment alone unlike combining lime with nutrients such as Phosphorus as in the study of Mutonyi (2014).

3.3.2 Effects of cropping systems, lime placement methods and lime rates on quality of sugarcane harvested for plant crop cycle

F – Test probabilities for the effects of cropping systems (CS), lime placement methods (LPM) and lime rates (LR) on quality of sugarcane for plant crop harvest are shown in Table 3.3. Cropping systems significantly ($P = 0.005$) affected the amount of sugarcane fibre (Table 3.3). Sugarcane harvested from plots under intercropped sugarcane and soybean recorded high fibre than sugarcane from plots under monocrop cropping system (Tables 3.3 and 3.4). Similar pattern was noted in sugarcane weight as affected by cropping system (Table 3.1 and 3.2). Fibre, being a component of dry matter in sugarcane increased in sugarcane under intercropped system attributed to the benefits of intercropping (Tang *et al.*, 2005; He *et al.*, 2006; Li *et al*., 2012).

Sugarcane from plots with lime shallow banded recorded high sucrose as measured in pol % juice, pol % cane and CCS (Table 3.5 and Figure 3.4). The findings in this study are consistent to the findings of Singha (2006) and Mutonyi (2014). Application of lime at 3 t ha^{-1} incorporated at shallow depth led to improved quality of juice from sugarcane harvested (Mutonyi, 2014). Sugarcane quality parameters, brix and purity, were not affected ($P \geq 0.05$) by cropping systems, lime placement methods or lime rates (Table 3.3).

Table 3.3: F – test probabilities for the effects of cropping systems, lime placement methods and lime rates on sugarcane quality traits for plant crop cycle

	F – Test Probabilities Sugarcane quality traits						
Source of Variation	Pol % Juice	Pol % cane	Brix % Juice	Brix % cane	Purity	Fibre	CCS
CS	0.373	0.493	0.592	0.339	0.776	**0.005**	0.788
LPM	**0.011**	**0.012**	0.069	0.078	0.133	0.639	**0.009**
LR	0.495	0.226	0.698	0.331	0.827	0.123	0.388
CS x LPM	0.077	0.070	0.069	0.086	0.725	0.794	0.170
CS x LR	0.415	0.302	0.136	0.089	0.357	0.661	0.687
LPM x LR	0.805	0.570	0.671	0.289	0.872	0.387	0.761
CS x LPM x LR	0.203	0.377	0.194	0.627	0.409	0.700	0.458
CV (%)	2.9	3.2	2.8	3.1	1.5	5.5	3.7

CS – cropping systems; LPM – lime placement methods; LR – lime rates; CV - coefficient of variation; CCS – commercial cane sugar

Table 3.4: Effects of cropping systems on fibre % cane for plant crop cycle

Cropping systems	Fibre % cane
Monoculture sugarcane (MC)	18.55b
Intercropped sugarcane (IC)	19.41a
LSD (P ≤ 0.05)	0.57
CV %	5.5

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level. Key: CV – coefficient of variation; MC – Sugarcane monoculture; IC – Intercropped sugarcane

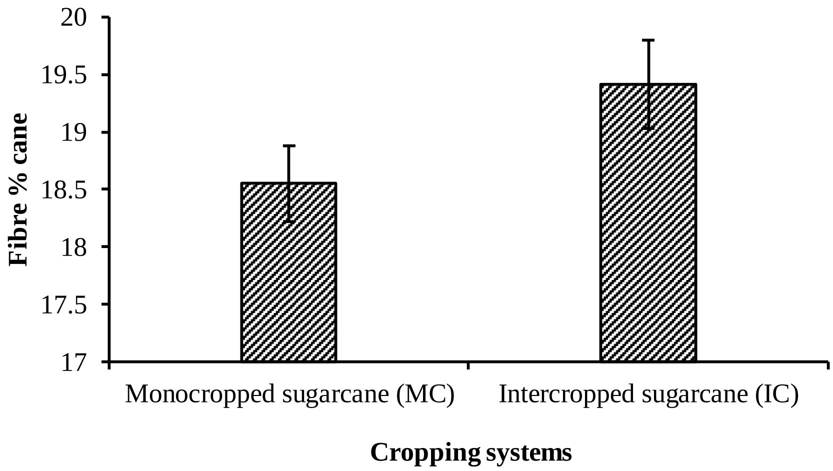

Figure 3.3: Effects of cropping systems on fibre % cane for plant crop cycle

Table 3.5: Effects of lime placement methods on pol % cane and CCS for sugarcane harvested for plant crop cycle

	Sugarcane quality parameters		
Lime Placement Methods	Pol % Juice	Pol % Cane	CCS
LBC	19.23b	14.59b	13.29b
LDB	19.56ab	14.85ab	13.48b
LSB	19.84a	15.09a	13.83a
LSD (P ≤ 0.05)	0.386	0.325	0.336
CV %	2.9	3.2	3.7

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level Key: CV – coefficient of variation; CCS – Commercial cane sugar

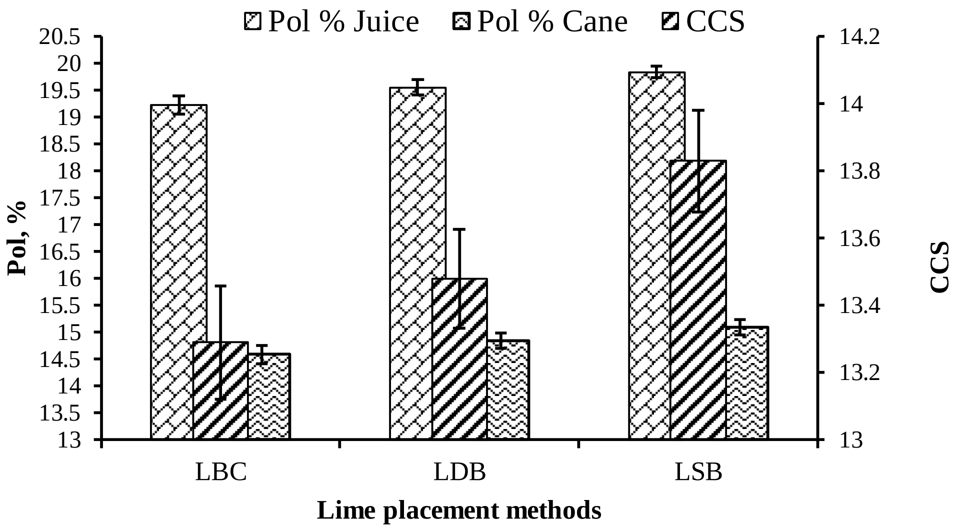

Figure 3.4: Effects of lime placement methods on pol % cane, pol % juice and CCS for sugarcane harvested for plant crop cycle

3.3.3 Effects of cropping systems, lime placement methods and lime rates on sugarcane yield for ratoon one crop cycle

F – Test probabilities for the effects of cropping systems (CS), lime placement methods (LPM) and lime rate (LR) on yield components for ratoon one crop harvest is shown in Table 3.6. The sugarcane yield and yield components for ratoon one crop cycle were not affected by the main treatments (Table 3.6).

Table 3.6: F – test probabilities for the effects of cropping systems, lime placement methods and rates yield components for ratoon one crop harvest

	Sugarcane stalk			Weight of sugarcane stalks
Source of variation	Girth	Height	Population	Tonnes Cane per Hectare
CS	0.471	0.232	0.979	0.884
LPM	0.358	0.05	0.340	0.543
LR	0.186	0.238	0.099	0.524
CS x LPM	0.748	0.838	0.555	0.353
CS x LR	0.829	0.995	**0.031**	0.111
LPM x LR	0.252	0.256	0.421	0.556
CS x LPM x LR	0.473	0.168	0.567	0.783
CV (%)	6.3	5.8	12.1	17.9

CS – cropping systems; LPM – lime placement methods; LR – lime rates; CV - coefficient of variation

Cropping systems, LPM and LR did not influence the sugarcane yield parameters for ratoon one crop (Table 3.6). Yield of ratoon sugarcane mainly depends on the number of tillers from the previous crop (Matsuoka and Stolf, 2012). These tillers translate to the population of stalks at time of harvest.

Therefore, the probable reason for non-significance in this study is that population of sugarcane stalks at plant crop harvest were not affected by the treatments applied, so the same was reflected on the yield parameters for ratoon one crop. The interaction effect between the cropping systems and lime rates significantly (P = 0.05) affected the number of sugarcane stalks, population (Table 3.6). Highest population of sugarcane stalks was recorded in plots that were under monoculture x lime rate, 1 t ha^{-1} (Table 3.6 and Figure 3.5). The least population of sugarcane stalks was in plots under monoculture x lime rate 2 t ha^{-1}.

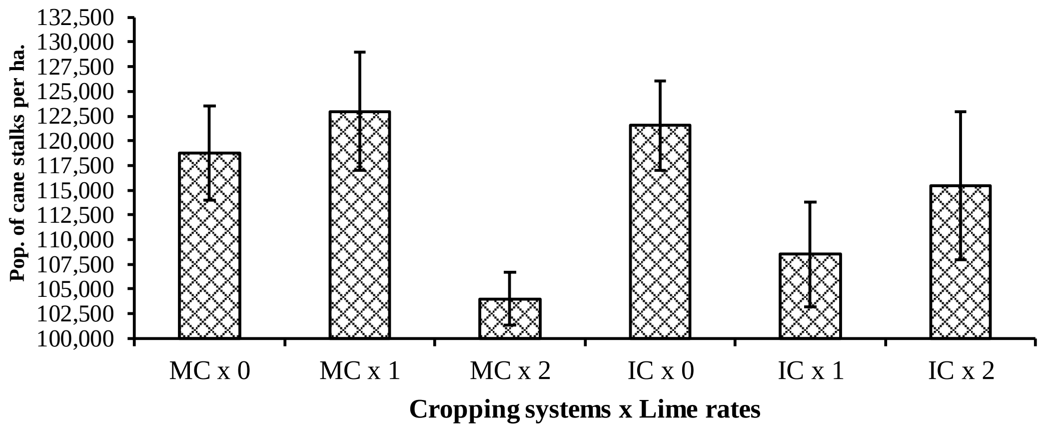

Figure 3.5: Interaction effect between cropping systems and lime rates on population (Pop) of sugarcane stalks per hectare

3.3.4 Effects of cropping systems, lime placement methods and lime rates on quality of sugarcane harvested for ratoon one cycle

F – Test probabilities for the effects of cropping systems (CS), lime placement methods (LPM) and lime rates (LR) on quality of sugarcane for ratoon one harvest is shown in

Table 3.7. Liming significantly (P = 0.05) affected the purity of sugarcane harvested for ratoon one crop. Sugarcane from lime applied plots showed less purity unlike sugarcane from control plots (Table 3.8).

Sugarcane purity is the % of sucrose in total solids in the juice. A higher purity is a result of higher sucrose content in the total solids present in juice (Engelke, 2002). The findings in this study are contrary to findings of Singha (2006) and Mutonyi (2014) who observed high purity and high pol % juice (sucrose) in sugarcane from lime treated plots. There was significant interaction effect between LPM and LR on purity of harvested sugarcane (Table 3.7). Also interactions amongst the CS, LPM and LR significantly affected the brix % juice as shown in bold values in Table 3.7. For lime rates, sugarcane harvested from plots that received 2 t ha^{-1} showed the least purity while sugarcane from control plots recorded the highest purity as shown in Table 3.8.

Table 3.7: F – test probabilities for the effects of CS, LPM and LR on quality of sugarcane for ratoon one crop harvest

	F – test probabilities		
	Sugarcane quality traits		
Source of variation	Pol % Juice	Brix % Juice	Purity
CS	0.508	0.634	0.545
LPM	0.289	0.748	0.301
LR	0.367	0.096	**0.014**
CS x LPM	0.472	0.548	0.144
CS x LR	0.852	0.774	0.065
LPM x LR	0.452	0.247	**0.049**
CS x LPM x LR	0.186	**0.028**	0.859
CV (%)	4.2	4.1	1.3

CS – cropping systems; LPM – lime placement methods; LR – lime rates; CV - coefficient of variation

Table 3.8: Effects of lime rates on purity of sugarcane harvested for ratoon one cycle

Lime rates, t ha^{-1}	Purity
0	97.34a
1	97.42a
2	96.23b
LSD ($P \leq 0.05$)	0.857
CV %	1.3

Means in the same column followed by the same letter(s) are not significantly different at 0.05 levels Key: CV – coefficient of variation

Interaction effects on sugarcane quality harvested for ratoon one crop

For interaction between CS and LPM, sugarcane harvested from plots under monoculture and lime deep banded showed the least purity. However, for the case of intercropped plots, the highest purity was recorded in plots where lime was broadcasted (Figure 3.6).

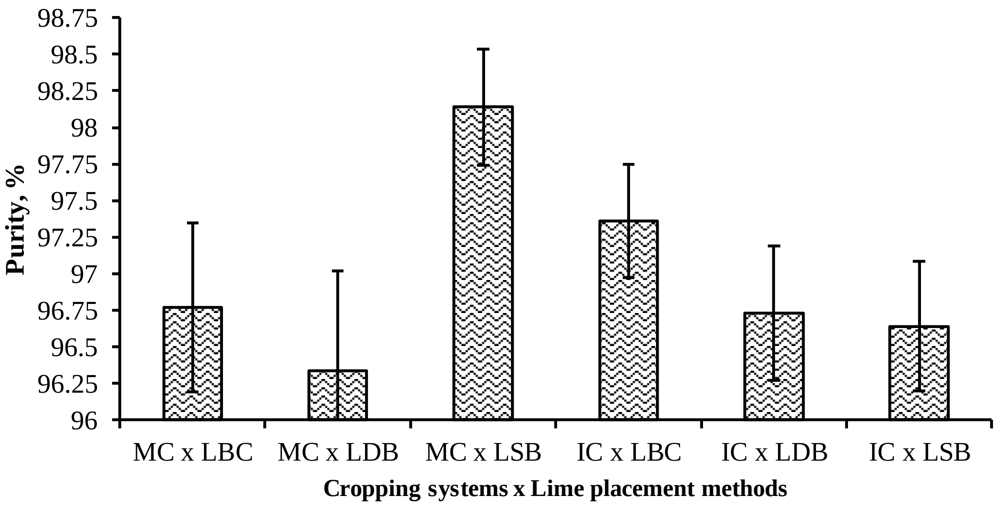

Figure 3.6: Interaction between CS x LPM on purity of sugarcane harvested for ratoon one

Interaction effects among cropping systems, lime placement methods and lime rates on brix % juice for sugarcane ratoon one harvest is shown in Figure 3.7. The highest brix % juice was recorded in interaction IC x LSB x 0 described as sugarcane under intercrop with no lime applied (Figure 3.7).

3.3.5 Sugarcane yield and quality comparison between plant crop and ratoon one harvest

The yields for the plant crop and ratoon one harvest were compared with the treatments and the F – Test probabilities are shown in Table 3.9. Cropping systems significantly (P = 0.02) affected the yields between the two crop cycles (Table 3.9). Sugarcane yields for the plant crop harvest were higher than for the ratoon one harvest (Figure 3.8). Lime placement methods, lime rates and respective interactions did not affect the other yield parameters when plant crop harvest and ratoon one harvest were compared (Table 3.9).

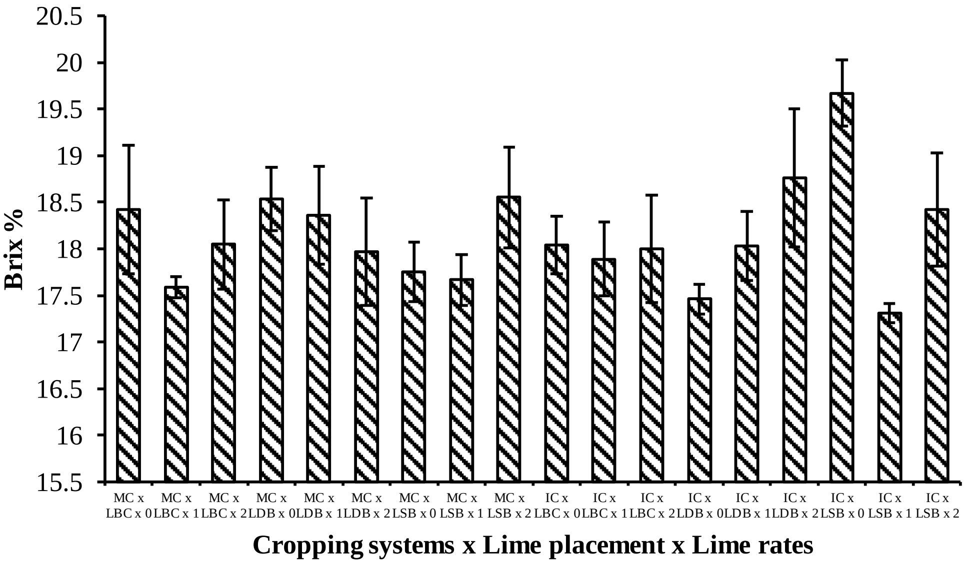

Figure 3.7: Interaction effects among cropping systems, lime placement methods and lime rates on brix % juice

The quality of sugarcane harvested for the plant crop and the ratoon one crop were compared vis a vis the treatments as shown in Table 3.10. Cropping systems significantly influenced pol % juice, brix % juice and purity when sugarcane harvested for plant crop and ratoon one cycle was compared (Table 3.10). Amount of sugarcane yield and quality for plant crop harvest was higher than those reported for ratoon one harvest (Table 3.9 and

3.10). Similar observation was reported by Kingston (2003) and Matsuoka and Stolf (2012).

Table 3.9: F – Test probabilities for the comparison of sugarcane yields between plant crop and ratoon one harvest

	F – test probabilities			
	Sugarcane stalks		Weight of sugarcane stalks	
Source of variation	Height	Population	Girth	Tonne Cane Hectare, TCH
CS	0.214	0.591	0.951	**0.02**
LPM	0.438	0.584	0.159	0.852
LR	0.116	0.482	0.536	0.992
CS x LPM	0.215	0.944	0.977	0.992
CS x LR	0.817	0.18	0.707	0.121
LPM x LR	0.153	0.427	0.501	0.464
CR x LPM x LR	0.145	0.250	0.151	0.284
CV (%)	5.4	17.6	6.5	19.7

CS – cropping systems; LPM – lime placement methods; LR – lime rates; CV - coefficient of variation

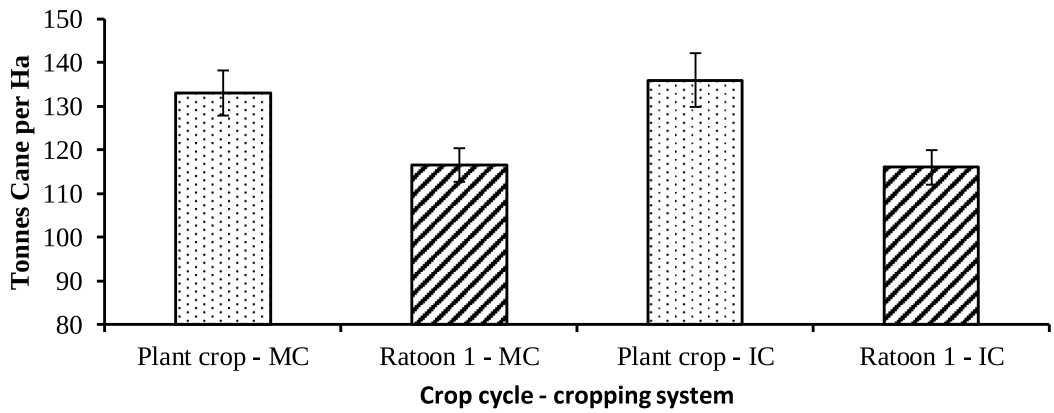

Figure 3.8: Comparison of sugarcane yields between plant crop and ratoon one harvest

Studies report that the decline of sugarcane yield and quality parameters from plant crop to ratoon crop harvest is a result of environmental effects rather than genetic deterioration (Matsuoka and Stolf, 2012). The influencing factors are: more shallow root system in ratoons hence difficulty in uptake of nutrients and water, increased incidences of root and stubble diseases, soil insects and nematodes etc.

Table 3.1010: F – test probabilities for sugarcane quality compared between plant crop and ratoon one harvest

Source of Variation	F – test probabilities Sugarcane quality traits Pol % Juice	Brix % Juice	Purity %
CS	**< 0.001**	**< 0.001**	**< 0.001**
LPM	0.187	0.577	0.563
LR	0.525	0.213	**0.025**
CS x LPM	0.235	0.231	0.213
CS x LR	0.576	0.223	**0.009**
LPM x LR	0.459	0.230	**0.040**
CR x LPM x LR	0.122	**0.017**	0.680
CV (%)	3.3	3.3	1.2

CS – cropping systems; LPM – lime placement methods; LR – lime rates; CV - coefficient of variation

Purity of sugarcane harvested between plant crop and ratoon one was significantly (P = 0.05) affected by lime rates, interactions CS x LR and also LPM x LR (Table 3.10). Interactions CS x LPM x LR also significantly affected brix % juice between sugarcane harvested in plant crop and ratoon one cycle. Pol % juice and brix % juice for sugarcane harvested at plant crop was higher than for sugarcane harvested at ratoon one regardless of the cropping system (Table 3.11). However, the reverse was noted for purity where it was highest in sugarcane harvested at the ratoon one cycle as compared to the plant crop cycle despite the cropping cycle as shown in Table 3.11.

Comparison between plant crop cycle and ratoon one cycle on sugarcane purity as affected by the lime rates is shown in Figure 3.9. Highest purity of sugarcane was harvested at ratoon one cycle and in plots that received 1 t ha^{-1} of lime and control (Figure 3.9).

Table 3.11: Comparison between plant crop and ratoon one cycle on pol %, brix % juice and purity as influenced by cropping systems

Crop cycle	Cropping system	Sugarcane quality traits Pol % Juice	Brix % Juice	% Purity
Plant crop	Monocrop	19.47a	22.29a	87.38b
Plant crop	Intercrop	19.61a	22.38a	87.33b
Ratoon one	Monocrop	17.57b	18.10b	97.09a
Ratoon one	Intercrop	17.66b	18.18b	96.91a
	LSD ($P \leq 0.05$)	0.536	0.434	1.683
	CV %	3.3	3.3	1.2

Means in the same column followed by the same letter(s) are not significantly different at 0.05 levels Key: CV – coefficient of variation

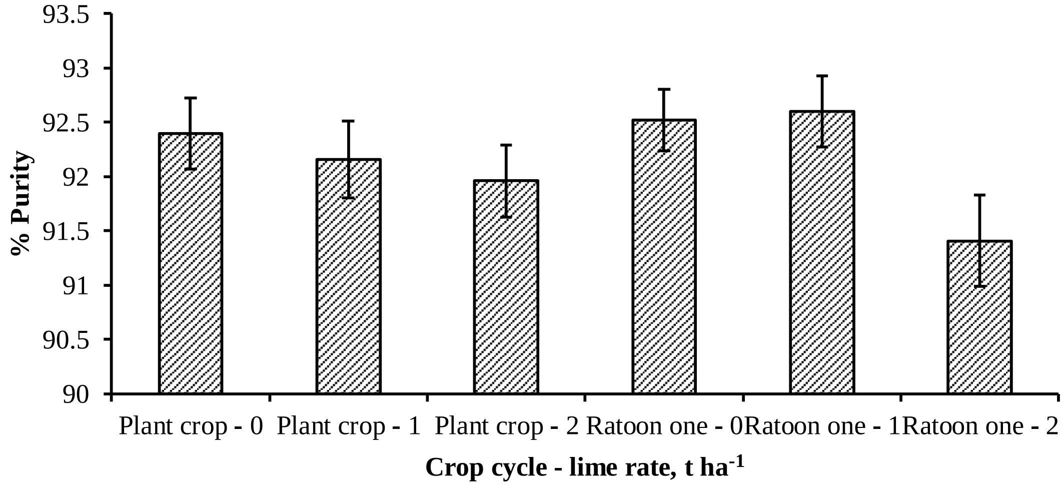

Figure 3.9: Comparison between plant crop and ratoon one cycles on pol %, brix % juice and purity as influenced by lime rates.

3.5 Conclusions

In view of the results, the following are concluded: Cropping systems affects sugarcane yields for the plant crop cycle but not for ratoon crop cycle. The high sugarcane yield witnessed under the intercrop system is probably due to a better sugarcane crop as a result of improved soil fertility i.e. biological nitrogen fixation by soybean, nutrient release upon decay and decomposition of incorporated soybean residues and better soil structure. Lime did not affect the sugarcane yields for the plant crop and ratoon crop cycles. This indicates that lime plays an indirect role in crop growth and yields, through ameliorating soil acidity and nutrient transformations. These effects coupled with other factors then affect crop yields.

Lime placement method was found to affect the quality of sugarcane both for the plant crop and also ratoon crop cycles. For example, sugarcane under shallow - banded lime gave the highest pol % cane and commercial cane sugar. There was decreased yield with subsequent crop cycle. Yields for the plant crop were higher than for the ratoon crop cycle. Similarly, the sugarcane quality traits, pol and brix were lower for the ratoon than for the plant crop harvest, except purity which showed the reverse.

3.6 Recommendations

In view of the above, it is recommended that:

i. Liming as a soil improvement strategy should be integrated with other nutrient improvement strategies such as appropriate cropping and fertilizer use for high yields to be realised.
ii. Liming may be a strategy to improve the quality of sugarcane especially with the introduction of payment of sugarcane based on sucrose in addition to weight.
iii. Further studies on the effect of lime on sugarcane quality are recommended.

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CHAPTER FOUR

4.0 EFFECTS OF LIMING AND NITROGEN RATES ON SOIL ACIDITY, NUTRIENTS AND YIELDS OF INTERCROPPED SUGARCANE UNDER ACID SOILS OF KIBOS, KISUMU COUNTY, KENYA

Abstract

A field study was conducted to investigate whether lime placement methods (LPM), lime rates (LR) and nitrogen rates (NR) for intercropped sugarcane with soybean under acid soils leads to increased soil pH, soil and sugarcane leaf nutrient status and also yields and quality. The Cambisol soils of the study site are acidic, hence detrimental to yields and beneficial organisms e.g. *Rhizobium*. Acidified soils are a constraint to crop production due to imbalance in availability of essential plant nutrients. Liming is known to increase soil pH, however, efficient use is critical to ensure cost effective use. Therefore, determination of efficient lime application method including lime rates and nitrogen rates was the basis of the study. Split – split plot randomized complete block arrangements was employed. The main plots were; LPM (lime broadcasted [L-BC], lime shallow banded, 0 – 15 cm [L-SB] and lime deep banded, 15 – 30 cm [L-DB]); sub plots, lime rates (0, 1 and 2 t ha^{-1}) and sub – sub plots (0, 50 and 100 kg N ha^{-1}). Lime rates significantly affected soil pH for both 0 – 15 cm and 15 – 30 cm soil depth. Lime rate, 2 t ha^{-1} led to the highest soil pH. Lime placement methods (LPM) and also nitrogen rates (NR) did not affect the soil acidity. Some soil chemical properties, specifically, exchangeable calcium (Ca), extractable manganese (Mn), zinc (Zn) and soil OC were affected by the LR but not the LPM. LPM affected sugarcane leaf total K, Ca, Mn and Zn while the LR affected total N and Mg. Lime shallow banded and lime broadcasted led to highest content of these nutrients. Sugarcane yield and quality parameters were not affected by the lime placement methods, lime rates and also nitrogen rates. Lime rate 2 t ha^{-1} is recommended for use to ameliorate soil acidity for acidified Cambisols soils of Kibos, Kisumu County, Kenya. Lime broadcasting or lime banding at shallow 0 – 15 cm soil depth should be used as a lime placement method.

Keywords: Lime placement methods, lime rates, nitrogen rates, nutrient content, sugarcane yields

4.1 Introduction

Soil acidity causes detrimental effects to plants and soil organisms (Bolan *et al.*, 2003). Nitrogen (N), a primary nutrient for crop production, is affected by soil acidity. Nitrogen is the most important plant nutrient for crop production because of its role as a constituent of the building blocks of almost all plant structures. For example, it is an essential component of chlorophyll, enzymes and proteins (Barker and Bryson, 2007). Apart from affecting N, soil acidity also affects availability of other macronutrients and micronutrients (Sumner *et al.*, 1991; Voss, 1998). Nitrogen use for crop production is mainly provided through inorganic and organic fertilization, through biological nitrogen fixation (BNF) and, to some extent, through atmospheric deposition (Hoofman and Cleemput, 2004). Inorganic fertilization input involves application of mineral fertilizers such as urea (46 % N). The relatively simple and less costly synthesis of urea and its high N content has made it the most commonly used N fertilizer in the world. Organic N sources are either from plant or animal sources. Plant material (catch or cover crops, legumes) is often added freshly cut (green manure) to the soil, and with crop nutrients available for the next crop ranging from less than 20 % to more than 50 % of what is applied. Legumes and manure can release quite high amounts of N in a rather short time. Biological Nitrogen Fixation occurs when *Rhizobium* species living in symbiotic relationship in root nodules of legumes (e.g. soybean) converts atmospheric N_2 gas to NH_3, which is further converted to amino acids and proteins. In exchange, the legumes provide the *Rhizobium* species with the energy they need to grow and to fix N_2. The process is depressed when other sources of N are abundant, and is also reduced in acid soils and in soils with low P availability (Hoofman and Cleemput, 2004).

According to Alexander (1977), acidity governs the type, number and activity of microorganisms, regulates the rate of organic matter decomposition, thereby reducing the number of simple organic molecules available for further decomposition and eventually rendering N and other constituent elements (P and S) soluble. Acidity has a deleterious effect on the symbiotic relationship between rhizobia and legumes, and generally in soils with pH below 6, poor nodulation and N_2 fixation result in. The inhibitory effect of acidity on biological N_2 fixation has also been attributed to the poor supply of Mo and Ca which are essential for N_2 fixation. Thus, when nutrient deficiencies, especially Ca and Mo are overcome in acid soils, biological N_2 fixation can be improved (Unkovich *et al*., 1996 in Bolan *et al*., 2003). In Kenya, most of the soils of the sugarcane growing areas are low in soil nitrogen (N) (Jaetzold *et al*., 2007). The low soil N coupled with long - term monocropping as a consequence of its pereniality, ability of the sugarcane to ratoon severally after harvesting and land scarcity justifies continued use of nitrogen fertilizer in the same field. Also, sugarcane is capable of rapidly depleting the soil of mineral elements, particularly N and potassium if sufficient N is not applied. On average, one tonne of sugarcane removes 1.16 kg N in a given crop cycle (Meyer, 2011).

Liming is a management practice to reduce the soil acidity and therefore one of the soil fertility management practices (AGRA, 2009). Most plants grow well at a pH range of 5.5 – 6.5 and liming is aimed to increase the pH to this range. The benefits of liming include: enhanced soil physical, chemical and biological conditions. The indirect benefits include mobilization of plant nutrients, immobilization of toxic heavy metals, and improvements in soil structure. Liming also causes an optimal condition that favours biological activities that include N_2 fixation and mineralization of N, P and S in soils (Bolan *et al*., 1991; Haynes and Naidu, 1998).

Enhancing the activities of beneficial microbes such as rhizobia, diazotropic bacteria, and mycorrhizae in the rhizosphere has improved root growth by the fixation of atmospheric nitrogen, suppressing pathogens, and producing phytohormones, enhancing root surface area to facilitate uptake of less mobile nutrients such as P and micronutrients and mobilizing and solubilizing unavailable nutrients (Baligar and Fageria, 1999). Literature provides ample evidence that low soil pH adversely affects activities of *rhizobium*, including a loss of its ability to fix nitrogen (Angle, 1998). Mulder *et al.* (1977) showed that low soil pH reduced the activity and their ability to multiply. Holdings and Lowe (1971) earlier demonstrated that low soil pH increased the number of ineffective rhizobia in soil. Angle (1998) reported that soil pH decline below 5.5 reduced rhizobial populations, and rhizobia that survive such a pH lack the capacity to fix atmospheric nitrogen. Ibekwe *et al.* (1995) showed that plants grown in an unamended control soil with low pH often exhibited low rates of nitrogen fixation. Ibekwe *et al.* (1995) also reported high rates of nitrogen fixation when high concentrations of heavy metals were present, but soil pH was nearly neutral. Franco and Munns (1982) found that decreasing the pH of nutrient solutions from 5.5 to 5.0 decreased the number of nodules formed by common bean. Lime ameliorates the harmful effects of soil acidity (Cregan *et al*., 1989). Studies on bacteria suggest that the success of liming may be due not only to an effect on the soil pH but also to a direct effect of increased Calcium on the bacteria themselves (Reeve *et al*., 1993).

In Kenya, the common sugarcane production practice is continuous sugarcane monoculture and use of acidifying fertilizers such as urea and diammonium phosphate (KESREF, 2009; Amolo *et al*., 2011). These fertilizers are favoured due to their cost and levels on nutrient element per weight compared to other nutrient fertilizer sources. The advantage of these fertilizers means their use will continue. This therefore calls for integrated use of these fertilizers with other soil improvement strategies that will mitigate against soil acidification, improve soil fertility and sugarcane nutrient uptake. Alternative strategies such as placement of lime allow low rates of lime to be used to reduce soil acidity. This, coupled with intercropped sugarcane and soybean, could decrease rates of Nitrogen use hence improve Nitrogen use efficiency, nutrients availability, yields and quality of sugarcane.

This study investigates whether lime use and intercropped sugarcane and soybeans leads to amelioration of soil pH, improve soil nutrient status and nutrient content of sugarcane leaves. Also, the study determines the best lime rate, placement methods for improved soil pH and fertility and sugarcane nutrition during plant crop and ratoon one cycle. It was hypothesized that lime placement methods, lime rates and nitrogen rates does improve soil chemical properties, leaf nutrient content, yields and quality of sugarcane for plant crop and ratoon one cycles in acid soils of Kibos, Kisumu County in Kenya.

4.2 Materials and Methods

4.2.1 Study site

The field experiment was conducted at field 6, experimental plots of Kibos (35^{o}13 E, 0^{o}06 S), under Kenya Agricultural and Livestock Research Organization – Sugar Research Institute. The elevation of the site was 1268 m above sea level and the agro – ecological zone was sub humid, marginal sugarcane zone. The soil type for the site was Eutric Cambisol characterized as dark reddish brown, friable sandy clay loam underlain by gravely red loam to light clay (Jaetzold *et al.*, 2007).

Soil chemical properties of the study site

Soil test for the study site was carried out prior to establishment of the field experiment. The soil test involved soil sampling, soil preparation and laboratory analysis for soil chemical properties. The methods used to analyse the soil chemical properties are the same as given in Table 2.1 of chapter 2.

4.2.2 Experimental description

4.2.2.1 Experimental design

The experiment design was split – split plot in randomized complete block design. The main plot was lime placement methods (LPM) with three levels namely: lime broadcasted (L-BC); lime shallow banded (L-SB) at depth 0 – 15 cm and lime deep banded (L-DB) at depth 15 – 30 cm. The sub plot was lime rates with three levels namely 0, 1 and 2 t ha^{-1}. The sub – sub plots was nitrogen rates with three levels, namely 0, 50 and 100 kg N ha^{-1}. This gave a total of 27 treatments which were then replicated three times to give 81 plots.

4.2.2.2 Experiment management

The field experiment was established in 2012 and managed up to 2014. The field research period coincided with sugarcane crop cycle namely plant crop (0 – 18 months after planting sugarcane setts) and ratoon one crop cycle (0 – 16 months after ratoon emergence). Soybean was intercropped and managed during the early growth stages of sugarcane which was about 0 to 60 days after soybean seeds were sowed. This early stage of sugarcane growth is referred to germination and emergence, about 45 days after planting sugarcane setts. It is then followed by tillering and canopy establishment stage usually about 2nd month to 7th month after sugarcane planting (Meyer and Clowes, 2011).

The experiment unit was plot which measured [5 m x 5 rows each 1.2 m apart] referred to as gross plot. Data was collected in the net plots described as the three inner rows with the one row in each side referred to guard rows. Sugarcane variety used was KEN 83 – 737 referred to medium maturity (0 – 18 months and 0 – 16 months for plant crop and ratoon crop cycle respectively). Soybean variety SB 19 was used as intercrop which was sowed in between sugarcane rows. The soybean was inoculated with rhizobial (Biofix ®) inoculant.

Agricultural lime (20 % CaO) mined in Koru, Kisumu County, was used as the liming material. The raw material limestone is carbonanite which is volcanic in origin. The lime as per treatment was applied prior to planting of sugarcane setts. Lime placement methods used were broadcasting, banding at 0 – 15 cm and also 15 – 30 cm. Germination was noted at 30 to 45 days after planting. At this time, soybean was sowed as intercrop, in between the sugarcane rows. Soybean was inoculated with rhizobial (Biofix ®) inoculants.

The sugarcane was managed for 18 months and harvested as the plant crop. It was also managed for the ratoon one crop for 16 months and harvested.

4.2.2.3 Nitrogen management

Nitrogen was applied as treatment rates of 0, 50 and 100 kg N ha^{-1}. Fertilizer used was urea 46 % N. Time when urea was applied was 4 months after planting sugarcane setts for plant crop cycle and 3 months after ratoon emergence for the case of ratoon crop cycle. The method of application was side dressing along the sugarcane rows (KESREF, 2010).

4.2.2.4 Sugarcane maintenance and management

Ratoon crop establishment involved trash alignment of the sugarcane trash in between sugarcane rows following green sugarcane harvest of plant crop cycle. Soybean intercrop was managed for 6 months and the pods harvested upon maturity. The above ground biomass residue was then incorporated into the soil during manual weed control using hoe. Weed control and other management practices were undertaken according to KESREF recommendations (KESREF, 2010).

4.2.3 Measured parameters

4.2.3.1 Soil chemical properties

Soil was sampled in each of the experimental plot referred to the sampling units. In every unit, diagonal pattern was used to mark the sampling points. Soil auger was then used to collect soil sample at depth 0 – 15 cm (top soil) and 15 – 30 cm (sub soil). The sampled soil was then prepared and analysed for soil chemical properties as given in Table 4.1. The parameters analysed included soil pH in water and 1 N KCL, total N, available P, extractable K, Ca, Mg, Mn, Fe, Zn, Cu and also OC, Na and cation exchange capacity

(CEC) according to standard methods of soil analysis (Moberg, 2001; Okalebo *et al*., 2002). The soil chemical results were interpreted according to ratings by Landon (1991) and Estefan *et al*. (2013). Details of the soil sampling methods were similar to those highlighted in section 2.2.3.2 of chapter 2.

4.2.3.2 Sugarcane nutrient content

Sugarcane leaf was sampled at 18th month of sugarcane age after planted for plant crop cycle and also at 9th and 12th month sugarcane age after ratoon one emergence. The sampling unit was sugarcane shoot / stool per experimental plot. Four sugarcane shoots were randomly selected within the net plots and marked. Third dew lap leaf from the tip was chosen and cut using scateur. The leaves were then placed in brown bags well labelled. The leaves sampled were then taken to the laboratory and prepared. The parameters analysed included total nitrogen, phosphorus, potassium, calcium, magnesium, manganese and zinc according to standard methods by Okalebo *et al*. (2002). Details of sugarcane leaf sampling, preparation and laboratory analysis were similar to those highlighted in section 2.2.4 of chapter 2. Results of the sugarcane leaf nutrient content were interpreted against the critical levels according to Calcino *et al*. (2000) and McCray and Mylavarapu (2013).

4.2.3.3 Sugarcane yield components

Sugarcane was harvested on the 18th month after planting for plant crop cycle and on the 16th month after ratoon one crop cycle. The mature sugarcane stalks were cut from the base and chopped at the end (breaking point) using a sharp disinfected knife. The yield parameters recorded were sugarcane stalk girth, height, population and weight. Girth is the diameter of the sugarcane stalk. The girth was measured using vernier callipers.

The height of sugarcane stalk was measured using meter rule from the base of the stalk to the top of the stalk. The population of sugarcane stalks was determined. The number of sugarcane stalks was counted per net plot and converted to per ha to give population. The weight of the sugarcane stalks per plot was measured using a weighing balance. The weight per net plot was then converted to per hectare to give tonnes cane per hectare (TCH).

4.2.3.4 Sugarcane quality components

The qualitative traits of the harvested mature sugarcane were determined as pol % cane, brix % cane, fibre % cane, and tonnes sugar per hectare (BSES, 1991; STASM, 1991). The description of the sugarcane quality traits is as follows: Brix % in cane refers to the total soluble solids content present in the juice and corrected to more accurately represent those of the total juice in cane. Pol % in juice refers to the sucrose content present in the juice expressed in %. Pol is derived from the name of the machine that measures the sucrose content, a polarimeter. Pol % in cane refers to the sucrose content present in the juice expressed in % and corrected to more accurately represent those of the sucrose in cane. Fibre % cane refers to amount of fibre in the cane expressed in %. Commercial cane sugar (CCS) refers to the total recoverable sugar % (sucrose) in the cane.

4.2.4 Statistical analysis

The statistical significance was determined using ANOVA to test treatment effects on soil chemical properties, sugarcane leaf nutrient content, sugarcane yield and quality. Comparisons of means were carried out using least significance difference (LSD) at the 5 % probability level (GENSTAT, 2011). The GENSTAT statistical package was used for the above statistical analysis (GENSTAT, 2011).

4.3 Results and Discussions

4.3.1 Effects of lime placement methods (LPM), lime rates (LR) and nitrogen rates (NR) on soil chemical properties for 0 – 15 cm and 15 – 30 cm depth

The influence of LPM, LR and NR and their interactions on soil pH, macro and micro nutrients, soil organic carbon (OC), exchangeable sodium (Na) and cation exchange capacity (CEC) for the 0 – 15 cm soil depth is shown in Tables 4.1 and 4.2 while for the 15 – 30 cm depth is shown in Tables 4.3 and 4.4.

Lime rates significantly ($P < 0.05$) affected soil pH, Ca, OC, extractable Mn and Zn at 0 – 15 cm depth (Tables 4.1 and 4.2). Similarly, lime rates treatment significantly ($P < 0.05$) affected soil pH (in water and KCl), OC, extractable Mn, Fe and Zn for 15 – 30 cm depth (Tables 4.3 and 4.4).

Increased lime rate led to increased soil pH and exchangeable Ca as given in Table 4.5 and 4.6. Plots that received lime at 2 t ha^{-1} showed the highest soil pH and Ca while the lowest soil pH and Ca was in control plots (no lime) (Tables 4.5 and 4.6). This trend was noted for both depths, 0 – 15 cm and also 15 – 30 cm, and also when pH was determined in water and KCl solution. The least amount of soil extractable Mn, Zn and OC was recorded in plots that received 2 t ha^{-1} of lime compared to the control and 1 t ha^{-1} (Table 4.6).

The increase in pH was due to the increase in basic cation calcium and neutralization of H^+ at the exchange complex (Brady and Weil, 2008). The reaction of CaO is that, lime dissolves in the soil then the Ca ions generated move to the surface of exchange site replacing the acidity. Meanwhile, the acidity reacts with the carbonate to form CO_2 and water (Brady and Weil, 2008). This finding is consistent with findings by Choudhry (1984), Mutonyi (2014).

Table 4.1: F – test probabilities for effects of LPM, LR and N rates on soil pH and macronutrients at 0 – 15 cm soil depth

	F Test probabilities						
	Soil pH (H_2O)	Soil pH (KCl)	Total N, %	Avail. P,	Ex. K, cmol (+) / kg	Ex. Ca, cmol (+) / kg	Ex. Mg, cmol (+) / kg
LPM	0.492	0.474	0.39	0.158	0.563	0.323	0.426
LR	**< 0.001**	**< 0.001**	0.084	0.073	0.238	**0.003**	0.446
NR	0.796	0.989	0.575	0.092	0.193	0.467	0.182
LPM x LR	**< 0.001**	**< 0.001**	**0.005**	**< 0.001**	0.187	0.263	**0.017**
LPM x NR	**0.018**	0.28	0.357	0.807	0.134	0.415	0.562
LR x NR	0.228	0.092	0.447	0.874	0.113	0.291	0.161
LPM x LR x NR	0.368	0.73	0.112	0.181	0.06	0.99	0.806

LPM – lime placement methods; LR – lime rates; NR – nitrogen rates; Avail. – Available; Ex. – extractable; N – nitrogen; P – phosphorus; K – potassium; Ca – calcium; Mg - magnesium

Table 4.2: F – test probabilities for effects of soil micronutrients, OC, Na and CEC at 0 – 15 cm depth

	F test probabilities						
	Ex. Mn	Ex. Fe	Ex. Zn	Ex. Cu	OC, %	Na	CEC
LPM	0.208	0.792	0.696	0.770	0.541	0.583	0.431
LR	**< 0.001**	0.949	**0.005**	0.630	**0.043**	0.45	0.101
NR	0.928	0.717	0.242	0.700	0.544	0.789	0.812
LPM x LR	0.056	**< 0.001**	0.257	0.561	**< 0.001**	0.978	**0.021**
LPM x NR	0.633	0.149	0.769	0.250	0.789	**0.013**	0.163
LR x NR	**< 0.001**	0.07	0.325	0.657	**0.048**	0.906	0.260
LPM x LR x NR	0.549	0.489	0.075	0.965	0.876	0.803	0.329

Significance tested at $P \leq 0.05$. LPM – lime placement methods; LR – lime rates; NR – nitrogen rates; Ex. – extractable; Mn - – manganese; Fe – iron; Zinc – zinc; Cu – copper; OC – organic carbon; Na – sodium; CEC – cation exchange capacity

The decreased concentration of soil extractable Mn and Zn decreased in the soil solution as lime rate increased (Table 4.6) are in agreement with Emeades (1982); Bolan *et al.* (2003). Edmeades (1982) reported a decrease in Mn with increased liming. According to Shauman (1986), the gradual decrease in Zn activity with increasing pH is attributed to increasing CEC. Similar observation was noted by Stahl and James (1991) who reported that increasing surface charge due to liming increased Zn retention.

Lime placement methods did not significantly affect the soil chemical properties for 0 – 15 cm depth but it affected the soil pH (in KCl), total N and OC for 15 – 30 cm depth (Table 4.3). Nitrogen rate affected only the soil available P for the 15 – 30 cm depth (Table 4.3). There was no significance influence of nitrogen rates on all the soil chemical properties for 0 – 15 cm depth.

Interaction effects of the main treatments were recorded for both 0 – 15 cm and 15 – 30 cm depths. Interaction between LPM and LR significantly (P < 0.05) affected the soil pH (both in water and KCl), soil total N, available P, exchangeable Mg, OC, CEC and extractable Fe for 0 – 15 cm depth (Table 4.1 and 4.2). Similarly, the same interactions significantly affected soil pH, total N, extractable Mg and OC for 15 – 30 cm depth (Table 4.3).

Table 4.3: F – test probabilities for effects of LPM, LR and N rates on soil pH and macronutrients at 15 - 30 cm soil depth

	F test probabilities						
	Soil pH (H_2O)	Soil pH (KCl)	Total N, %	Avail. P,	Ex. K, cmol (+) / kg	Ex. Ca, cmol (+) / kg	Ex. Mg, cmol (+) / kg
LPM	0.340	**0.041**	**0.04**	0.081	0.758	0.958	0.155
LR	**0.006**	**< 0.001**	0.113	0.136	0.062	0.117	0.54
NR	0.380	0.301	0.72	**0.049**	0.362	0.118	0.167
LPM x LR	**0.003**	**< 0.001**	**0.018**	0.346	0.161	0.512	**0.007**
LPM x NR	0.160	0.366	0.292	0.359	0.784	0.065	0.538
LR x NR	0.349	**0.006**	0.734	0.089	0.366	0.276	0.291
LPM x LR x NR	0.539	0.276	0.238	0.385	0.969	0.61	0.133

Significance tested at $P \leq 0.05$. LPM – lime placement methods; LR – lime rates; NR – nitrogen rates; Avail. – Available; Ex. – extractable; N – nitrogen; P – phosphorus; K – potassium; Ca – calcium; Mg – magnesium

Table 4.4: F – test probabilities for effects of soil micronutrients, OC, Na and CEC at 15 – 30 cm depth

	F – Test probabilities						
	Ex. Mn	Ex. Fe	Ex. Zn	Ex. Cu	OC, %	Na	CEC
LPM	0.393	0.756	0.651	0.193	**0.023**	0.181	0.662
LR	**0.027**	**0.006**	**0.006**	0.243	< **0.001**	0.784	0.17
NR	0.79	0.920	0.289	0.158	0.115	0.368	0.682
LPM x LR	0.325	0.120	0.339	0.107	< **0.001**	0.164	0.481
LPM x NR	0.703	0.233	0.809	0.749	0.259	0.442	0.717
LR x NR	0.09	0.442	0.594	0.927	0.524	0.71	0.09
LPM x LR x NR	0.243	0.599	0.955	0.516	0.817	0.088	0.75

Significance tested at P ≤ 0.05. LPM – lime placement methods; LR – lime rates; NR – nitrogen rates; Ex. – extractable; Mn - – manganese; Fe – iron; Zinc – zinc; Cu – copper; OC – organic carbon; Na – sodium; CEC – cation exchange capacity

Table 4.5: Effects of lime rates of soil pH at 0 – 15 cm and 15 – 30 cm depth

	0 – 15 cm soil depth			15 - 30 cm soil depth		
Lime rates, t ha^{-1}	Soil pH (water)	Soil pH (KCl)	CEC cmol(+)/kg soil	Soil pH (water)	Soil pH (KCl)	CEC cmol(+)/kg soil
0	6.06b	6.01b	15.77	4.81c	4.70b	17.06
1	6.28a	6.12a	16.53	5.07b	4.88a	16.41
2	6.34a	6.15a	16.63	5.23a	4.89a	15.61
LSD (P ≤ 0.05)	0.10	0.09	0.856	0.11	0.07	1.523
CV (%)	3.0	2.8	9.6	4.3	2.9	17

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level of significance. Key: CEC – cation exchange capacity

Table 4.6: Effects of lime rates on soil exchangeable Calcium, Manganese, Zinc and Organic carbon at 0 – 15 cm depth

	Soil chemical properties			
Lime rates, t ha^{-1}	Ex. Ca, cmol (+)/kg	Ex. Mn, mg kg^{-1}	Ex. Zn, mg kg^{-1}	OC, %
0	20.43b	214a	1.57b	1.38ab
1	23.42a	199a	1.84a	1.45a
2	23.74a	178b	1.44b	1.30b
LSD (P ≤ 0.05)	2.06	15.8	0.24	0.11
CV (%)	16.7	14.7	27.1	15.2

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level of significance. Key: Ex – exchangeable; Ca – Calcium; Mn – Manganese; Zn – Zinc; OC – Organic Carbon

4.3.2 Effects of lime placement methods, lime rates and nitrogen rates on nutrient content of sugarcane leaf for plant crop and ratoon one cycles

Effects of lime placement methods, lime rates and nitrogen rates on sugarcane leaf nutrients; nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn) and zinc (Zn) for plant crop cycle is given in Table 4.7. The same treatment effects on the sugarcane leaf nutrients for sugarcane aged 9 months after ratoon emergence and 12 months after ratoon emergence are given in Table 4.8 and Table 4.9 respectively. Lime placement methods, LR, NR and interactions did not affect nutrient content in sugarcane for the plant crop cycle except total Mn in sugarcane leaves under the LPM x LR x NR treatment interaction (Table 4.7).

Lime placement methods, interaction LR x NR and interaction LPM x LR x NR significantly affected the sugarcane leaf K content for leaves sampled at 9th month of ratoon one cycle (Table 4.8). Other nutrients such as N, P, Ca, Mg, Mn and Zn were not significantly affected by the treatments.

Table 4.7: F – test probabilities for effects of LPM, LR and NR on nutrient content of sugarcane leaves for plant crop cycle

	F – test probabilities						
	N	P	K	Ca	Mg	Mn	Zn
LPM	0.217	0.137	0.655	0.067	0.666	0.873	0.728
LR	0.654	0.722	0.728	0.365	0.423	0.344	0.930
NR	0.162	0.608	0.510	0.92	0.972	0.706	0.616
LPM x LR	0.698	0.859	0.887	0.945	0.900	0.085	0.124
LPM x NR	0.636	0.546	1.000	0.244	0.162	0.303	0.837
LR x NR	0.920	0.294	0.994	0.425	0.255	0.536	0.821
LPM x LR x NR	0.113	0.276	0.932	0.699	0.606	**0.048**	0.934

Significance tested at $P \leq 0.05$. N – nitrogen, P – phosphorus, K – potassium, Ca – calcium, Mg – magnesium, Mn – manganese, Zn - zinc

For sugarcane leaves sampled at 12 months after ratoon emergence, lime placement methods significantly affected sugarcane leaf K, Ca, Mg, Mn and Zn content (Table 4.9). Lime rates significantly affected sugarcane leaf N and Mg content. Interaction LPM x LR significantly affected sugarcane leaf K content, while interaction LPM x NR significantly affected sugarcane leaf N content (Table 4.9).

Table 4.8: F – test probabilities for effects of lime placement methods, lime rates and nitrogen rates on nutrient content of sugarcane leaves for ratoon crop cycle at 9 months after ratoon emergence

	F test probabilities						
Source of variation	N	P	K	Ca	Mg	Mn	Zn
LPM	0.746	0.960	**0.035**	0.953	0.870	0.400	0.801
LR	0.747	0.929	0.096	0.075	0.155	0.097	0.266
NR	0.636	0.470	0.071	0.827	0.929	0.996	0.572
LPM x LR	0.970	0.442	0.201	0.960	0.308	0.397	0.615
LPM x NR	0.418	0.915	0.227	0.799	0.379	0.992	0.990
LR x NR	0.840	0.718	**0.011**	0.981	0.570	0.871	0.747
LPM x LR x NR	0.379	0.638	**0.024**	0.985	0.969	0.698	0.840

Significance tested at $P \leq 0.05$. N – nitrogen, P – phosphorus, K – potassium, Ca – calcium, Mg – magnesium, Mn – manganese, Zn - zinc

Table 4.9: F - test probabilities for effects of lime placement methods, lime rates and nitrogen rates on nutrient content of sugarcane leaves for ratoon crop cycle at 12 months after planting

	F test probabilities						
Source of variation	N	P	K	Ca	Mg	Mn	Zn
LPM	0.330	0.478	< **0.001**	**0.024**	**0.049**	**0.027**	**0.034**
LR	**0.029**	0.218	0.26	0.076	**0.014**	0.429	0.16
NR	0.491	0.680	0.169	0.416	0.532	0.160	0.866
LPM x LR	0.124	0.809	< **0.001**	0.728	0.385	0.936	0.979
LPM x NR	**0.035**	0.889	0.823	0.395	0.516	0.308	0.596
LR x NR	0.230	0.711	0.077	0.168	0.813	0.054	0.063
LPM x LR x NR	0.238	0.32	0.053	0.662	0.609	0.667	0.972

Significance tested at $P \leq 0.05$. N – nitrogen, P – phosphorus, K – potassium, Ca – calcium, Mg – magnesium, Mn – manganese, Zn - zinc

Highest amount of sugarcane leaf K, Ca, Mg, Mn and Zn was recorded for sugarcane leaves sampled in plots that were lime shallow banded (L-SB) while the lowest was in plots that were lime deep banded, L-DB (Table 4.10).

Table 4.10: Effects of lime placement methods on nutrient content of sugarcane leaves at 12 months after ratoon emergence

	Sugarcane leaf nutrient content				
Lime placement methods	K, %	Ca, %	Mg, %	Mn, mg kg^{-1}	Zn, mg kg^{-1}
Lime Broadcasted	0.47b	0.70a	0.23ab	57b	17.8a
Lime deep banded	0.47b	0.53b	0.15b	52b	13.4b
Lime shallow banded	0.57a	0.68a	0.25a	60a	18.4a
LSD ($P \leq 0.05$)	0.05	0.13	0.07	6.1	4.0
CV %	19	37	30	19	44

Means in the same column followed by the same letter(s) are not significantly different at 0.05 level Key: CV – coefficient of variation; K- potassium; Ca – calcium; Mg – magnesium, Mn – manganese; Zn - Zinc

With the exception of sugarcane leaf K content, all other nutrients were in adequate amount above critical levels, according to Calcino *et al.* (2000) and McCray and Mylavarapu, 2013). The greater sugarcane leaf nutrients content noted in sugarcane plots shallow - banded with lime was perhaps due to enhanced uptake of the nutrients in the 0 – 15 cm depth. However, this could not be related to the soil chemical properties investigated since lime placement methods did not influence the soil chemical properties. The findings are in agreement with Mutonyi (2014) who reported high sugarcane leaf K content in plots where lime was integrated with mineral fertilizer and compost in ratoon one crop cycle, season 2.

4.3.3 Effects of lime placement methods, lime rates and nitrogen rates on sugarcane yield for plant crop cycle

Effects of lime placement methods, lime rates and nitrogen rates on yield components and yield of sugarcane harvested for plant crop cycle are given in Table 4.11. Similarly, the same treatment effects on sugarcane quality parameters are shown in Table 4.12. The LPM, LR, NR and the interactions did not significantly ($P > 0.05$) affect the girth, height, population and weight of sugarcane stalks as shown in Table 4.11. Lime placement methods significantly affected the brix % juice and purity of sugarcane. Lime placement, lime rates, nitrogen rates and interactions did not affect the quality of sugarcane. Sugarcane harvested from plots where lime was shallow banded (LSB) recorded highest brix % juice while it was the lowest in purity (Table 4.13).

Table 4.11: F - test probabilities for the effect of lime placement methods, lime rates and nitrogen rates on sugarcane yield components for plant crop cycle

	F test probabilities			
	Girth Stalk	Height Stalk	Population of stalks	Weight of stalks, t ha^{-1}
LPM	0.765	0.053	0.496	0.618
LR	0.652	0.717	0.827	0.730
NR	0.794	0.701	0.619	0.603
LPM x LR	0.115	0.749	0.971	0.891
LPM x NR	0.939	0.152	0.118	0.065
LR x NR	0.304	0.071	0.189	0.105
LPM x LR x NR	0.287	0.776	0.082	0.218

Significance tested at $P \leq 0.05$.

Table 4.12: F – test probabilities for effects of lime placement methods, lime rates and nitrogen rates on sugarcane quality for plant crop cycle

	F test probabilities						
	Pol % Juice	Pol % cane	Brix % Juice	Brix % Cane	Fibre	Purity	CCS
LPM	0.209	0.555	**0.034**	0.222	0.518	**0.014**	0.941
LR	0.567	0.703	0.356	0.559	0.382	0.663	0.597
NR	0.651	0.937	0.408	0.646	0.399	0.987	0.943
LPM x LR	0.111	0.626	0.321	0.684	0.269	0.115	0.46
LPM x.NR	0.525	0.812	0.336	0.615	0.816	0.173	0.536
LR x NR	0.159	0.561	0.564	0.587	0.608	0.673	0.612
LPM x .LR x NR	0.248	0.849	0.251	0.566	0.423	0.51	0.822

Significance tested at $P \leq 0.05$.

Sugarcane quality is important for sugar production during processing the cane into sugar and its products (Engelke, 2002). The parameters of sugarcane quality investigated against the treatments used in this study were pol % juice, brix % juice, pol % cane, brix % cane, Fibre, purity and CCS.

Table 4.13: Effects of lime placement methods on brix % juice and purity of sugarcane harvested for ratoon one cycle

	Sugar quality parameters	
Lime placement methods	Brix % juice	Purity
Lime broadcasted	23.09ab	86.04ab
Lime deep banded	22.90b	86.76a
Lime shallow banded	23.49a	85.59b
LSD	0.451	0.776
CV %	3.6	1.7

Means in the same column followed by the same letter(s) are not significantly different at $P \leq 0.05$ level. Key: CV – coefficient of variation

This study showed that only lime placement method significantly influenced brix % juice and purity (Table 4.13). Lime rates and also nitrogen rates did not affect the quality of sugarcane. These findings are consistent with findings those Mahadevaswamy and Martin (2002), Nazir *et al.* (2002) and Yang *et al*. (2013) who reported non - significance in the response on sugarcane quality under sugarcane intercropped system. In India, a study showed that high nitrogen rate did not affect sugarcane juice quality (Madhuri *et al*., 2011; Singh *et al*., 2011).

4.5 Conclusions

Liming with reference to lime rates affected the soil pH for both 0 – 15 cm and 15 – 30 cm. Lime placement methods (LPM) and also nitrogen rates (NR) did not affect the soil acidity. Increased lime rate led to increased soil pH. Some soil chemical properties, specifically, Ca, Mn, Zn and OC were affected by the LR but not the LPM. These trends were similar between depth 0 – 15 cm and 15 – 30 cm. Lime rate, 2 t ha^{-1} led to the highest soil pH. Significant effects of the sugarcane nutrient content as affected by the treatments was noted for ratoon crop aged 12 months after ratoon emergence. LPM affected total K, Ca, Mn and Zn while the LR affected total N and Mg. Lime shallow banded and lime broadcasted led to highest uptake of these nutrients. Sugarcane yield and quality parameters were not affected by the lime placement methods, lime rates and also nitrogen rates. In view of the findings, lime rate 2 t ha^{-1} is recommended for use to ameliorate soil acidity for acidified Cambisols soils of Kibos, Kisumu County, Kenya. Lime broadcasting or lime banding at the shallow depth, 0 – 15 cm, should be used as a lime placement method.

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CHAPTER FIVE

5.0 GENERAL DISCUSSIONS

5.1 Components of the study

In western Kenya, the soils are acidic in nature, e.g. Acrisols, Ferralsols and Cambisols. Acidification of these soils is exacerbated by long term use of ammonium based fertilizers namely urea and diammonium phosphate (Omollo and Abayo, 2011). Amolo *et al*. (2011) revealed a decline of soil pH to 5.5 for Cambisols under sugarcane growing areas of western Kenya. Bolan *et al.* (2003) stated that regular fertilizer use is one of the major causes of soil acidification under managed ecosystems. Acidity threatens food and cash crop production in Western Kenya where the region contributes significantly to the Kenyan economy (Okalebo *et al*., 2009). Acid soils are a constraint to crop production since they cause soil fertility problems such as aluminium (Al) and manganese (Mn) toxicity, calcium (Ca) and magnesium (Mg) deficiency and low molybdenum (Mo) and phosphorus (P) availability (Kamprath, 1984; Kanyanjua *et al.*, 2002., Bolan *et al.*, 2003). Also, acidity negatively affects the symbiotic relationship between Rhizobia and legumes. Poor nodulation and N fixation is noted when soil pH is less than 6.0. This inhibitory effect is attributed to poor supply of Mo and Ca, essential for N fixation (Sumner *et al*., 1991; Bolan *et al*., 2003; Fageria and Baligar, 2008).

Sugarcane intercropping, also considered as crop diversification, is one of the cropping systems practiced on small - holder farms with less than 2 ha in western Kenya (Wawire *et al.*, 2006; KESREF, 2009). The small - holder farmers, also referred to as out-grower farmers practice sugarcane intercropping with annual crops for both food security and household income (Wawire *et al*., 2006). The benefits of sugarcane - soybean intercropping are diverse crops yield, increased income, nutrition and also biological nitrogen fixation (BNF) which can cut costs on the use of N fertilizers and therefore reduce soil N mining (Chianu *et al*., 2008).

Liming traditionally is considered as a management practice to reduce the soil acidity and therefore one of the soil fertility management practices (AGRA, 2009). Most plants grow well at a pH range of 5.5 – 6.5 and liming is aimed to increase the pH at this range. The benefits of liming include: enhanced soil physical, chemical and biological conditions (Haynes and Naidu, 1998; Bolan *et al*., 1999; Bolan *et al*., 2003). The enhanced mineralization of these nutrient ions is likely to cause an increase in their concentration in soil solution for plant uptake and for leaching (Lyngstad, 1992; Neale *et al*., 1997). Nitrogen fixing bacteria in legume plants require Ca, hence liming is likely to enhance N fixation (Muchovej *et al*., 1986). Studies on lime use in Kenya has centered on the lime rate with limited work on lime use efficiency (Nekesa, 2007; Okalebo *et al*., 2009). Lime is an input cost to soil fertility management and therefore its judicious use is paramount. Lime placement is considered a strategy that can increase lime use efficiency. (Gonzalez-Erico *et al*., 1979 cited in Kamprath, 1984) studied lime placement and found that incorporation of lime to a depth of 30 cm resulted in higher grain yields than when lime was incorporated only in the top 15 cm. Caires *et al*. (2005) found that surface application of lime at 4 t ha^{-1} under no till system significantly reduced acidity problem (pH, Al and basic cations) at different depths 0 – 5 cm and 5 – 10 cm within 1 year onward and also 10 – 20 cm from 2.5 years. Okalebo *et al*. (2009) found that lime at 2 t ha^{-1} combined with phosphorus at 26 kg P ha^{-1} and nitrogen at 75 kg N ha^{-1} raised the soil pH to the range of 5.8 – 6.5, available P to above 10 mg P ha^{-1} and also significant maize yield of 6 t ha^{-1}. Mbakaya *et al*. (2010) recorded increased yield of 3.6 t ha^{-1} in lime treatments compared to inorganic fertilizer treatments which recorded 2.6 t ha^{-1} maize yield.

There exist knowledge gap in our understanding of lime placement and efficient amelioration of soil acidity for increased soil nutrient availability, nutrients uptake by sugarcane, yields and quality of sugarcane. This therefore calls for efficient use of lime to be integrated with soil fertility management practices so as to ensure reduced acidity, nutrient availability and nutrient uptake and yields of sugarcane and quality of sugarcane

Two field experiments was conducted at field 6, experimental plots of Kibos (35^{o}13 E, 0^{o}06 S), KALRO – Sugar Research Institute, Kisumu County in Kenya. The site elevation is 1268 m above sea level, located at LM 2, agro – ecological zone referred to sub – humid, marginal sugarcane zone with a soil type Eutric Cambisol (FAO, 2006; Jaetzold *et al*., 2007).

Field experiment one, included effects of lime placement in ameliorating soil acidity for improved performance of sugarcane – soybeans in Cambisols of Kibos. The hypothesis was that cropping systems, lime placement methods and lime rates does not increase soil pH, soil nutrient availability, and nutrient uptake by sugarcane, yield and quality of harvested sugarcane. Field experiment two, included effects of lime placement in ameliorating soil acidity for increased nitrogen use efficiency and performance of sugarcane and soybean intercrop. The hypothesis was that lime placement methods, lime rates and nitrogen rates do not increase soil pH, soil nutrient availability, and nutrient content by sugarcane, yield and quality of harvested sugarcane.

5.2 Synthesis of main findings and implications

In view of the study, the synthesis is presented based on the chapters as follows: Chapter 2: In Kenya, liming studies have centered on lime rates and food crop production (Nekesa, 2007; Okalebo *et al*., 2009; Mbakaya *et al*., 2010). There is limited knowledge on lime placement methods as a means of increased lime use efficiency for increased soil pH, soil nutrient availability and nutrient uptake by sugarcane. Findings in the present studies revealed that lime rate, 2 t ha^{-1} was the best to ameliorate soil acidity from 6.1 to 6.4 (soil pH in water) [or from 4.9 to 5.2 (soil pH in KCl)]. Increased lime rate led to decreased levels of manganese, iron, and copper hence liming has the potential to reduce toxicity caused by high levels of the micronutrients. For lime placement methods, Lime deep banded (L-DB) increased soil pH and available phosphorus for sub depth 15 – 30 cm. This shows that, sub soil acidity is best limed when lime is deep banded (L-DB) as a lime placement method is employed. Intercropped sugarcane and soybeans (IC) led to increased acidity and soil organic carbon (SOC). The increased acidity is a result of the reaction during decomposition of soil organic carbon / soil organic matter generated from sugarcane and soybean residues. Intercropped sugarcane and soybeans increased uptake of calcium and manganese by sugarcane. This increase is attributed to decomposition of soybean residues which then produced calcium. Lime broadcasted (L-BC) caused high uptake of nitrogen and phosphorus by sugarcane; however, the levels were below the critical values. Lime shallow banded resulted to increased uptake of Ca and Zn to optimum levels. The study concluded that lime rate 2 t ha^{-1} should be recommended for use to ameliorate soil acidity for acidified Cambisols soils of Kibos, Kisumu County, Kenya. Lime broadcasted, still remains the preferred lime placement method to ameliorate soil pH within plough depth 0 – 15 cm when acidity is identified. Also, lime placement methods should take into consideration the soil pH stratification with depth. Lime banded should only be employed when sub soil acidity is identified.

Chapter 3: This study investigated whether appropriate lime placement methods, lime rates and intercropped sugarcane with soybeans leads to amelioration of soil pH hence increased yields and quality of sugarcane for the plant and ratoon one crop cycles. Cropping systems affected sugarcane yields for the plant crop cycle but not for the ratoon crop cycle. The high sugarcane yield witnessed under the intercrop system is a result of the benefits of intercrop cropping system. Lime applied did not affect the sugarcane yields for the plant crop and ratoon crop cycles. This indicates that lime plays an indirect role in crop growth and yields. Lime plays a direct role on ameliorating soil acidity and nutrient transformations. These effects coupled with other factors then affect crop yields. Lime was found to affect the quality of sugarcane both for the plant crop and also ratoon crop cycles. For example, sugarcane under lime shallow banded gave the highest pol % cane and commercial cane sugar. There was decreased yield with increased crop cycle. Yields for the plant crop were higher than for ratoon crop cycle. Similarly, the sugarcane quality traits, pol and brix were lower for the ratoon than plant crop harvest, except purity which showed the reverse. The study implies that liming is a strategy that ameliorates soil acidity and transforms nutrient availability and has no direct effect on sugarcane yields. Liming as a soil improvement strategy should be integrated with other nutrient improvement strategies such as appropriate cropping and fertilizer use for high yields to be witnessed. Liming may be a strategy to improve the quality of sugarcane especially with the introduction of payment of sugarcane based on sucrose content in addition to sugarcane weight. However, further studies on the effect of lime on sugarcane quality are recommended.

Chapter 4: This study investigated whether lime placement methods (LPM), lime rates (LR) and nitrogen rates (NR) for intercropped sugarcane with soybeans under acid soils leads to increased soil pH, soil and sugarcane nutrient status and also yields and quality. Liming with reference to lime rates affected the soil pH for both 0 – 15 cm and 15 – 30 cm. Lime placement methods (LPM) and also nitrogen rates (NR) did not affect the soil acidity. Increased lime rate led to increased soil pH. Some soil chemical properties, specifically, Ca, Mn, Zn and OC were affected by the LR but not the LPM. These trends were similar for depth 0 – 15 cm and 15 – 30 cm. Lime rate, 2 t ha^{-1} led to the highest soil pH. Significant effects of the sugarcane nutrient content as affected by the treatments was noted for ratoon crop aged 12 months after ratoon emergence. LPM affected total K, Ca, Mn and Zn while the LR affected total N and Mg. Lime shallow banded and lime broadcasted led to highest uptake of these nutrients. Sugarcane yield and quality parameters were not affected by the lime placement methods, lime rates or nitrogen rates. In view of the findings, lime rate 2 t ha^{-1} is recommended for use to ameliorate soil acidity for acidified Cambisols soils of Kibos, Kisumu County, Kenya. Lime broadcasting or lime banding at shallow depth, 0 – 15 cm should be used as a lime placement method.

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CHAPTER SIX

6.0 GENERAL CONCLUSIONS AND RECOMENDATIONS

6.1 General conclusions

In view of the findings, it is concluded that:

Liming ameliorated soil acidity for acid Cambisols of Kibos, Kisumu County. Lime rate, 2 t ha^{-1} increased soil pH from 6.1 to 6.4 (soil pH in water) and also from 4.9 to 5.2 (soil pH in KCl). Increased lime rates caused a decrease of soil Mn, Fe and Cu therefore confirms the inverse relationship between soil pH and these micronutrients. This shows potential of liming as a strategy to reduce toxicity caused by high levels of the micronutrients. Lime placement methods seemed to affect soil properties although variedly. Lime deep banded (L-DB) increased soil pH and available phosphorus for sub depth 15 – 30 cm. This shows that, sub soil acidity is best ameliorated when lime deep banded is employed as the lime placement method. Intercropped sugarcane and soybeans (IC) led to increased acidity and also soil organic carbon (SOC). The increased acidity is a result of the reaction during decomposition of soil organic carbon / soil organic matter generated from sugarcane and soybean residues. Intercropped sugarcane and soybeans increased uptake of calcium and manganese by sugarcane. This increase is attributed to decomposition of soybean residues which then produced calcium. Lime broadcasted (L-BC) caused high uptake of nitrogen and phosphorus by sugarcane, however the levels were below the critical values. Lime shallow banded resulted to increased uptake of Ca and Zn to optimum levels. Cropping systems affects sugarcane yields for plant crop cycle but not for ratoon crop cycle. The high sugarcane yield obtained under the intercrop system is a result of the benefits of intercrop cropping system. Lime applied did not affect the sugarcane yields for the plant crop and ratoon crop cycles. This indicates that lime plays an indirect role in crop growth and yields. Lime plays a direct role on ameliorating soil acidity and nutrient transformations. These effects coupled with other factors then affects crop yields. Lime was found to affect the quality of sugarcane both for plant crop and also ratoon crop cycles. For example, sugarcane under lime shallow banded gave the highest pol % cane and commercial cane sugar. Liming with reference to lime rates affected the soil pH for both 0 – 15 cm and 15 – 30 cm. Lime placement methods (LPM) and also nitrogen rates (NR) did not affect the soil acidity. Increased lime rate led to increased soil pH. Some soil chemical properties, specifically, Ca, Mn, Zn and OC were affected by the LR but not the LPM. These trends were similar between depth 0 – 15 cm and 15 – 30 cm. Lime rate, 2 t ha^{-1} led to the highest soil pH. Significant effects of the sugarcane nutrient content as affected by the treatments was noted for ratoon crop aged 12 months after ratoon emergence. Lime placement methods affected total K, Ca, Mn and Zn while the LR affected total N and Mg. Lime shallow banded and lime broadcasted led to highest uptake of these nutrients.

6.2 Recommendations

In view of the results, the following are recommended:

i. Liming still remains the best management strategy to ameliorate soil acidity. For the case of acid Cambisols of Kibos in Kisumu County, the lime rate 2 t ha^{-1} is recommended to raise the soil pH to about 6.5 when Koru limestone (21 % CaO) is used. There is a need to also consider use of other sources of lime such as calcitic limestone, dolomitic limestone and wood ash which are also found in the country. Further research on the effects of these liming materials on soil acidity is recommended.

ii. Use of lime placement methods should take into consideration the soil acidity stratification with depth. Lime broadcasting and lime shallow banding should be used when acidity is noted within depth, 0 – 15 cm. Lime deep banding should only be applied when soil acidity is noted to increase with depth. The scope of this research study did not assess acid stratification with depth; hence, further study is recommended for these areas.

iii. Liming was observed to improve some parameters of sugarcane quality. Liming may be a strategy to improve the quality of sugarcane especially with the introduction of payment of sugarcane based on sucrose content in addition to sugarcane weight is currently advocated in the Kenyan sugar industry. However, further studies on the effect of lime on different aspects of sugarcane quality are recommended.

iv. Liming as a soil improvement strategy should be integrated with other nutrient improvement strategies such as appropriate cropping and fertilizer use for high yields to be achieved.