# UNIVERSITY OF NAIROBI

# "INFLUENCE OF SOIL PARENT MATERIALS ON POTASSIUM AVAILABILITY TO MAIZE IN WESTERN KENYA"

BY

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# DEDICATION

To: my father, Arthur; my mother, Frieda; and my late brother, Paul. Their vision for a better tomorrow is unrivalled by the best educators in my life

*I planted, Apollos watered; but God gave the increases*

*1 Cor, 3: 6*

# SPECIAL APPRECIATION

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# DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

Signature

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25/01/06 Date

This thesis has been submitted for examination with our approval as University Supervisors

Signature

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26 January 2006 Date

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| | |
|---|---|
| ACT | Almanach Characterization Tool |
| ATP | Adenosine Triphosphate |
| BCSR | Base Cation Saturation Ratio |
| BNF | Biological Nitrogen Fixation |
| CEC | Cation Exchange Capacity |
| CIPW | Cross, Iddings, Pirsson and Washington |
| CSTV | Critical Soil Test Values |
| DAE | Days After Emergence |
| DAP | Diammonium Phosphate |
| DAS | Days After Sowing |
| DMG | Department of Mines and Geology |
| ECEC | Effective Cation Exchange Capacity |
| ESRI | Environmental Systems Research Institute |
| EU | European Union |
| FURP | Fertilizer Use Recommendation Project |
| GIS | Geographical Information Systems |
| GLP | Grain Legume Project |
| GPS | Global Positioning System |
| GRV | Great Rift Valley |
| GS | Geomorphic Surface |
| ICRAF | International Centre for Research in Agro- Forestry |
| IFA | International Fertilizer Association |
| KARD | Kenya Agricultural Research Database |
| KARI | Kenya Agricultural Research Institute |
| KEFRI | Kenya Forestry Research Institute |
| KENSOTER | Kenya soil and Terrain Database |
| KSS | Kenya Soil Survey |
| LAI | Leaf Area Index |
| MOA | Ministry of Agriculture |
| NAL | National Agricultural Laboratories |
| NARL | National Agricultural Research Laboratories |
| NEK | Non-exchangeable potassium |
| NGA | Northern Geomorphic Area |
| PLAR | Participatory Learning and Research |
| RCBD | Random Complete Block Design |
| SGA | Southern Geomorphic Area |
| SRD | Scientific Research Division |
| TSBF | Tropical Soil Biology and Fertility |
| UoN | University of Nairobi |

*All soil- forming processes occur in all soils; only the balance among the processes is not the same and is determined by the geographical position (Simonson, 1959).*

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*There seems to be little merit in liming soils to* $pH_{H2O}$ *5.5 at which exchangeable Al is effectively neutralized (Sumner and Yamada, 2002)*

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*Geologic time is vast; geologic processes are slow, but they have literally all the time in the world in which to operate and thereby cause tremendous changes. Hunt, C.B. (1972)*

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# ABSTRACT

Potassium (K) deficiency is an emerging problem in intensively cropped soils of Kenya; which contradicts a hitherto existing belief that Kenyan soils have adequate K to meet crop needs. The emerging K deficiency is attributed to a net negative K balance in soils, as a result of greater losses than gains. Weathering of parent materials is an important nutrient input pathway, which has hardly been studied in Kenya. This study was conducted to test the general hypothesis that there is a relationship between the mineralogy and geo-chemical properties of parent rocks and plant available K in soils. The four specific objectives used to test the general hypothesis were: (i) to establish whether areas in Kenya with an emerging K deficiency can be mapped from existing soil and climatic databases, and validate the map so-developed; (ii) to determine the relationship between mineralogical and geo-chemical properties of parent rocks, and amount of clay, clay mineralogy, and potassium status of overlying soils; (iii) to determine the relationship between amount of clay and clay mineralogy, and the distribution of soil K in various pools and K availability to maize plants; and (iv) to determine the agronomic and economic benefits of K fertilizer application in maize optimally fertilized with N and P in field soils with an emerging K deficiency.

Areas likely to have K deficiency were mapped in Geographical Information Systems (GIS), using geo- referenced database in the Almanach Characterization Tool (ACT). Studies were done at six sites, located in two major geomorphic areas, in western Kenya. Three sites: Ebukanga, Yala and Kabula, were in the northern geomorphic area (NGA), and three sites: Itare, Keumbu and Ndanai, in the southern geomorphic area (SGA). Hand specimens of rocks, and soil samples were analysed for physical, chemical and mineralogical properties; and results used to test their relationships. The soils were exhaustively cropped with maize in the greenhouse, and analysed for dry matter and K uptake. Field experiments were conducted in farmers' fields, to determine the effect of increasing K (0, 25, 50 and 75 kg ha$^{-1}$) in one factor, randomised complete block design (RCBD), receiving 75 kg of N and $P_2O_5$ ha$^{-1}$, as top-, and basal- dressing respectivly.

Mapped region covered about 13 % of the land area in Kenya (about 7.5 million hectares). Exchangeable K ranged from 0.2 – 1.6 cmol kg$^{-1}$ in soils from farmers' fields, and was consistently deficient in the NGA, due to low soil organic matter. Soils from the SGA were not deficient in K due to high organic matter. This fact is confirmed by the high correlation obtained between exchangeable

K and organic C ($r^2 = 0.859$, $P = 0.015$). The map developed from climatic data requires revision; in view of new insights obtained from this research work.

The mafic (ferromagnesian) - to- felsic (quartz, feldspar rich), mineral ratio in rock samples ranged from 0.05 – 2.33, and decreased with increase in $SiO_2$ content. Clay content of studied soils ranged from 35.5 – 65.5 %, but was not significantly related to mafic/felsic ratio in rocks, perhaps because of: incongruent weathering of parent rocks, colluvial clay deposits from higher grounds to soils in Kabula and Ndanai, and plinthitization of soils in Kabula. Observations made in the field confirmed these facts. The illite/kaolinite mineral ratio in studied soils ranged from $4.6 - 11.8 \times 10^{-2}$ and decreased with increase in mafic: felsic mineral ratios of rocks, due to extreme weathering of mafic- rich parent rocks.

Total K in rocks did not influence the exchangeable K in studied soils significantly, probably because of K release from organic matter; relative biotite/ orthoclase content in rocks, which have different susceptibility to weathering; and colluvial addition of K in Kabula and Ndanai soils. In studied soils: total K ranged from 10.7 – 48.5 cmol ($p^+$) $kg^{-1}$, exchangeable K from 0.1 – 0.35 cmol ($p^+$) $kg^{-1}$, and solution K from 0.0048 – 0.0182 cmol ($p^+$) $kg^{-1}$, all of which decreased with increase in clay content of soils. The decreases were attributed to observed decrease in orthoclase in sand fraction, decrease in 2: 1 clay minerals as clay content increased in soils, and assumed low diffusive flux in clayey soils. Average K uptake by maize plants ranged from 0.24 – 0.79 g $pot^{-1}$, and decreased with increase in clay content due to the limited labile K in fine textured soils.

Maize response to increasing rates of K from 0 – 75 kg K $ha^{-1}$ (as KCl), was not significant, possibly because: the three-season testing period was too short, fixation by illites identified in this study, high incidence of striga weed, and Ca and Mg deficiency found in soils from the NGA. The probability of response to K fertilizers increased with seasons, as readily available K got depleted in soils. Economic returns to K fertilizer application were positive and K fertilizer was recommended at 25 kg K $ha^{-1}$ in 40 % of the farms in both NGA and SGA. Response to K fertilizers is expected to increase as more N and P fertilizers are applied in maize to increase yields, in an effort to fight hunger and reduce poverty among the Kenyan people, as stipulated in the millennium development goals, that Kenya has commited herself to meet by 2015.

# CHAPTER 1: INTRODUCTION

Soils to the west of the Great Rift Valley (GRV) in Kenya lie in the highlands, more than 1000 m above sea level. Like most of East Africa, Kenyan highlands are densely populated and intensively cropped to meet human demands for food and feed for the livestock (Jama *et al.,* 1997). Climatic conditions in the highlands are suitable for cash crops, where bananas, maize, sugarcane, tea, coffee, pyrethrum and vegetables are grown and sold to earn income for the family. According to Jama *et al.* (1997), highlands in East Africa cover about 20 % of the land area but play host to about 60 % of the population. The majority of farmers are small scale holders with < 1.0 ha of land per household, due to repeated sub-division of land, as population density increased (Sanchez *et al.,* 1997).

About four decades ago, Kenyans living in the highlands, like the rest of the country, were practising traditional agriculture. Traditional systems were characterized by long fallow periods, shifting cultivation, and in some cases application of manure, recycling of crop residues, mulching -and multiple cropping (Anderson, 1973). The traditional farming systems have ceased to be employed due to inevitable socio-economic changes. Land sub-division into small units as a result of increased population density cannot support shifting cultivation, long fallow periods, and large number of livestock for manure; while mulching materials are either scarce, or have better/ alternative uses in feeding animals and sources of fuel (Nandwa and Bekunda, 1998).

High population density and reduction in farm sizes has exerted a lot of pressure on efforts to raise per capita food production in the highlands. As recognized earlier by Barber (1995), plant growth involves the interaction of soil and plant parameters. Since 1960s, the Government and other organizations in Kenya have made commendable progress in breeding of superior crop varieties in terms of yields and harvest quality. Improvements in soil fertility and plant nutrition strategies has not been as succcessiful. The majority of farmers still depend on low cost sources of nutrients like manures, composts and biomass transfer, but use of mineral fertilizers is low (Jama *et al.,* 1997). While it is true that such low cost inputs have helped the farmers, yields obtained are lower than the breeders' potential, and have been declining over the years (Ayaga *et al.,* 2004). Declining soil fertility has been identified as a major constraint to increased food production (Ayaga *et al.,* 2004).

When compared with local maize cultivars, improved varieties perform better under mono-cropping systems and have higher demand for nutrients to produce high yields. The changes in cropping systems, coupled with use of crop residues as cattle feed and fuel for cooking (Nandwa and Bekunda, 1998), have interfered with the soil-crop-animal-manure-soil cycle of nutrients (Sumner and Yamada, 2002). The result is a negative nutrient balance and deficiency of nutrients like K, which are seldom applied externally through fertilizers (Stoorvogel *et al.*, 1993; Smaling *et al.,* 1997).

Where mineral fertilizers have been used, nutrient mix is largely imbalanced, with N and P fertilizers dominating the local market (Mwaura and Woomer, 1999). Nitrogen and P fertilizers have in the past increased crop yields by big margins, to the satisfaction of many farmers. It is however, felt that sole fertilization with N and P has accelerated the rate of depletion of nutrients like Ca, Mg, and K, which are taken up by plants in large quantities, yet not applied alongside N and P (Stoorvogel *et al.,* 1993; Smaling *et al.,* 1993; Nandwa and Bekunda, 1998). Consequently, yields have not only declined (Ayaga *et al.,* 2004), but the impact of N and P fertilizers has dropped over the years (ICRAF, 1997). There have been efforts to revise fertilizer programs for various cropping systems, so that farmers can enjoy full benefits from gains made in genetic improvement of crops.

The element potassium (K) occurs in high concentrations in plant tissues and is only surpassed by nitrogen (N), in some crops (Tisdale and Nelson, 1975). In the plant, K is involved in osmoregulation, maintenance of electrochemical equilibrium, pH stabilization and activation of enzymatic reactions. In many crops, K nutrition is associated with important produce qualities like crude protein content in wheat, 1000-grain weight in wheat, maize and rice, starch content in cassava and sugar content in sugarcane, bananas and tomatoes (Peter, 1980).

Potassium deficiency has been identified as an emerging problem in intensively cropped soils of Kenya (Kanyanjua and Buresh, 1999). The emerging deficiency is attributed to over- exploitation of soils in the continuously cropped systems, and induced effects after prolonged use of sole N-P based fertilizers (Nandwa and Bekunda, 1998). There is, unfortunately, inadequate empirically obtained data to convince farmers, policy makers and other stakeholders of the need to change fertilizer programs of food crops from the hitherto nitrogen and phosphate (N-P) based, to programs incorporating potassium (N-P-K). Worse still, areas that are experiencing K deficiencies have neither been identified, nor the magnitude of economic losses in crop production. The working hypothesis is that such data if made available would show a need for applying K fertilizers in food crops for high and sustained yields.

Potassium deficiency may occur where losses through leaching, surface runoff, erosion and crop uptake surpass additions through rock weathering and inputs of organic and inorganic nature (Stoorvogel *et al.*, 1993, Smaling *et al.*, 1993, Loes and Ogaard, 2003). Continuous cropping and adoption of superior varieties has increased K uptake per unit of cropped land, while destruction of vegetation cover and poor land preparation methods have increased the rate of soil erosion and surface runoff (Kanyanjua and Buresh, 1999; Gachene, 1986). There is also little work done in Kenya to determine the contribution of weathering of soil parent materials to plant K.

Use of K fertilizers in Kenya has remained low, as a result of a belief, passed through generations, that soils in Kenya are well supplied with K and crops would not benefit from K fertilizer application (Kanyanjua and Buresh, 1999). Laboratory assessment of K fertilizer needs in Kenya has relied heavily on the Mehlich 1 method (Mehlich, 1953). This contrasts sharply with practice in other parts of the world, where neutral $NH_4OAc$ is used, and good correlations have been obtained between exchangeable K and crop response to fertilizers (Hinrich *et al.*, 1985, Haby *et al.*, 1990, Echert, 1994). Mehlich 1 method relies on K intensity measurements in soils, but does not show the soil potential to release non- exchangeable K (Cox *et al.*, 1999, Cox and Joern, 1997).

Soils in western Kenya occur in different soil associations, characterized by unique pedogenetic development processes. Soils close to the Great Rift Valley (GRV) are developed on recent volcanic outflows, and fertility status is dependent on the chemical composition of parent magmas (Nyamweru, 1980). Variation in relief due to volcanic activities results in equally varying climatic conditions, which affect the rate of rock weathering, soil erosion, surface runoff, and turnover of vegetation, all of which influence the K status in cropped soils (Shephered *et al.*, 2001, Loes and Ogaard, 2003). Soils further to the west of the GRV are developed on old basement rocks (Nyamweru, 1980), and are equally old. According to Sumner and Yamada (2002), many tropical soils, as those under current study fall in the Oxisol and Ultisol Orders, and are naturally acid, low in base status and contain toxic levels of $Al^{3+}$. The soils are often infertile and unproductive, unless a complete suite of nutrients and lime are applied (Sumner and Yamada, 2002).

Different types of rocks of extrusive and intrusive origin underlay the major soils in western Kenya (Nyamweru, 1980, Corbett *et al.,* 1999). The rocks differ in structural and textural properties, geochemical and mineralogical properties, and their age. Consequently, the rocks have weathered to different extents, and have therefore, released different amounts of $K^+$ and other cations to the soil (Harley and Gilkes, 2000). This study addressed the general hypothesis: that the amount of K and other cations, and type of cation - containing minerals in parent rocks, determine the amount of $K^+$, $Ca^{2+}$ and $Mg^{2+}$ in soils, while overall mineralogy of rocks determines the texture of soils, and ease with which $K^+$ is available to crops.

Potassium is the most abundant in the soil among the cations: Ca, Mg, Na and K, with total contents averaging 1.7 % (w/w) (Sparks, 1987). Contents in the earth's crust are higher at around 3.11 % (w/w), (Barber, 1995), where it is the seventh most common element (Csatho, 2002). In the soil phase, K is distributed among soluble, exchangeable, non-exchangeable and mineral forms, which are in a thermodynamic equilibrium, and which have different crop availability indices (Haby *et al.,* 1990). Crops absorb K from soil solution pool, as a function of solution concentration, mean root radius, and plant absorbing power (Mengel, 1985). During uptake, solution concentration declines and further uptake depends on replenishment through K diffusion from other pools (Greenwood and Karpinets, 1997). Diffusive flux is a function of the amount and type of clay, which in turn determines the buffer power of soils towards K (Mengel, 1985; Grimme, 1979).

The ultimate source of K in soils is from the weathering of parent rocks, rich in K-feldspars and micas (Haby *et al.*, 1990). According to Barber (1995), total (w/w) K content in minerals increases in the order: biotite and phlogopite (8.7%) < muscovite (9.8%) < K- feldspar (13.7%). Corresponding figures by Haby *et al.* (1990) were 7 %, 8 % and 11 – 15 %, respectively. Potential of K release depends on ease of weathering, governed by the mineral position on the Bowen's reaction series (Harley and Gilkes, 2000). Ease of weathering increases in the order: muscovite < K-feldspar < biotite and phlogopite.

One way to explain the emerging K deficiency is to envisage a "parent material- soil- plant K" continnum, that has failed to meet K needs of a continuously cropped system. This study proposed to map areas prone to K deficiency, and determine the relationship between geo-chemical and mineralogical properties of parent rocks and K status in soils developed from them. In addition, the relationship between amount of clay and rate of K uptake by maize determined. Field experiments in areas considered likely to have K deficiency were conducted to test the hypotheses laid down. The objectives and hypotheses are summarized below:

*Objectives*

*(i)* To establish whether areas in Kenya with an emerging K deficiency can be mapped from existing soil and climatic databases, and validate the map so-developed.

*(ii)* To determine the relationship between mineralogical and geo-chemical properties of parent rocks, and amount of clay, clay mineralogy, and potassium status of overlying soils.

*(iii)* To determine the relationship between amount of clay and clay mineralogy, and the distribution of soil K in various pools and K availability to maize plants.

*(iv)* To determine the agronomic and economic benefits of K fertilizer application in maize

optimally fertilized with N and P fertilizers in field soils with an emerging K deficiency.

*Hypotheses*

(i) Areas having potassium deficiency can be mapped from existing soil and climatic databases, as long as the data are geo-referenced.

(ii) Rocks composed of easily weatherable minerals break down into fine textured soils and clay mineralogy indicative of advanced weathering. Also, rocks rich in the bases, Ca, Mg and K would weather into soils equally rich in these bases.

(iii) The distribution of K in various soil pools, losses through leaching and K availability to crops is dependent on the amount of clay and clay mineralogy of soils.

(iv) Applying K fertilizers in soils with an emerging K deficiency would increase maize yields profitably and significantly.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Farming in the Kenya highlands- a historical perspective.

Many agricultural soils in the Kenyan highlands (> 1000 m.a.s.l) are located in humid and sub-humid agro-climatic zones, where annual average precipitation (r), is > 65 % of the annual average potential evaporation, (*Eo*), (Jaetzold and Schmidt, 1982). The favourable climatic conditions in the highlands support intensive cultivation of food and cash crops, and has attracted more people (Jama *et al.,* 1987), than arid and semi-arid areas, that cover about 83 % of the total land area in Kenya. At independence, about four decades ago, population density in the highlands was low and farmers practiced traditional cultivation methods, characterized by shifting cultivation and long fallow periods. In addition, agriculture was characterized by multiple cropping of low yielding, traditional cultivars, whose demand for nutrients was low.

Mulching was introduced alongside the cash crops in the earlier years of Kenyan agriculture, as a means of controlling weeds and conserving soil moisture, but mulching materials brought in nutrients to balance losses through crop harvest as well (Qureshi, 1979). The land currently under cultivation was cleared from grasslands, bushy grasslands, bushland and forests (Corbett *et al.,* 1999). Burning or leaving the cleared vegetative materials to rot resulted in surface soils that were high in nutrients. The high fertility status of such soils gave way to bounteous harvests, and yields were maintained for years without external inputs. The status quo was maintained for the greater part of the first two decades, since the 1960s.

As population pressure increased, continuous cultivation replaced nutrient- conserving, traditional systems (Jama *et al.,* 2000). Advancement in agriculture resulted in breeding of high yielding varieties grown in monocropped systems, whose demand for nutrients is much higher. The high demand for nutrients was primarily met from application of farmyard manure, which was easily available from large herds of livestock, while those with some cash to spare bought N and P fertilizers. This set -up supported high yields for improved varieties, to the satisfaction of breeders and farmers.

Population pressure resulted in further sub-division of land, reduction of the number of livestock and scarcity of farmyard manure (Recke *et al.,* 1997). Despite the high investment in genetic improvement of major food crops, yields were declinining with time (Ayaga *et al.,* 2004), while application of N and P fertilizers was found to have less impact than earlier witnessed (ICRAF, 1997). Inhabitants of the then regarded "high potential areas", could no longer claim to produce enough food to feed themselves (Sanchez *et al*., 1997).

## 2.2 Options for fertility improvement in intensively cropped soils of Kenya

To stop further decline in crop yields, and increase the productivity of available land, the Government and other bodies in Kenya have been testing various options that are considered affordable and sustainable. Research in mineral fertilizers has been going on since pre-independence days (Wapakala, 1973), and a big effort was put through the Fertilizer Use Recommendation Project (FURP), which conducted N x P response trials in farmers' fields, during the period 1987 – 1991. After the project, site and crop specific fertilizer recommendations were published in 24 district-based volumes and circulated widely in Kenya (KARI, 1995). The adoption of these recommendations, however, has been low, and only restricted to a few farmers endowed with resources, such as land and cattle, and with high off-farm income (Jama *et al.,* 2000).

The majority of farmers are resource poor, and have resorted to low cost, farm- based options of maintaining soil fertility. The most popular alternatives to mineral fertilizers include use of composts, manures and biomass transfer (Jama *et al.,* 1997). These options can however not reverse soil fertility decline because the materials used are not available in sufficient quantities on most farms, are low in nutrients and their processing and application are labor demanding (Palm *et al.,* 1997). There is need to intensify research on inorganic fertilizers, focussing mainly on increased use efficiency, as other arms of Government look for means by which farmers can access inputs through credit offered by micro-financing institutions.

## 2.3 Mineral fertilizer research in Kenya and findings related to potassium

### *2.3.1 Poor response to potassium fertilizer*

In Kenya, the Scientific Research Division, under the Ministry of Agriculture (MOA), has detailed information dating back to the 1950s on fertilizer response results for various crops. Muchena (1975), gave special attention to K. According to MOA (1964), "all minus one" trials involving the six macro- nutrients (N, P, K, Ca, Mg and S), were first conducted in preliminary, exploratory stages, to determine the limiting nutrient(s). Once identified, the limiting nutrient(s) were then subjected to a series of "fertiliser rates" experiments where increasing rates of the nutrient(s) were applied to determine the fertiliser responses and recommendations. The recommendations were then passed on to the farmers through an elaborate extension program.

In most of the trials conducted in Kenya since independence (1963), many workers did not obtain good responses in crop yields after applying K fertilisers. Potassium application either had no effect or depressed yields of food crops. Wapakala *et al.* (1969) reported that K fertilizer had no effect on finger millet and fiber crops in Kenya. In Kakamega, NPK fertilizers did not have significant effects on yields of groundnuts (MOA, 1964), beans (MOA, 1975) and finger millet (Rutto *et al.,* 1982). Ouma and Wapakala (1986) reported depressed sugarcane yields with K application in the Nyanza sugar belt. Olang (1980) reported no response to K on maize in Kitale while Hinga *et al.* (1972) reported no response to K on tomatoes when working in a greenhouse. During the period 1976 -77, the Grain Legume Project (GLP) conducted NPK fertilizer trials on beans in western Kenya and reported depressed yields with K fertilization.

In a limiting nutrient trial, conducted on maize for three years in Kakamega and Busia districts in western Kenya (MOA, 1964), K came third after P and N as the most limiting nutrient. Application rates of 40, 100 and 40 kg of N, $P_2O_5$ and $K_2O$ $ha^{-1}$ respectively were recommended after the trials and economic returns were profitable. Potassium fertilizer was recommended, despite lack of significant difference between plots with and those without K, in the first two years. Hinga and Kuria (1976) recommended K in soils with low mineral reserves but which may not respond to K fertilization in the beginning.

Crops might not show significant response to K fertilizer when tested for only a few seasons. Hinga and Kuria (1976) reported insignificant response to K fertilizers in the beginning, but responses appeared later when, according to them, the easily accessible K was depleted from the soil. Kemmler and Malicornet (1976) found that response of crops to K fertiliser occurs in second, third or fourth year of cropping, when readily available K is exhausted. Hinga and Foum (1972), and Kemmler and Hobt (1986) agreed that initially the crops may not respond to K fertilizer but yields drop after some years of cropping due to K deficiency, in fields with optimal N and P applications. Drop in yields depends on how well the soil is buffered with regard to K.

Results from such old fertilizer trials were used to coin and perpetuate the belief that soils in Kenya have adequate K content and crops would not benefit from application of K fertilizers. None of these workers proved beyond doubt that lack of response was due to high K content in soils. No correlation studies were done to show the relationship between K uptake by crops, crop yields and soil K variation over cropping years. It was also necessary to identify the source of K in soils, and sustainability of the readily available K utilized by crops, if indeed the soils had adequate K.

### *2.3.2 Good response to potassium fertilizers*

Several workers have reported increased yields or crop quality when K was combined with other nutrients in trials. Poultney (1957) while working in Kitale found increased Lucerne yields with K application. Nandwa (1988) and Mochoge (1991) reported strong response to K in major food crops in central Kenya. ICRAF (1997) obtained improved maize yields with K application and associated the positive effect of applying *Tithonia diversifolia*, a locally available green manure, on maize yields, with high K content in tithonia biomass and subsequent K release to soils. Iqbal *et al.* (1995), when working on a K deficient soil in a glasshouse, in Pakistan, reported increased maize yields, when K fertilizer levels were increased from 0 to an equivalent of 80 kg K ha$^{-1}$.

In an FAO fertilizer program in Kenya (1968 – 74), Zschernitz *et al.* (1974), found positive K effects on beans, potatoes and groundnuts in western Kenya. Qureshi (1989) reported increased potato yields after applying K in the form of KCl. In Kitale, application of both N and K fertilizers improved grass yields by 33.7 % while N alone increased yields by 23.7 % (relative yields = 0.70). Likimani (1973) observed increased total solids and ascorbic acid in potatoes when K and P fertilisers were applied. Singh and Singh (1995) recorded increased potato tuber yields and number of large and medium sized tubers with increasing rates of K fertilizer. They also observed a decline in the number of small tubers (Ø < 3.75 cm) as K rates increased. Singh *et al.* (1996) reported a decrease in total soluble solids and an increase in starch content, crude protein and K content in potato tuber and haulm after applying K fertilizer. Malakouti and Hosseinpour (1996) found increased potato yields as K was progressively increased from 0 – 200 kg K $ha^{-1}$. In cereals, K was particularly found important in improving the number of grains per ear and weight of grains (Kemmler and Hobt, 1986).

Some workers have reported increased resistance to disease and reduced deterioration in storage with K fertilizer application in crops. Cepeda *et al.* (1996) when working in Mexico on maize observed enhanced resistance to *Fusarium moniliforme* after applying KCl. Ivezic *et al.* (1996) noted a reduction in parasitic nematodes in maize after K application. Singh *et al.* (1996) applied K at increasing rates of between 0 and 150 kg K $ha^{-1}$ in potatoes, and reported reduced storage losses and sprouting percentages in tubers at higher application rates.

Results for good responses contrast sharply with those of poor or non-response, sometimes from the same areas and same crop types. There is inadequate information accompanying the results, which can be used to separate well responding and non- responding circumstances for proper planning. Those who got good responses in Kenya did not compare their results with those showing non-response as a way of challenging the belief that Kenyan soils are adequately supplied with K. Many crops were not included in the trials, while experiments were conducted for different durations of time, thus giving biased results (Loganathan *et al.,* 1995).

### *2.3.3 Factors that influence the response of crops to K fertilizers*

#### *2.3.3.1 Crop characteristics*

According to Anderson (1973), crops that show good response to K fertilizer include tea, tobacco, bananas, Irish potatoes, sweet potatoes, coconuts, and pastures; that are cut for hay or silage. Other crops that would respond if grown continuously without farmyard manure or mulch include coffee, sugarcane, sisal, cotton, maize, beans and wheat. This list of crops suggests that crops with all or part of the foliage harvested (e.g. tea, pastures and tobacco), or produce a lot of foliage when fully grown, and which may never be recycled back to the same farm (e.g. bananas, coconuts and potatoes), respond to K fertilizers better. The list also conforms to arguments for greater possibilities of K mining from soils, where crops grown have high K uptake during growth (Haby *et al.,* 1990; Okalebo, 1979; Hafner *et al.,* 1993).

Mehlich *et al.* (1964) singled out differences in ability of plants to mobilize plant nutrients from the soil to the plant roots as a factor that determines the yield response to fertilizer application. Grimme (1979) associated efficiency of nutrient uptake with root surface area. Most grasses with a fibrous root system have high surface areas when compared with crops with a tap root system. Sangakkara *et al.* (1996), associated improved bean performance after K fertilizer application with development of a more extensive; root branching pattern, by inducing a greater number of second and third order roots.

#### *2.3.3.2 Soil characteristics*

Anderson (1973) predicted higher responses of crops to K on very sandy soils, moderate to strongly acid soils, and calcareous soils. The prediction does not make our attempt to identify the soils that may respond to K fertilizers any easier. Prediction of higher response to K fertilizers in sandy and acid soils implies stronger response where leaching of exchangeable bases is greater, but does not recognize the role that other input pathways; e.g. weathering of parent materials, deposition from adjacent fields, or mineralization of organic matter, may play in balancing the losses through leaching. There are more factors than just the soil type, which determine crop response to K fertilizers. Soil maps may not solely show what areas are prone to K deficiency unless other factors are considered as argued in the aforegoing discussion.

According to Heckman and Kamprath (1995), K fertilization should be related to the capacity of the soil to supply K with sufficient rapidity to match the maximum rate of K accumulation by a crop, and supply sufficient amount of K, to meet the total K requirement of the mature crop. These workers defined the K accumulation rate requirement as that level of accumulation per unit of time that is required to achieve a certain yield goal, and a total K crop requirement as equivalent to the level of K accumulation that benefits yield or crop quality. Potassium supplying power of soils must satisfy both the total K requirement and the K – accumulation-rate requirements for high yields. Intensively cropped soils of Kenya have not been characterized with regard to these two important attributes of K availability in soils.

Panique *et al.* (1997) associated low response of tomatoes to K fertilizers with a high soil test K value. In newly opened volcanic soils at the foot slopes of Mt Kenya, Zschernitz *et al.* (1974) did not get K response in potatoes because of high K reserves in the soil. According to Heckman and Kamprath (1995), this observation remains true for short season crops, where the most important determinant of K uptake is the K accumulation rate, a factor dependent on the labile pools of K. For long-season crops, part of the total K requirements is met from non-labile pools, which are related to the buffer power of soils towards K.

Though most of the plant available K is held in the soluble and exchangeable pools, ease of release of exchangeable K depends on the strength of adsorption (bonding energy), on negatively charged sites. According to Barber (1995), bonding energy is greatest in 2:1 clays with isomorphous substitution in the tetrahedral, than in clays where substitution occurs in octahedral positions, because the octahedral position is further from the saturating cation than the tetrahedral position. The relationship between force of attraction between two particles and the distance between them is expressed as Coulomb's law, thus:

$$F_a = q1q2/d^2D$$

Where $F_a$ is the force of attraction, $q1$ and $q2$ are the electrical charges, $d$ is the distance separating the charges, and $D$ is the dielectric constant (78 for water at 25 ° C).

The most loosely bound K occurs in exchange sites on broken crystal edges (e.g. kaolinite), and other pH- dependent charges (organic matter and amorphous soil constituents). In general, K is held with decreasing bond energy in the order: 2:1 clays > kaolinite > organic matter and amorphous constituents (Barber, 1995). Most soils in the Kenyan highlands are rich in organic matter, and often test high in exchangeable K. Mature soils from warm and humid environments are dominated by kaolinite and sesquioxides (Harley and Gilkes, 2000; De'Conninck, 1987).

Uribe and Cox (1988), and Haby *et al.* (1990), reported that due to the weak bond between $K^+$ ions and organic matter, such soils have a higher K concentration in the equilibrium solution than soils of equivalent exchangeable K but low in organic matter. Soils in Kenya may show high K content due to the comparatively large labile fraction, which has little to do with the long-term K supply. There is need to relate exchangeable K contents in soils to differences in organic matter content, and amounts and types of clay minerals, before a judgment is made on the K supply potential of soils.

### *2.3.3.3 Interaction with other exchangeable cations*

When an ion, like $K^+$ is adsorbed on clay, exchangeability with a second ion (e.g. $NH_4^+$); depends on exchangeability and degree of saturation of complementary ions associated with it on exchange sites (Barber, 1995). According to Mehlich *et al.* (1964), and Barber (1995), the ease of release of cations from exchange complex decreases with increase in bonding energy of cations under consideration. Strength of bonding of cations by negative charge depends on the nature of source of negative charge, among the permanent and pH-dependent (Barber, 1995).

When cation valency is the same, permanent charge has a preferance for cations of small hydrated radius ($K^+ > Na^+$, $Ca^{2+} > Mg^{2+}$). On the other hand, exchange sites on pH- dependent sites, e.g. organic matter have a preference for ions of smaller, non-hydrated ionic radius, i.e., $Na^+ > K^+$, $Mg^{2+} > Ca^{2+}$. In both permanent and pH-dependent sites, bonding energy increases with increase in valency of cation (Barber, 1995). Exchangeable cations are, therefore, displaced to soil solution, with decreasing ease in the order: Na > K > Mg > Ca. Ease with which cations can be leached or eroded from the soil may follow the same sequence, which conforms to the relative composition of exchangeable Ca, Mg, K and Na, in normal soils. Davis (1996) associated K response in maize grown on loamy sand with high K demand as a result of leaching losses on soils of a coarse texture.

Work by Barber (1995), suggests that in soils with greater part of the exchange sites saturated with divalent cations e.g. $Ca^{2+}$ and $Mg^{2+}$ (alkaline soils), $K^+$ ions would be displaced more to equilibrium solution and weaker exchange positions, and such soils may test high in exchangeable K. Exchangeable bases have a preference for permanent charge in 2: 1 clays, while $H^+$ and Al species have a preference for pH-dependent charges (Barber, 1995). Potassium ions once displaced by $Ca^{2+}$ and $Mg^{2+}$ ions on the permanent charges move to weaker sites on kaolinite and organic matter, where they are loosely held and easily exchanged. Variation in pH influences the dissociation of proton- binding groups, such as carboxyl on organic matter and $OH^-$ groups on surface of oxides and hydroxides (Parfitt *et al.,* 1999), and the CEC of soils. Hydrogen ions would not easily displace $K^+$ from exchange sites on 2: 1 clays. On the contrary, $K^+$ ions displace $H^+$ and Al ions from exchange sites on clay to weaker exchange positions, resulting in increased activity of $H^+$ ions and lower pH of the soil solution. Potassium fertilizers, therefore, may result in the lowering of soil pH.

Ion uptake increases with decrease in amount of interaction between the ion and negatively charged phospho- and sulfo- lipids, and proteins on root cell membranes (Marschner, 1995). Interractions with cations and anions increase in the order: uncharged molecules < monovalents < divalents < trivalents; and uptake in the reverse order. For ions of same valency, the less hydrated (usually bigger non-hydrated radii), interact less with root membranes and are preferred in uptake process.

Root membranes, therefore, have a behavior closer to the pH-dependent exchange sites than the permanent charges, with high bonding energy working against uptake. Potassium out-competes $Ca^{2+}$ and $Mg^{2+}$, while both $Ca^{2+}$ and $K^+$ out- compete $Mg^{2+}$, on both the cell wall and plasma membranes. Application of K and Ca fertilizers, and high content of $Mn^{2+}$ in soils depresses $Mg^{2+}$

uptake, leading to deficiencies (Marschner, 1995). Barber (1995), reported 17 and 25 % decrease in $Ca^{2+}$ and $Mg^{2+}$ content in corn plants, respectively, when K levels were increased from 0 to 100 mg $kg^{-1}$ in the nutrient solution.

The relationships between $NH_4^+$, $H^+$ and $K^+$ ions in soils is of special importance. Ammonium ion ($NH_4^+$), which may accumulate in poorly aerated, acid soils (Springob, 1999), is a product of organic matter decomposition, and is often applied through mineral fertilizers. Hydrogen ($H^+$) ions are dominant in acid soils, and often exuded from root surfaces as a means of maintaining electroneutrality (Marschner, 1995). Being positively charged monovalent cations, it is expected that $K^+$ activity in soils would be influenced by $NH_4^+$ and $H^+$ ions. According to Rao *et al.* (1997), both $NH_4^+$ and $H_3O^+$ ions have a similar geometry to that of $K^+$, and can easily fit in the wedge zones of clay lattice, thus releasing the $K^+$ ions from clay structure. Organic matter decomposition may, therefore, lead to increased $NH_4^+$ activity, which expels $K^+$ from interlayers to weakly adsorbing sites, where it is exchanged more easily, as well as compete with $K^+$ ions during uptake.

According to Tang *et al.* (1996), $NH_4^+$ was preferentially fixed to $K^+$, when $K^+$ was added with or prior to $NH_4^+$ to a fixing soil. This is because the non-hydrated $NH_4^+$ ion is bigger and has less hydration energy than the $K^+$ ion and is, therefore, preferentially admitted into the interlayers. When $NH_4^+$ ion is applied in the soil, it enters the interlayer space without the water sheath and forces the interlayer to close, stopping any further release of fixed K to the soil solution. Potassium release from soils rich in micaceous minerals (illites, vermiculites, smectites), and K uptake by crops, may be greatly reduced, after applying $NH_4^+$ fertilizers or urea. The converse (inhibition of $NH_4^+$ uptake by $K^+$); has not been observed. High $K^+$ concentration in soil solution would equally suppress the release of $K^+$ from interlayers due to the reduced diffusion gradient.

Both $NH_4^+$ and $K^+$ ions in the closed- in interlayer position are fixed and not readily exchanged with other cations.

Cation adsorption by soil organic matter occurs in either readily exchangeable form, or as coordination complexes for multivalent cations (Barber, 1995), while monovalent $K^+$ can only exist in exchangeable form. Coordination complexes do not readily exchange with monovalent cations and do not dissociate readily in soil solution. Some coordination complexes exist as soluble organic compounds; which increases the respective cation concentration in solution. Most of the trace element cations, $Cu^{2+}$ and $Zn^{2+}$, exist in soil solution as complexed soluble organic compounds. Organic adsorption sites are primarily pH dependent, and cations are preferentially adsorbed with decreasing relative dehydrated size (Barber, 1995). For that reason, relative preference may increase in the order: $NH_4^+ < K^+ < Ca^{2+} < Na^+ < Mg^{2+} < Al^{3+}$. The sequence may change slightly because divalent cations are attracted more tightly than monovalent cations.

Potassium in soils rich in $Ca^{2+}$ and $Mg^{2+}$, and high in organic matter (pH- dependent charges), would occur with greater part, either desorbed (solution K), or weakly bound by organic matter (readily available K). Potassium in soils deficient in $Ca^{2+}$ and $Mg^{2}$ (acid soils) would be tightly bound by permanent charge in clays, with limited availability to crops. For the same reason, liming of acid soils would have the effect of improved $K^+$ availability. In acid soils rich in $K^+$ (e.g. soils with high decomposing organic residues), the counter ions would be $H^+$ and Al species, the latter having preference for kaolinite and organic matter, and K in permanent CEC, where it is less readily desorbed and leaching is unlikely. Stucki and Huo (1997), found that in general, clay surfaces exhibit overwhelming preference for divalent over monovalent cations, due to higher charge density (i.e. charge – to- radius ratio), exhibited by multivalent cations. The trend is reversed by reduction of Fe in illites, because reduced soils have greater selectivity for $K^+$ to $Ca^{2+}$.

### *2.3.3.4 Nutrient balancing*

Anderson (1973) stressed the need for adequate supply of other macro- nutrients (N, P, Ca, Mg and S) in soils, for optimum K response. One great limitation in the results from old fertilizer experiments in Kenya is lack of data on the chemical properties of soils. While there are indications that N and P fertilizers were uniformly applied in trials as rates of K fertilizer were increased, the same cannot be said of the status of other macro- nutrients, Ca, Mg and S. To date, very little has been done on the interaction between lime, magnesium, sulfur and K in Kenyan soils, and how the interractions may affect crop yields.

Anderson (1973) and Barber (1995), recommended application of calcitic lime where Ca is deficient and dolomitic lime where both Ca and Mg are deficient to prevent induced Ca and Mg deficiency, due to impeded uptake by crops after applying K fertilizers. Qureshi (1979) reported Mg deficiency in coffee after application of K-rich grass mulches. Messing (1974) reported reduced response to K fertilizer in bananas when $Ca^{2+}$ and $Mg^{2+}$ levels decreased in cropped soils of West Indies. Liming of soils, however, requires prudent management. Dixit and Sharma (1993), applied lime by broadcasting, followed by irrigation, four weeks before planting wheat in the acid Alfisols of India. According to Sumner and Yamada (2002), there is no merit in liming soils beyond pH- water, 5.5, unless the intention is to correct deficiency for Ca, Mg, N, S, P and Mo; the nutrients inherently deficient in acid soils.

The main aim of liming is to neutralize the toxicity emanating from high Al and Mn, in pH values $< 5.5$. Beyond this pH, liming can only be beneficial in augmenting nutrient availability and supply, and improved Biological Nitrogen Fixation (BNF). If not well managed, liming may result in poor availability of trace element metal cations like Fe, Zn, and Mn.

### *2.3.3.5 Potassium fixation*

Qureshi (1979) attributed low crop response to K fertilizers to K fixation. He observed up to 50 % fixation of applied K fertilizer in Kisii soils, as a function of textural and mineralogical composition of the soil. He, however, did not identify the clay minerals, or undertake any correlations between types of clay in soils and K fixation. Crop response to K can only occur after the K-fixing sites are saturated. Before saturation, moderate K fertilizer application does not result in significant increase in soil solution K, and no K response would be observed (Grimme, 1979).

Rao and Subramanian (1995) and Yakimenko (1995) reported increased K fixing capacity in soils where crop K is obtained from non-exchangeable pool. This is because future application of K replenishes the non-exchangeable forms, in order to keep the normal distribution of K among various pools, found in clay and humus components. Release of non-exchangeable K is triggered by depletion of the readily available (soluble, exchangeable) forms of K, during crop uptake. There is no evidence to rule out the possibilities of K fixation in Kenyan soils. Stucki and Huo (1997), observed an increase of fixed K from about 2.5 to about 35- cmol ($p^+$) $kg^{-1}$ in smectite, due to Fe reduction. Soils that experience cyclic redox events have been seen to form illite from smectite and vermiculite, over time, with increased but irreversible K fixation.

Barber (1979) compared K fixation in 13 Kenyan soils equilibrated with K at rates of 0 – 1000 mg $kg^{-1}$. Fixation was directly related to rates of K application, but the ratio of fixed K to amount applied was negatively correlated to rates of application. Increased fixation with rates of K application obeyed the law of mass action, where increased K occupied more of the unsaturated sites and displaced other cations. Reduced proportion in amount of K fixed, at high rates of application, is explained in terms of diminished access to the fixing surface. Barber (1979) and Tiwari *et al.* (1995) reported that K fixation is directly proportional to clay content but depends on the mineralogical composition of the clay fraction.

Barber (1979) reported that amongst the clays, fixation decreased in the order: montmorillonites > amorphous clays > kaolinites. Tiwari *et al.* (1995) reported higher fixation in illitic and sodic soils when compared with smectitic and kaolinitic soils. In soils that are rich in 2:1 clays, and particularly illite, K like $NH_4^+$, is fixed by being entrapped in the inter- layers and is not readily available for crop uptake.

Fixation of $K^+$ is a very important process as it holds the $K^+$ against leaching after fertilization, particularly in high rainfall areas. There is a positive correlation between $K^+$ fixation and amount of clay and silt but a negative correlation with sand content (Sparks, 1980). Significant amount of applied $K^+$ is fixed and unavailable for immediate use by plants. It is however gradually released to growing plants. Sparks (1980) reported a decline in K leaching with increase in organic matter and clay content in sandy coastal soils of the Atlantic. High organic matter may increase K retention against leaching (Kemmler and Hobt, 1986; Hinga and Foum, 1972).

### 2.3.3.6 *Cropping and fertilizer history*

Crop response to K fertilizer depends on the cropping and fertilizer history of an area. Since K fertilizers are rarely applied in food crops in Kenya, crop K is always and continuously drawn from stocks originally in the soil. Anderson (1973) emphasized the importance of time since opening of new land previously under fallow or pasture. Long- term cropping with little application of external inputs is felt to be responsible for the net annual depletion of N, P and K nutrients in the densely populated highlands of east and central Africa (Stoorvogel *et al.,* 1993).

In the long- term trial at NARL (1976 – 2006), where some plots have been cropped continuously with optimal application of N and P fertilizers but no K fertilizer, soil chemical data show continuously declining exchangeable K values with time. In the same experiment, the importance of recycling straw as opposed to total removal is indicated by improved K buffering power of the soil during the trial period (Kanyanjua and Buresh, 1999). Stoorvogel and Smaling (1990) reported that East Africa is the area with highest annual nutrient depletion rates in Africa of more than 40 kg N, 6.6 kg P and 33.2 kg K $ha^{-1}$. Follow-up work in the Kisii highlands by Smaling *et al.* (1997) showed annual depletion rates in Kisii district of 112 kg N, 2.5 kg P and 70 kg K $ha^{-1}$; with crop removal as the main depletion pathway followed by runoff and leaching (for N). Pyrethrum (*Chrysenthemum cinerariaefolium*) was singled out as the main nutrient miner in Kisii.

### *2.3.4 Evidence of K deficiency in Kenyan soils and caution on management practices*

After analyzing soil and agronomic data from the Fertilizer Use Recommendation Project (FURP), (1986 – 1991), there were clear indications that some intensively cropped areas of Kenya were showing K deficiency, and indeed, various crops responded significantly to K fertilizer application (Nandwa, 1988; Mochoge, 1991). Other reports of K deficiency were made after the soil fertility work in western Kenya, jointly conducted by KARI, ICRAF, KEFRI, TSBF and other research organizations. According to ICRAF (1997), a number of soil samples analyzed showed K deficiency; to which poor maize yield response to N and P fertilizers was attributed. Maize yields increased significantly after application of K fertilizers (ICRAF, 1997).

Potassium deficiency in western Kenya can partly be attributed to intensive cropping and non-application of K fertilizers. In the Kisii highlands for example, relay cropping is common and fields are never without a crop. In such a system, nutrients like K that are taken up by crops in large quantities which are never returned through fertilizers are removed from the soil at high rates, resulting in negative balances (Stoorvogel *et al.*, 1993; Smaling *et al.*, 1993).

In West Indies, Messing (1974) linked the sugar industry to depletion of soil fertility, particularly P and K by exclusively using N fertilizer due to high economic returns to N. It was very difficult to correct the deficiencies after the change of crop from sugarcane to bananas. Though soils can derive K from rock weathering and decomposition of organic matter, poor husbandry practices, like uphill ploughing, result in substantial losses of K from the soil through leaching, surface runoff, soil erosion, and crop uptake. Gachene (1986) recorded 1.05 to 2.23 times as much K in eroded soil material compared to un-eroded material.

To improve potassium fertilizer use efficiency; time, rates and mode of K fertilizer application remain important management decisions. Grewal and Sud (1995) applied both N and K fertilizers as top-dress, at the time of earthing up of potatoes. Singh and Singh (1995, 1996) when working on potatoes obtained significantly higher potato yields when they applied the recommended 140 kg K ha$^{-1}$ in two equal splits (basal and 30 days after sowing) than when they applied all at once at the beginning of the season. High doses of K result in luxury consumption, as was reported by Karachi (1984) in sweet potatoes.

Mullins and Burmester (1997) found no significant difference in seed cotton yields when K fertilizer was broadcast, banded on the surface or banded at a depth of 30 cm. Roberts *et al.*

(1997), when working on high yielding cotton, found that foliar application of K was profitable. Chang and Oosterhuis (1995) tested $KNO_3$, KCl, $K_2SO_4$, $K_2S_2O_3$, $K_2C0_3$ and KOH as foliar sprays and found that although cotton yields increased in all cases, salts differed in their phyto-toxicity. Davis (1996) reported improved cotton yields when a soluble K source, e.g. KCl, was mixed with a slow release fertilizer at planting on sandy soils. Sandy soils have a low CEC and are subject to leaching losses. Once the areas that are likely to have K deficiency are identified, and if experiments show a need to apply K fertilizer in food crops, then, fertilizer programs of major crops will change to include K fertilizer. Potassium fertilizer will be applied either as a basal application or a side-dress.

## 2.4 Potassium fertilizer use in Kenyan agriculture and alternative K sources

When soil sources of K are insufficient to meet crop demand, K can be added through organic or inorganic fertilizers. The most widely used sources of K worldwide are inorganic fertilisers (IFA, 1992). Two straight fertiliser grades available in the local market are KCl (0-0-60), and $K_2SO_4$ (0-0-50). Singh *et al.* (1996) compared the effects of KCl and $K_2SO_4$ on potatoes and found that tuber yields, storage and processing qualities were similar whether K was sourced from KCl or $K_2SO_4$.

Panique *et al.* (1997) did not find significant differences in potato tuber yields whether fertilized with KCl or $K_2SO_4$ at similar K rates. These findings suggest that if indeed K fertilizers will be recommended, the right K- containing fertilizer will be chosen on the basis of market price, availability and convenience during application. In saline soils and for $Cl^-$ sensitive crops, however, $K_2SO_4$ is the preferred choice because KCl has a high salt index. Farmers are used to the routine of basal and top-dressing for P and N fertilizers, respectively, and efforts will be made to avoid excessive digression from such practices.

In Kenya, insignificant quantities of K fertilizers have been used in food crops since independence. Data from the Ministry of Agriculture (MOA), for the period 1989/90 – 1996/97 show that the proportion of K has remained steady at 7 % of the 100,000 Mg of NPK nutrients imported annually. The little imported K is used mostly in cash crops like coffee and tea (Kanyanjua and Buresh, 1999). From a survey conducted by Mwaura and Woomer (1999) involving 139 stockists located at 74 market centres in six provinces of Kenya, only 4 % had stocked straight or compound fertilizers containing K, mainly KCl.

According to Jama *et al.* (1997), there has been little use of industrial fertilisers in many regions of tropical Africa for years and farmers have relied on farmyard manure, crop residues, composts, green manures, agroforestry systems and biomass transfer, to meet nutrient requirements for various crops. Use of fertilizers is usually low and mineralization of soil organic N is the principle source of plant-available N in smallholder subsistence agriculture in the tropics (Shepherd *et al.*, 2001). At the moment, farmyard manure is used by over 95 % of all smallholder farmers in the Kenyan highlands (Karanja *et al.*, 1997). Lekasi *et al.* (1998) found variable K content in manure samples collected from Kiambu and Murang'a districts of central Kenya. Published data by Kanyanjua *et al.* (2000) show variable K content in manure, depending on source animal. Application of manure increases the K saturation in soils but has also been known to disrupt the Mg: K and Ca: K ratios causing deficiencies of Ca and Mg in crops (Wapakala, 1976).

Agarwal *et al.* (1993) observed increased CEC and exchangeable K in soils after a long-term application of farmyard manure. According to Qureshi (1979) mulching with napier- grass, in coffee increased exchangeable K levels in the topsoil, leaf K and the size of coffee beans. Coale *et al.* (1993) reported that of the total accumulated K in sugarcane, 64 % was removed from the field in millable sugarcane. Okalebo (1979) found that 84.3 % of the total K taken up by maize remains in the stover. Hafner *et al.* (1993) observed increased K concentrations in tissues and K uptake in pearl millet (*Pennisetum glaucum L.*) after recycling the straw. Where straw was used, K concentration in tissues and total uptake was higher by 51% and 64 %, respectively, than when NPK fertilizers were used. Thus, application of manure and recycling of crop residues can raise and sustain K levels in intensively cropped soils. Indeed, data from the long- term trial at NARL has demonstrated the importance of recycling straw as opposed to total removal, through improved buffer of soils towards K (Kanyanjua and Buresh, 1999).

Biomass transfer can be used to correct K deficiency in depleted soils. Potassium content in above ground parts of most plants is much higher than that of Ca or Mg. The amount of K that can be made available to crops is in the range of 40 – 50 kg K ha$^{-1}$ from forage, grain, oil, fruit and vegetable crops, 500 kg K ha$^{-1}$ from alfalfa, napier grass and pineapple, and > 1400 kg K ha$^{-1}$ from banana plants (Haby *et al.,* 1990). Kaboneka and Sobbe (1995), studied the nutritional value of soybean and corn residues and found Ca, Mg and K contents of 15.3, 2.65 and 17.4 g kg$^{-1}$ DM in soybean and 3.7, 1.75 and 15.45 g kg$^{-1}$ DM in corn residues. Calcium levels were significantly higher in soybean than in corn. There is therefore a big potential in biomass transfer, and recycling of crop residues to correct nutrient imbalances. *Tithonia diversifolia*, a common hedge plant, is rich in K and has been successifully used to increase crop yields in poor soils of western Kenya (ICRAF, 1997).

Natural fallows have been used to overcome soil fertility depletion for a long time in tropical Africa

(Nandwa and Bekunda, 1998), while a lot of efforts have been put on improved fallows in recent times (ICRAF, 1995). A number of agroforestry based trees; among them *Sesbania sesban*, *Calliandra calothyrsus* and *Leucaena leucocephala* have been used in Kenyan agroforestry systems for a long time, and have proved useful in increasing crop yields (ICRAF, 1995). A lot of studies have been conducted on the potential of such systems in boosting N availability for crop production, but little has been done on their K benefits in Kenya.

## 2.5 Potassium in the soil-plant system

### *2.5.1 Physiological role of K in the plant*

Unlike such nutrients as C, H, O, N, P, S and micro- nutrients, K does not form part of the organic compounds in plant and animal tissues. Potassium moves easily from one part of the plant to another, within individual cells, within tissues and in long distance transport through xylem and phloem vessels (Marschner, 1995). In cells and tissues, K is essential for osmoregulation, maintenance of electrochemical equilibrium (ion homeostasis), pH stabilization and activation of enzymatic reactions.

Variation of K concentration in cell vacuoles controls the turgor pressure in cells (Marschner, 1995). In drought conditions, K concentrates in roots, thereby increasing the osmotic gradient to promote uptake of water, and moves out of guard cells to close the stomata and reduce transpiration. Anuradha and Sarma (1995), when working on soybeans, reported significant yield increase under moisture stress conditions from plants fertilized with K when compared to plants without K. Barber (1971) reported comparatively high response to K fertilizer in soybean in seasons with less rain after planting than in wetter seasons.

Humid and sub-humid areas of Kenya are characterized by high mean annual rainfall figures, which can be poorly distributed during the growing months. Potassium fertilizers would, therefore, support continuity in growth during the dry months. In some plants (e.g. sunflower), leaf blades re-orient toward light sources to increase light interception or away to avoid damage by excess light. These movements of leaves are brought about by reversible changes in turgor pressure through movement of K into and out of specialized tissues.

High concentration of K in the cytoplasm is essential to neutralize the negative charge from soluble organic and inorganic anions and insoluble macromolecular anions (Marschner, 1995). By neutralizing the negative charge, K maintains electro-chemical balance in plant tissues. Potassium stabilizes the cell pH at between 7 and 8, which is most ideal for enzymatic activity. Potassium activates not less than 60 different enzymes involved in metabolic activities in the plant, e.g. photosynthesis and protein synthesis. Amount of K in the cells determines how many of the enzymes in a cell can be activated and the speed of reactions.

Kemmler and Hobt (1986) found high ATP concentrations in chloroplasts of leaves with high K, than in leaves with less K content in various crops during photosynthesis. High energy ATP is the first product of photosynthesis, and K is known to maintain an electrical charge balance at the site of ATP production. When plants are K deficient, the rate of photosynthesis and the rate of ATP production are reduced, and all of the processes dependent on ATP are slowed down. Potassium is essential for nutrient and water uptake, and the translocation of assimilates (e.g. soluble sugars), to the grains, fruits and tubers; a prerequisite for sustained assimilation of $CO_2$ during photosynthesis. Speedy removal of assimilates is largely associated with a good filling of cobs and heavier grains in maize. Translocation is energy demanding and slows down when ATP is limited in plants.

Potassium hastens the rate of N uptake from the soil and conversion of amino acids to proteins (Kemmler and Hobt, 1986). Potassium works as a nitrogen pump by neutralizing the negative charge in $NO_3^-$ during uptake in xylem vessels and pumping it into the leaves. It then flows through the phloem by inverse flux combined with organic acids to collect more $NO_3^-$. Cooke and Gething (1978) reported positive NxK interactions in various crops that resulted in both a saving on N requirement to achieve a certain yield and high absolute yields. Koch and Mengel (1974) reported accumulation of low molecular weight intermediate products of protein synthesis like amino acids and amides, in K deficient plants as opposed to proteins in high K plants. Potassium may be responsible for the activation of nitrate reductase, the enzyme that catalysis the formation of proteins from nitrates. Potassium enhances nitrogen fixation in leguminous crops by promoting the development of bigger nodules (Kemmler and Hobt, 1986).

One consequence of K deficiency in plants is a drop in quality of crop produce. Peter (1980) reported a drop in % crude protein in wheat, 1000- grain weight in wheat, rice and maize and % grain filling in rice and maize. He also reported a significant drop in sugar content in sugarcane, bananas and tomatoes, as well as reduced starch content in cassava and reduced acidity in tomato, orange and pineapple, as a result of K deficiency.

### 2.5.2 *Occurrence of potassium in soils*

Of the major and secondary nutrient elements, K is the most abundant in the soil (Sparks,1980). Potassium has the largest non-hydrated size among the mineral cations, and lowest hydration energy (Sparks, 1980). The primary sources of soil K are the micas and potassium feldspars in parent rocks. These minerals are also found in intermediary weathering products and in soil particles of the various size ranges. An average igneous rock contains 2.6 % K by weight (Mohr *et* *al.* 1972) while the average soil contains 1.7 % K [43.6 cmol $(p^+)$ $kg^{-1}$] (Sparks, 1980). It is the 7th most abundant cation in the earth's crust after, Si > Al > Fe > Ca > Mg > Na > K (Csatho, 2002). Total contents however, though giving an indication of the potential reserves in soils, show little information on its availability to crops.

With regard to K availability for crop uptake, Tisdale and Nelson (1975) and Ahn (1970) grouped soil K in three pools that are in a dynamic equilibrium, i.e. unavailable K, slowly available K and readily available K. Unavailable K accounts for 90 - 98 % of the total K and the slowly available K for 1 - 10 % (Tisdale and Nelson, 1975). It has however been shown (Sparks, 1980, Cox *et al.*, 1999), that the unavailable and slowly available pools of soil K may under some circumstances also contribute to the total K uptake in crops.

Available K refers to the labile pools composed of solution and exchangeable fractions. Labile pool is depleted as the plants grow, and soil solution K has to be replenished from other pools, mainly through diffusion. Decline in concentration depends on soil buffering capacity towards K (Kemmler and Hobt, 1986). Buffer power of soils towards K is a function of soil texture and type of constituent clay minerals, and is closely linked to type of parent material.

Haby *et al.* (1990) described four fractions of soil K that exist in a dynamic equilibrium i.e. (i) structural K as found in crystalline structures of K- feldspars, micas and other K– bearing minerals (ii) fixed (non-exchangeable) K that is alternately released or fixed in interlayer spaces of illites and vermiculites, and (iii) exchangeable K on cation exchange sites of organic matter, sesquioxides and clay minerals and (iv) K in soil solution. Fractions (iii) and (iv) form < 1-4 % of the total K but are a measure of the plant available K referred to as exchangeable K. Sparks

(1980) found that exchangeable and water soluble forms, which were always $< 0.2$ cmol $(p^+)$ $kg^{-1}$, accounted for only 0.4 % of the total K in samples of 20 soils analyzed from New Jersey. According to Barber (1995), the bio- availability of soil K is determined by the ratio:

*Quantity of exchangeable K (Q)/ Intensity or concentration of K in solution (I)*

Concentration of $K^+$ in soil solution is an important factor that determines K uptake by crops. Haby *et al.* (1990), and Barber (1995), gave a range of 2 - 5 mg $L^{-1}$, as normal concentrations in soils of the humid regions, but values as high as 100 mg $L^{-1}$ were found in soils from arid zones (Barber, 1995). Sparks (1987) reported that only 2 % of the total K in soils is found in soil solution. According to Knudsen *et al.* (1982), exchangeable K refers to the amount extracted with neutral 1 N $NH_4OAc$ minus the water soluble K. In non-saline soils however, amount of water soluble K is so small that no appreciable error is made by including it in soil analysis.

Sparks (1980), singled out sand and silt fractions of the soil as home for reserve K that buffers up the K adsorbed in clays. Singh and Agrawal (1995) reported that in normal soils, available K showed significant positive correlations with organic matter and clay (soil colloids). Sandy and kaolinitic soils have poor K buffering capacity in contrast to soils containing 2: 1 minerals (vermiculite, illite or smectite). Hinga and Kuria (1976) reported that soils with a high capacity to supply K were rich not only in the exchangeable but other pools as well.

### 2.5.3 *Contribution of non-exchangeable (fixed) K to plant uptake*

Rao and Subramanian (1995), when working on vegetable crops, found that in cases where no fertilizer was applied, K was released from non-exchangeable sources. Richards and Bates (1989) reported a significant contribution of non-exchangeable K to crop uptake in soils from Ontario, Canada, which were rich in illites and vermiculites. Potassium supply in such soils is best characterized by either: (i) measuring a proportion of the non-exchangeable K that can become available during the growing season, or, (ii) showing the relationship between readily available levels and the potential for release of non-exchangeable K over a wide range of soils (Cox *et al.*, 1999). Soils with high amounts of non-exchangeable K fix a lot of $K^+$ and $NH_4^+$ ions.

Release of non- exchangeable K held in the inter-layers of expandable 2:1-type clay minerals, such as illite and vermiculite, is triggered by a low K concentration in the labile pool as a result of crop uptake and leaching (Sparks, 1980, Cox *et al.*, 1999). Loganathan *et al.* (1995) induced the release of non-exchangeable K to the plant available pool by successive cropping of maize in the greenhouse. Contribution of the non-exchangeable pool to total K uptake in maize was dependent on the type of geological deposits from which the soils had developed. This inter-layer K is the major source controlling the long-term K –supplying potential of soils (i.e. the capacity). Fixation and release of non-exchangeable K affect the abundance and binding strength of exchangeable K as well as the quantity- intensity factors (Cox *et al.*, 1999). Agarwal *et al.* (1993) reported that the release of K from non-exchangeable to exchangeable pools slowed down K depletion in soil solution that normally occurs during crop uptake.

According to Parfitt *et al.* (1995), K dynamics in the soil is a function of the amounts and type of clay mineral. Illite, chlorite and vermiculite minerals have high selectivity for K and thus favor retention, while kaolinite and montmorillonite have low selectivity and facilitate losses through leaching. Selectively adsorbed K is not easily exchanged with $Ca^{+2}$ and $Mg^{+2}$ ions as is the $K^{+}$ adsorbed on kaolinite and smectite soils. On the other hand, $K^{+}$ can be irreversibly fixed by vermiculite and illite minerals to such an extent that it would not take part in exchange reactions. According to Mamo and Haque (1988), the fixation and release of K in soils is a function of the amount and nature of clay in soils and determines the crop response to K fertilizers.

### *2.5.4 Potassium uptake from the soil*

Soil solution is the primary source of K for plant absorption (Uribe and Cox, 1988), which makes up only a small fraction of the total K in soils. During uptake, K depletion occurs in the vicinity of the roots (Greenwood and Karpinets, 1997) and continued uptake depends on replenishment after K movement from further away. According to Grimme (1979), diffusion accounts for 90- 99 % of all the K movement to the roots. The driving force for K diffusion to the root surface is the K activity gradient between the bulk soil solution and the root surface (Uribe and Cox, 1988). Other mechanisms of K movement are mass flow where dissolved K moves in the transpiration stream and root interception in which the growing roots come into contact with available K (Schroeder, 1974).

Plant K uptake is dependent on solution $K^{+}$ concentration in the vicinity of the roots and the plant‘s absorbing power (Mengel, 1985). The relationship between solute uptake (U), by a one-meter long root tissue, solute concentration in soil solution, and root absorptive power is represented by an equation:

$$U = 2\pi\, r.\, \alpha.\, C_r$$

Where U = uptake, r = mean root radius, $\alpha$ = root absorptive power, and $C_r$ = solute concentration in soil solution.

Potassium solution concentration is maintained through diffusive flux from the bulk soil (Meyer and Junk, 1993). The distance for diffusive – nutrient movement through the soil to the root is not extensive, and usually in the range of 0.1 – 15 mm (Barber, 1995). Ficks first law of diffusion describes the steady state diffusive flux (F), in a homogeneous fluid media (water, air), in µmol:

$$F = - DA\ \delta C/\delta X$$

Where D is diffusion coefficient, that describes diffusivity in a homogeneous system, A is the area for diffusion, and $\delta C/\delta X$ = concentration gradient (µmol $cm^{-3}$), perpendicular to root surface (difference in concentration between root surface and bulk soil solution). Negative sign indicates that movement is from higher to lower concentration (Barber, 1995). Accordingly, rates of K release from interlayers increase if $C_r$ decreases at the root surface. According to Springob (1999), K concentration in root surface decreases to low levels and K release may not occur until $C_r < 10$ µmol $cm^{-3}$. The author reported exponential increase in release, in concentrations < 3 µmol, and levels as low as 2.5µmol $cm^{-3}$ were recorded.

After a concentration gradient is created, desorption of $K^+$ from external surfaces is quite rapid, but the release from interlayer of clay minerals is much slow. Rate of release from interlayers is limited by the rate of diffusion of $K^+$ and the cations with which it exchanges through the interlayer space (Springob, 1999). In the heterogeneous soil media, diffusion coefficient is adjusted by indices for volumetric water content ($\theta$), tortuosity of diffusion path ($f_e$), and the buffer power of soil towards the cation ($\Phi$) (Mengel, 1985, Grimme, 1979), to give the equation,

$$D_e = D.\ \theta.\ f_e\,(c_e/C),$$

Where,

$D_e$ = effective diffusion coefficient of the heterogeneous system

$D$ = diffusion coefficient of the soil solution

$\theta$ = proportion of soil volume filled with water

$f_e$= impeadence factor, tortuosity of diffusion path

$c_e/C$ = ratio of solution K / exchangeable K (reciprocal of buffer power, $\Phi$) in bulk soil

Both terms, $\theta$ and $f_e$, reduce the value of D, because diffusion only occurs in fluid, and a tortuous path impedes diffusion. Loss of soil organic matter results in reduced diffusion and mass flow, and K movement towards the root surface (Grimme, 1979). Buffer power ($\Phi$), is defined as the ability of a soil to maintain a nearly constant K concentration in solution, or intensity when the nutrient is either added to or removed from the solution (Uribe and Cox, 1988).

The potential buffering capacity of soils, $\Phi$ is the slope of sorption – desorption (Q/I) curves, (Schneider, 1997), where Q refers to quantity (total diffusible ion concentration, exchangeable K), and I the Intensity (solution K). Effective diffusion coefficient for soils decreases with increase in $\Phi$ (Mengel, 1985). All the correction factors, $\theta$, $f_e$ and $\Phi$ are soil physical attributes influenced by soil texture and structure. They are also related to the mineralogy of parent rocks and organic matter content of soils (Sumner and Yamada, 2002)

High plant absorptive power means that a high proportion of ions impinging on the root surface is absorbed. Mehlich *et al.* (1964) singled out the ability of plants to mobilize plant nutrients from the soil to the plant roots as a factor that determines nutrient uptake. Grimme (1979) associated efficiency of nutrient uptake with root surface area. Deep- rooted crops can reach leached K in deeper horizons of the soil, thereby exploiting a bigger soil volume than shallow rooted crops.

According to Barber (1995), fresh roots are assumed to have a density of 1 Megagram (Mg) $m^{-3}$, and a mean root radius (r), estimated from root volume (V) and length (L), using the formula:

$$r = (V / L. \pi)^{1/2}$$

Root length and root surface area, are the two important characteristics that influence the nutrient absorbing power of a plant (Barber, 1995). In Kenya, many cropping systems have a combination of a grass plant like maize (*Zea mays*), and a legume plant. Due to the root advantage of maize in such cropping systems, pulses are often out- competed with regard to nutrient uptake.

Absorptive power depends on the crop metabolic activities, which determine the energy status of plant roots. According to Marschner (1995), the source of energy in non-photosynthesizing cells and tissues is respiration. The substrates for respiration are carbohydrates translocated from photosynthesizing leaves. Depending on plant species and developmental stage, an average of 25 - 50 % of the photosynthates produced, are allocated to the roots, with half of the allocation going to respiration (Marschner, 1995). There is a positive correlation between rate of photosynthesis and root development (number and weight of new roots), hence, factors that influence the rates of photosynthesis would also influence the rates of K uptake. In the rhizosphere, important characteristics like oxygen tension, and temperatures, affect the rate of respiration and K uptake (Grimme, 1979).

Another important factor is the presence and concentration of other cations. Degree of dissociation (exchangeability), of a cation is influenced by the degree of saturation and exchangeability (ease of desorption), of the accompanying ion on the exchange complex. This effect, termed complementary ion effect (Barber, 1995), shows that a divalent ion (e.g. $Ca^{2+}$), bonds more tightly to clay and displaces the monovalent cation (e.g. $K^+$), to weaker sites, where it is more readily desorbed. The presence of $Ca^{2+}$ increases uptake of many ions including $K^+$, termed Viets effect (Marschner, 1995), because $Ca^{2+}$ ions are able to counter the negative effects of high $H^+$ ion concentration on plasma membrane, by enhancing the activity of the proton-efflux pump, and general integrity of the cell membrane (Barber, 1995).

High concentrations of $NH_4^+$ and $H^+$ ions depress K uptake due to the competition for carriers on cell membranes of plant roots. Marschner (1995) reported that for pH values below 4.0, $K^+$ ions leave the plant roots to the soil, possibly because the ability of plasma membrane to stop K- efflux is impaired, and can cause K deficiency. Some ions that are closely related in hydrated size and charge can proxy for one another in the plant; and competition for uptake is great. These ion groups include $K^+$ and $Rb^+$, and $Ca^{2+}$ and $Sr^{2+}$ (Barber, 1995). Competition occurs at absorption (carrier sites), and during translocation. Both $K^+$ and $NH_4^+$ ions depress $Mg^{2+}$ uptake, because of their low binding strength on cell wall and plasma membrane. In several occasions, positively charged ions will always depress $K^+$ uptake if they are present in excess amounts (Messing, 1974). Of the basic hydrated cations: $Ca^{2+}$, $Mg^{2+}$ and $K^+$, $K^+$ is relatively preferred in exchange reactions due to the high polarizability factor (Sparks, 1987), and lowest bonding energy.

Messing (1974), when working on bananas in the West Indies, reported reduced response to K fertilizers when exchangeable levels of $Ca^{2+}$ and $Mg^{2+}$ decreased in soils, as a result of excessive

$Mg^{2+}$ and $Ca^{2+}$ mining. The crop responded well when fertilized with fertilizers that were rich in $Mg^{2+}$ but low in $K^+$. Fonseca *et al.* (1997), when working on maize in Brazil, found that excessive K fertilizer application inhibited $Mg^{2+}$ uptake, but excessive $Mg^{2+}$ did not inhibit uptake of $K^+$. In forage crops, K-induced Mg deficiency (hypomagnesaemia), also called grass tetany, was reported (Haby *et al.*, 1990).

Greenwood and Karpinets (1997) reported increased K availability to crops with increase in K activity ratio in soil solution, given by:

$$AR_K = [K]/([Ca] + [Mg])^{0.5}$$

Where $A_R$ = Activity ratio for K, and [K], [Mg] and [Ca] are the molar concentrations in soil solution.

According to Verloo (1990), the formula for calculating activity ratio, given by Greenwood and Karpinets (1997), has to be corrected by multiplying the molar concentrations with activity coefficients. Activity coefficients are calculated from the Dubel Huckel equation given by Verloo (1990). When $Na^+$ levels are in excess (sodic soils), they also compete with $K^+$ for uptake. Potassium improves crop production in saline soils as it out-competes $Na^+$ during uptake. Potassium sulfate is preferred to KCl in saline soils because it has a lower salt index.

Mehlich *et al.* (1964) reported that the ratio of K: Mg should be 1: 4, and that for K: Ca should be 1:10 in healthy soils. The approach, known as the basic cation saturation ratio (BCSR), was later shown to be inappropriate, because an ideal BCSR does not exist for all soils (Uribe and Cox, 1988). In Armenia, a good K: Mg: Ca balance is maintained by applying potassium lime (7.12 % $K_20$ + 16 % CaO + 0.08 % MgO) and K- Ca – Mg fertilizers (6.5 % $K_20$ + 9.7 % CaO + 5 % MgO). With such applications, yield and quality of barley and potatoes were improved, soil acidity was reduced, levels of Ca and Mg were increased and the general base saturation of soils was increased (Belyayev *et al.,* 1995). Silva *et al.* (1995) reported that K effects on cotton yield were more evident with liming. In the absence of liming, the highest K rate promoted plant injury.

### *2.5.5 Potassium in plant tissues*

Potassium concentration in plant tissues is generally high and only surpassed by N in some crops (Tisdale and Nelson, 1975). Schwartz *et al.* (1996) when working on tomatoes in a greenhouse found K and N uptake of 459 and 303 kg $ha^{-1}$, respectively, after growing the crop for six months. Okalebo (1979) when working on maize reported an average uptake of 190 kg K $ha^{-1}$, with 84.3 % of total uptake remaining in stover. Grewal and Sud (1995) while working on potatoes found K concentration ranges of 2.5 – 4.0 % in leaflets, 30 days after sowing (DAS). At harvest, potato yields were highly correlated to K concentration in tissues and yields were raised after increasing K saturation in tissues from the lower to the upper value. In tea (*Camellia sinensis L.*), a positive correlation was reported between the activity of nitrate reductase enzyme (used as an indicator for growth rate in tea), and level of potassic fertilizer application (Venkatesan *et al.,* 2004).

During the "grand growth period" (Coale *et al.,* 1993); when biomass increase is very rapid, rate of K accumulation in some plants is high and normally exceeds that of dry matter accumulation (Haby *et al.,* 1990). Marschner (1995) reports that after growing maize in a balanced nutrient solution, K concentration in the roots was 80 times higher in the cell sap than in the nutrient solution. Differences in concentrations of other nutrients were smaller, implying that K was selectively taken up and against a high concentration gradient. According to Haby *et al.* (1990), Ca content in most crops is normally about half that of K, while Mg is normally about half that of Ca concentration. In a K uptake growth model by Greenwood and Karpinets (1997), % K content in tissues declines with increase in plant mass; termed the dilution effect.

### 2.6 Soil analysis for potassium determination in Kenya and other countries

Apart from the data from ICRAF where modified Olsen method (Yurimaguas Experimental Station, 1989) has been used since 1994, all the other soil databases currently existing in Kenya are closely linked to analytical methods used at the National Agricultural Research Laboratories (NARL). At NARL, the Mehlich I method (0.1 N HCl + 0.025 N $H_2SO_4$) by Mehlich (1953), has been used as a routine method to extract available K, while use of neutral $NH_4OAc$ is recommended for exchangeable K (Qureshi, 1979). In a greenhouse experiment, Hinga and Kuria (1976), reported good correlation between exchangeable K, Mehlich available K and K activity ratio with dry matter yields and K uptake in sorghum for some Kenyan soils.

The Mehlich (1) extraction method and a critical value of 0.2 cmol ($p^+$) $kg^{-1}$, which have been used to give fertilizer recommendations in Kenya, have identified some K deficient soils in central and western districts of Kenya (Kanyanjua and Buresh, 1999). Few correlations, however, have been undertaken between K levels in the soil and K uptake and crop response, while some crops have not been studied at all. The rarity of K deficient samples has contributed to the belief, that Kenyan soils are rich in K (Kanyanjua and Buresh, 1999).

Extraction of exchangeable $K^+$ involves the exchange of $K^+$ in the soil with a cation in the extracting solution. Thomas (1982) defined exchangeable cations as those that can be exchanged by a cation of an added salt solution. In general, any added cation will exchange with the soil cations, but there are quasi-exchangeable cations like $K^+$ in micaceous soils, $Al^{+3}$ in acid soils and $H^+$ in practically all soils (Thomas, 1982). Mehlich 1 reagent depends on the $H^+$ ion exchanging for $K^+$ and other cations ($Na^+$, $Ca^{2+}$ and $Mg^{2+}$). With its low binding energy and high preference for pH-dependent charges (Barber, 1995), $H^+$ may not be a very effective exchanger.

In the USA and Canada, an estimate of exchangeable K, which normally includes soil solution K, is the standard index of K availability (Haby *et al.*, 1990). In the neutral 1 M $NH_4OAc$ extractant, $NH_4^+$ ion, as with other large monovalent cations like $Rb^+$ and $Cs^+$, block the release of interlayer $K^+$ by collapsing the inter-layer space (Springob, 1999). Potassium extracted by this method, therefore, is restricted to the outer surface charge. Another method is the ammonium lactate method (AL-method), which extracts similar amounts of K as the neutral, 1 M $NH_4OAc$ extractant (Csatho, 2002). The AL-method is widely used in the Scandnavian, Benelux, Baltic and central European countries; for determining soil K test values for fertilizer recommendation systems.

In the USA, Mehlich 1 method has been revised twice giving way to new extractants in form of Mehlich II and Mehlich III ($HNO_3$ + $NH_4F$ + $CH_3COOH$ + $NH_4NO_3$ + EDTA), (Mehlich, 1984). According to Eckert (1994), the two most widely used methods in the USA are the neutral 1M $NH_4OAc$ and Mehlich- III combination extractant (Mehlich, 1984). There is a good correlation; not only between the two methods, but also with crop yields; and are used as universal extractants.

Walmsley *et al.* (1971) when working on bananas in West Indies; compared six extractants and established correlation coefficients between the various soil test data sets with crop response to KCl. The extractants included 1 M $NH_4OAc$ at pH 7, cold sulphuric acid, hot nitric acid, 0.01 M $CaCl_2$, Morgan reagent (0.5 M acetic acid in 0.75 M sodium acetate, pH 4.8) and Egner- Riehm (0.1 M ammonium acetate, 0.4 M acetic acid) reagents. Best correlations between soil tests and crop response were obtained from the 1 M $NH_4OAc$ and cold sulphuric acid that extract exchangeable K. Results agreed with Hinrich *et al.* (1985), Haby *et al.* (1990) and Eckert (1994), who reported good correlation between exchangeable K levels and plant available K under a wide range of conditions.

Contrary to the foregoing, soil test values may not correlate with yields or results of fertilizer experiments, because soil solution K is not simply a function of exchangeable K. At the same level of exchangeable K, sandy soils will have more K in soil solution than clay soils (Kemmler and Hobt, 1986). At the same clay content, 2:1 clays, i.e. illites and vermiculites; have lower K concentrations in soil solution than kaolinitic clays. According to Shen and Stucki (1994), soil tests for K often fail to reveal the true fertilizer demand in the field, resulting in unreliable and inefficient fertilizer recommendations. They attribute the low predictability to uncontrolled and unrecognized transitions between the various K -forms in the soil between the time of testing and time when plant roots attempt to absorb K.

Srinivasa *et al.* (2000) found high K uptake and high mobilization rate of soil K by sorghum from soils with high chemical estimates of K. Shen and Stucki (1994) however cautioned that soil tests for K often fail to reveal the true fertilizer demand in the field. Although neutral $NH_4OAc$ is the most widely used method for determining the exchangeable K in soils, Barber (1979) reported that it may extract more K than there is in the exchange equilibrium in the soil solution and preferred to use 0.25 M $CaCl_2$.

Cox and Joern (1997) reported better predictions of plant available K after extracting soils with modified sodium tetraphenylboron ($NaBPh_4$) than with neutral 1M $NH_4OAc$. According to Cox *et al.* (1999), the $NaBPh_4$ method was developed to release interlayer K in soil micas. The mode of action is shown in the equation:

$$\text{Soil-K} + NaBPh_4\,(aq) \longrightarrow \text{Soil-Na} + KBPh_4\,(s)$$

Precipitation of $KBPh_4$ mimics the action of plant roots during uptake of solution K, which triggers further release of exchangeable and non-exchangeable K. Neutral, 1 M $NH_4OAc$ method does not measure the plant- available fraction of non-exchangeable K, or the relationships among different pools of K. Non exchangeable K forms a major source of plant available K in soils rich in illite and vermiculite minerals. Richards and Bates (1989) identified a fraction of the non-exchangeable K that they called Step K, the loosely bound non-exchangeable K released by repeated extraction with 1M $HNO_3$.

Subba Rao and Srinivasa Rao (1996), when working in India, used different reagents to extract K from the different pools that exist in the soil. Neutral 1 M $NH_4OAc$ was used to extract available K. Non-exchangeable (fixed) K was determined as the difference between total K in the soil (by boiling in 1 M $HNO_3$) and the available K. Sparks (1980) recommends extraction of solution K with water, exchangeable K with neutral 1M $NH_4OAc$, non-exchangeable K with $NaBPh_4$ and total K with hydrofluoric acid (HF).

No efforts have been made in Kenya to relate K uptake with non-exchangeable quantities as was done by Cox and Joern (1997) for Indiana soils. Mehlich 1 method has relied heavily on determining the K intensity (I) in soils and not the K capacity that reflects buffering power of soils. Buffering power of a soil can be assessed after characterizing soils in terms of texture, and clay mineralogy. Data from extractions that target different K pools should be correlated with uptake and crop yield response, for callibration of recommendations targeting a particular crop and region (Csatho, 2002). My hypothesis is that the Mehlich I method used at NARL has given an erroneous picture of the K status in Kenyan soils, by underestimating K needs in intensively cropped areas of Kenya.

### 2.7 Soil potassium data and critical soil test values

Walmsley *et al.* (1971) defined a good laboratory method as one whose analytical results can most accurately predict yield response of a particular crop to applied nutrients, under the growth conditions. For a laboratory to interpret the chemical data, critical soil test values (CSTV) for the various nutrients and crops have to be established. Simply defined, the CSTV is the laboratory soil test value above which crop response to fertilizer is unlikely and below which a response is likely to occur, and hence a fertilizer will be recommended (Cate and Nelson, 1965). Generally speaking, lack of information on critical limits of K for important crops limits the ability of agronomists to make fertilizer recommendations. For example, in India, Subba and Srinivasa (1996) could not give K fertilizer recommendations after a nationwide survey of K status in soils because of lack of $CSTV_K$. According to Eckert (1994), the critical or sufficiency level is that level of extracted soil K that gives optimum yield of a crop without addition of fertilizer.

Some recommendations aim at maintenance fertilization, where rates applied replace the K lost through crop uptake. Soils with K levels above the sufficiency level can be allowed to draw down the K stocks, and crops are grown without application of K fertilizer. Crops meet their K requirements from the soil, allowing reserve levels to fall as long as they remain above the critical value. In soils with K levels that are below the sufficiency level, yields obtained remain sub-optimal unless fertilizers are applied. Some recommendations aim to buid up soil reserves, which are raised gradually to reach the critical level. In some cases, response fertilization is adopted, whose aim is to achieve a certain yield without any consideration as to what happens to the reserve K (Eckert, 1994).

Mehlich *et al.* (1964) when working at NARL; fixed the CSTV for K at 0.2 cmol $(p^+)$ $kg^{-1}$ for low K requiring plant species and 0.4 cmol $(p^+)$ $kg^{-1}$, for high K requiring plant species. Walmsley *et al.* (1971); established a critical exchangeable K value of 0.4 cmol $(p^+)$ $kg^{-1}$ for bananas. Foster (1972) found that Ugandan soils with K values < 0.46 cmol $(p^+)$ $kg^{-1}$ are potentially deficient and respond to K fertilization after a few years of cropping. Oduor (1983) reported 0.56 cmol $(p^+)$ $kg^{-1}$ as the CSTV for plant available K in major agricultural soils of Kenya.

Eckert (1994) and Fisher (1974) defined K-sufficiency levels as a function of the cation exchange capacity (CEC) of a particular soil. Walmsley (1971) suggested a minimum of 2-5 % K saturation of the CEC, which agrees with the minimum of 2 % given by Anderson (1973). Fisher suggested the equation:

$SL_K = (110 + 2.5 \times CEC)/390$, where:

$SL_K$ = K sufficiency level [cmol (p+) $kg^{-1}$]

CEC = cation - exchange capacity [cmol (p+) $kg^{-1}$]

## 2.8 Available soil data and mapping of areas in Kenya with an emerging K deficiency

### *2.8.1 Overview*

Even though a number of cases of K deficiency have been reported in Kenyan soils by various workers (Muchena, 1975; Nandwa, 1988; Mochoge, 1991; ICRAF, 1997); none of them indicated the extent of areas likely to have an emerging K deficiency or the national economic importance of such findings. In Kenya, no deliberate effort has been made to conduct a nationwide survey on K status in soils but K has always been reported in the various soil fertility evaluation reports since the 1960s (Mehlich *et al.,* 1964). Soil analytical methods used in Kenya have identified few samples that are low in K and K fertilizer is rarely recommended.

### *2.8.2 The Soil databases*

A number of databases exist in Kenya, that, if re-packaged can be used to identify areas that are either low at the moment, or are likely to lose the adequate K status in the near future. The databases are in different utility status, and can therefore serve this purpose to different degrees of precision. Re-packaging of data for mapping purposes would involve sorting the existing laboratory soil data to identify K deficient samples and plotting sampling points on the Kenyan map, using Geographical Information Systems (GIS).

This approach has three limitations: (i) soil analysis data is in "point form", and cannot be easily transformed to "polygon form", (ii) many sampling data points were not geo-referenced, yet cannot be retraced to take geographical coordinates, and (iii) some places have never been sampled and large amounts of resources have to be commited for fresh sampling at an appropriate scale. Another database exists in the Almanach Characterization Tool (ACT), (Corbett *et al.,* 1999), a simplified, easy to use GIS tool, with different types of data that include: climatic, edaphic, topographic, political and demographic information for Kenya and other countries. This data is in a better utility status for mapping, if good hypotheses are formulated.

### *2.8.3 Description of available databases*

#### *2.8.3.1 Soil data from farmer advisory services*

The National Agricultural Research Laboratories (NARL) in Nairobi, which were established in 1903 have continued to offer farmer advisory services. Soil data from advisory services at NARL is not properly documented and in particular is not geo-referenced. It is difficult to use this data to determine the spatial variability of K supplying capacity among the soils of Kenya. The services have always relied on available K data determined by the double acid extraction method (Mehlich, 1953). A similar but well organised database is kept and maintained by Mumias Sugar Company in western Kenya, mainly for the sugar belt.

#### *2.8.3.2: FURP soil database*

The FURP soil database at NARL consists of chemical data for soil samples collected from 64 trial sites spread in the high and medium rainfall areas of Kenya. In addition, associated yield data exists for 14 food crops grown on 28 soil sub-orders, collected for varying periods during the years 1987 - 91. The locations of FURP trial sites are geo-referenced and all the data is well preserved in an excel spreadsheet at NARL. FURP sites were spread from the west to east side of the country; covering the areas of main agricultural activity where both cash and food crops are grown. Eighteen out of the 64 (28 %); had available K values below 0.4 cmol $(p^+)$ $kg^{-1}$ the upper limit of critical range set by Mehlich (1964), for Kenyan soils. Potassium deficient sites are mainly located in Lake Victoria basin that includes Western and Nyanza Provinces, Central Kenya around the foot-slopes of Mt Kenya and the Aberdares, and a few sites at the coast. Areas within the Rift Valley and the semi-arid areas of eastern Kenya had high K values (FURP, 1987).

### *2.8.3.3: Other soil databases*

Other databases are in existence in various institutions that can be used to assess K – supplying capacity of soils from various regions of the country. At the Kenya Soil Survey (KSS), the Exploratory Soil Map (E1) of 1980 was digitized during the years 1990 - 91 and was updated with data from KENSOTER (1993-94) and later on with data from FURP. Further updating is going on with data from district reconnaisance soil maps at a scale of 1:100,000. The updated E1 map has been used to draw a sketch map for K status in Kenya at a scale of 1: 1,000,000.

Another soil database is maintained at ICRAF and can, in addition to all the other recent data, be used to improve the E1 map at KSS further. If all these data were added to the E1 map in GIS, the improved map would show soils of the entire range of K supply status. Data in the ACT (Corbett *et al.*, 1999); overlaps significantly with the E1 data at KSS and the two databases can be used for a better product. The available soil data may be insufficient to predict the long term K supplying power of soils unless a relationship is established between the data and K buffer capacity of soils.

## 2.9 Parent materials and K-supplying capacity of soils

### *2.9.1 Parent rocks and agriculture*

Parent materials refer to the mineralogy and chemical composition, structure and texture of the bedrock; the same properties used to classify igneous rocks (Marechal *et al.*, 1983). The original source of K and other mineral cations in soils is from weathering of parent rocks, which have such cations in their crystalline structure (Haby *et al.*, 1990). Structural and textural features are important characteristics of rocks, which determine the rate of weathering (Marechal *et al.*, 1983). With regards to soil fertility, however, the final products of weathering are most important, which are dependent on the mineralogy and chemical composition of rocks.

According to Harley and Gilkes (2000), there is a big potential in use of ground rock as a slow release fertilizer for highly weathered soils, and leaching environments, where soluble fertilizers may be easily lost. Use of ground rock may also give a possible use for the waste products of quarrying. Organic farmers can also use ground rock as a source of nutrients, which suits their tendency to desist from the use of mineral fertilizers and pesticides (Loes and Ogaard, 2003). Hinga and Kuria (1976) examined the mineralogy of selected Kenyan soils and found a high correlation between the soil mineralogy and K uptake in plants and dry matter yields. There was a good correlation between the K and Mg content and biotite in sand fractions of the soil.

Mineralogy of rocks refers to type and relative abundance of constituent minerals (Marechal *et al.*, 1983). According to Harley and Gilkes (2000), the most important rock-forming minerals are: quartz, ferromagnesian silicates (olivines, pyroxenes and amphiboles), feldspars and micas. The rock-forming minerals differ in both the chemical composition and the ease with which they weather to release niutrients and form secondary minerals.

### *2.9.2 Weathering of primary minerals*

Weathering of rock forming minerals comes about as a result of the differences that exist between the conditions in the soil environment and the conditions of crystallization of minerals from the original magma. Minerals were crystallized under reducing environments, under low water contents and under conditions of high temperatures and pressures, than occurs in the soil (Harley and Gilkes, 2000). Minerals that crystallized at higher temperatures are the least stable in the soil and weather faster than those that crystallized last (Harley and Gilkes, 2000).

On exposure to the soil environment, minerals decompose because of their instability. Two types of weathering, physical (mechanical), and chemical, take place simultaneously. Physical weathering constitutes a series of physical processes (Aide and Smith- Aide, 2003), which break the rock into smaller pieces without affecting it chemically. This increases the surface area and results from the effects of water (after adsorption and during transport), frost, plant roots, heat (thermal expansion) and wind. Chemical weathering, on the other hand, consists of chemical reactions that change the original composition of minerals that are unstable at the earth's surface to new components that are stable (Aide and Smith- Aide, 2003). Water is the most active agent of chemical weathering.

N.L. Bowen worked out a series in the 1900's, showing the ease with which minerals weather into soils; referred to as the Bowen's Reaction Series (Fig 1). As magmatic temperatures drop, mineral crystallization follows two different paths, appearing as separate branches in Fig 1. The left branch is referred to as discontinuous reaction series, because minerals formed as crystallization temperatures dropped have different structural properties, and are immissible in the solid state. The right branch is called the continuous reaction series, where minerals formed are miscible in all proportions in the solid state. According to Bowen's Reaction Series, olivines and anorthite crystallized first and are therefore most weatherable, while quartz crystallized last, and is most stable.

### *2.9.3 Primary minerals and plant nutrients*

Primary rock-forming minerals are grouped into mafic and felsic minerals. The reason for this grouping is that the dark coloured, mafic, or ferromagnesian minerals, often containing Mn, contrast with the important group of feldspars, i.e. the Ca – Na - K bearing light coloured silicates, or felsic minerals (Mohr *et al.*, 1972).

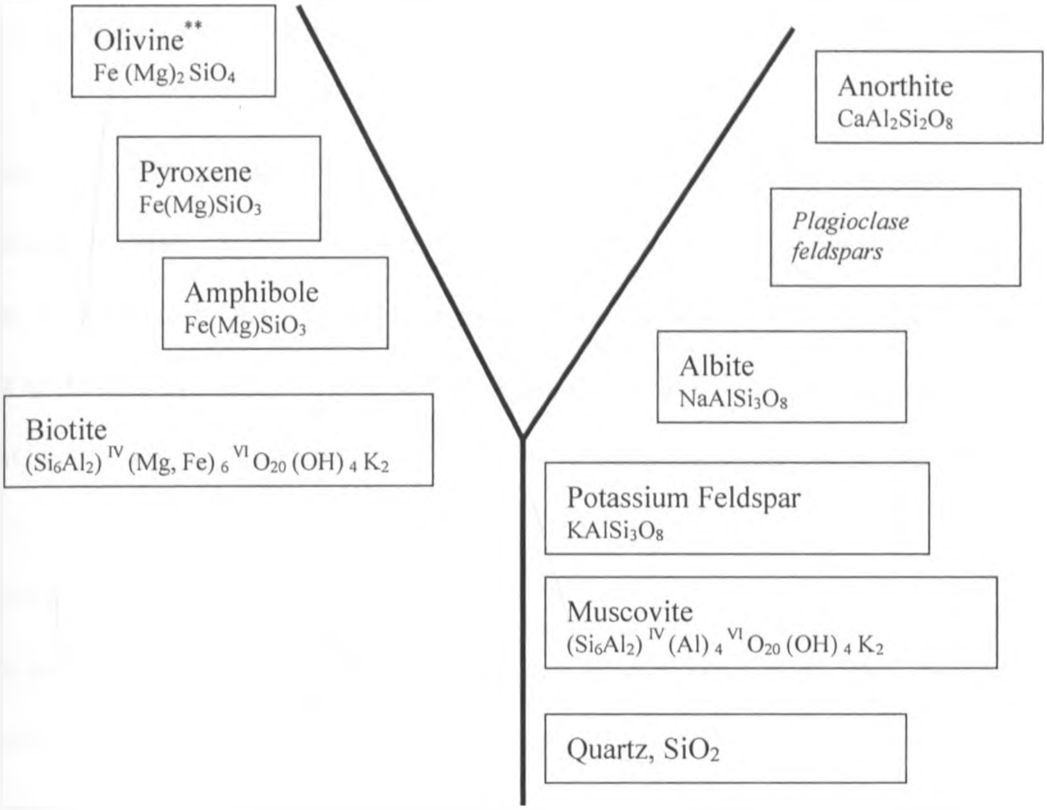

Fig 1: Bowen's Reaction Series

** Structural formulae adopted from De' Conninck, 1987

### *2.9.3.1: Ferromagnesian silicates*

Ferromagnesian minerals at the top of the left arm are the most weatherable rock- forming minerals, with ease of weathering decreasing in the order: olivine > pyroxene > amphiboles (De'Conninck (1987). According to Mohr *et al.* (1972), ferromagnesian silicates are rich in Fe, Mn and Mg oxides.

Ferromagnesian silicates allow substitution of a wide and diverse range of elements (De'Conninck (1987). On weathering, ferromagnesian minerals form important sources of Fe, Mg, Ca, Na and trace elements. They dissolve congruently (completely), or alter to Mg – rich trioctahedral expansive clay minerals or chlorite (Harley and Gilkes, 2000).

Weathering of ferromagnesian silicates releases all elements common in the soil except K. Pyroxenes are important sources of Fe, Mg, Ca and Na, with augite, a pyroxene having upto 20 % CaO, and wallastonite; another pyroxene having the chemical formula $CaSiO_3$. Hornblende is an important amphibole and contains 14 % CaO (De'Conninck (1987). Pyroxenes and amphiboles can be present in the sand and silt fractions of soil, but not in the clay fraction (De'Conninck, 1987).

### *2.9.3.2: Feldspars*

Feldspars are the most abudant rock -forming minerals (Harley and Gilkes, 2000). Feldspars are alumino-silicates, and form a solid solution of three end members: K-feldspars (microcline, orthoclase), Ca- feldspars (anorthite) and Na-feldspars (albite). End members between Na and K are called alkali feldspars, and between Na and Ca, plagioclase feldspars (De'Conninck (1987). Plagioclase feldspars form the right branch of the Bowen's reaction series (Fig 1), and form a continuous series between albite and anorthite. Calcium decreases from pure anorthite to albite, as Na content increases. Anorthite is the most weatherable among feldspars, followed by albite, and K feldspars the most resistant to weathering (Fig 1).

Feldspars belong to a larger group of framework silicates, with their oxygens linked to two tetrahedra (De'Conninck (1987). Other members are feldspathoids (e.g. nepheline), and zeolites. Framework silicates differ in the extent of isomorphic substitution, and compactness of the structure.

Feldspars have the least substitution and are more compact than feldspathoids. Zeolites form a very open structure, and have large interconnecting channels (De'Conninck, 1987). Feldspars, unlike ferromagnesian silicates and micas do not have octahedrally coordinated cations (Al in feldspars is in tetrahedral position). This means that the entire structure has to be destroyed during weathering before secondary minerals can form from feldspars. In addition, secondary clay minerals cannot inherit any structures from feldspars (De'Conninck, 1987). For these reasons, feldspars persist in soils where other primary minerals have altered to secondary minerals (Harley and Gilkes, 2000). On weathering, feldspars release Na, Ca and K to the soil, as well as Al and Si.

Soil pore waters generally have a composition closer to saturation with respect to K feldspars (Harley and Gilkes, 2000). Potassium feldspar dissolves at a relatively slower rate than plagioclase feldspars (Harley and Gilkes, 2000). According to Khan and Fenton (1996), the release of K from weathering of K feldspar is a slow process that does not contribute appreciable amounts of available K in soils. Potassium feldspars may result in high total K analysis of rocks and soils, but do not contribute much to K uptake by crops, because the minerals are resistant to decomposition.

### *2.9.3.3: Micaceous minerals*

Biotite, phlogopite and muscovite belong to the mica group of rock- forming minerals (De'Conninck, 1987). They have the characteristic platy structure, with a 2:1 arrangement, where one octahedral sheet is sandwitched between two tetrahedral sheets. Iron (II) and Mg occupy the octahedral positions in biotite and phlogopite, and Al in muscovite. Due to isomorphic substitution of Al for Si in the tetrahedral position, there is a net negative charge, balanced by K. Structural K, therefore, forms the link between two adjacent 2: 1 layers (De'Conninck, 1987).

Micas weather by admitting water into the interlayer space and allowing other cations like $Ca^{2+}$ and $Mg^{2+}$ to exchange with $K^+$. The plant nutrients: Mg, Fe and K may result from biotite and phlogopite decomposition, but only K may be of some use to crops after muscovite decomposition (Fig 1). Micaceous minerals are very common in soils and are normally inherited from parent materials. Potassium in muscovite, biotite and phlogopite belongs to the structural pool and is not available for crop uptake. Ease of weathering of K- containing minerals decreases in the order: biotite > phlogopite > K-feldspar > muscovite (De'Conninck, 1987).

During the transformation of micas in soils, a series of changes take place that include: $K^+$ depletion, gain in hydrated exchangeable cations and oxidation of structured $Fe^{2+}$; which cause the transformation of biotite into vermiculite and smectite, in which Al interlayering may occur (Maes *et al.,* 1999). Loes and Ogaard (2003) were able to identiy increased CEC after K depletion due to the transformation of primary minerals to expandable clay minerals. In their case, the amount of illite declined after soils were depleted of K, due to K removal from interlayers of illitic minerals. With prolonged depletion, vermiculite and eventually smectite may be produced.

### *2.9.3.4: Other rock-forming minerals*

Another rock- forming mineral, quartz ($SiO_2$); is the most resistant to weathering (Fig 1). It does not contain plant nutrients that are required by common plants. Illite is either a secondary mineral or a weathering product of muscovite and biotite (De'Conninck, 1987). Illites originating from biotite and phlogopite (tri-octahedral micas) have much higher Mg content than those from muscovite and therefore give more fertile soils. In illite, K ionic bonds are weakened by water and part of the K is exchangeable with such other cations as $Na^+$ and $Ca^{2+}$(De'Conninck, 1987). Illite is usually the main reserve of K in soils (Munsuz *et al.,* 1996).

### *2.9.4: Soil minerals*

Clay mineralogy studies for soils are meant to identify the petrographic origin, the stage of weathering and mineral reserves in soils (Mohr *et al.,* 1972). In the current study, however, clay mineralogy information would also give an idea of the ease with which K diffuses from various pools to soil solution in response to depletion during crop uptake. Potassium in illites is said to be in the fixed pool and is gradually released into the soil solution. Fertilizer K can also get locked up in the inter-layers and may be temporarily out of reach of plant roots (Tiwari *et al.,* 1995).

Complete removal of ionic K and replacement with hydrated cations results in formation of vermiculite and smectite minerals, the dominant minerals in clay fractions of some soils (De'Conninck, 1987). The two minerals differ in amount of charge between the two layers and the extent to which they can expand. Vermiculites have higher charge and cannot expand as much as the smectites (De'Conninck, 1987). Potassium held in the interlayers of vermiculites and smectites is in the exchangeable pool and exists in equilibrium with the K in solution pool. Further disintegration of vermiculites and smectites forms kaolinites and sesquioxides (De'Conninck, 1987). Kaolinite is a typical 1/1 clay mineral of soils developed under humid tropical climate (De Coninck, 1987). Cox *et al. (*1999), reported a decrease in extractability of K by $NaBPh_4$ from some layer silicate minerals, in the order: vermiculite > illite > biotite > phlogopite > muscovite.

### *2.9.5: The weathering processes*

According to Mohr *et al.* (1972), the formation of all types of soils, *in situ,* from parent rocks starts with alteration processes, converting the parent rock into the parent material. Alteration processes consist of weathering of primary minerals with subsequent formation of clay-sized minerals and salts. The processes are qualitatively similar in temperate and tropical conditions but quantitatively influenced by permeability and drainage conditions in the weathering zones, and temperatures. A second step involves the leaching of soluble salts.

Mafic minerals (ferromagnesian silicates and trioctahedral micas) are considered more weatherable than felsic minerals (feldspars, muscovite, quartz) (De'Conninck, 1987). The majority of rocks have different combinations of mafic and felsic minerals, although a few can be said to be mono-minerallic. Due to the difference in susceptability to weathering, some minerals decompose quickly and release cations to the soil solution but leave the more resistant minerals in place, referred to as incongruent weathering (Harley and Gilkes, 2000). For a rock rich in plagioclase and alkali feldspars, plagioclase feldspars weather faster, releasing Ca, but leave orthoclase unweathered. Incongruent dissolution results in the mineral left unweathered forming a protective layer covering the surface, and slowing down further decomposition of the weatherable mineral (Harley and Gilkes, 2000).

After weathering of individual minerals, Ca, Mg and K are released and removed, as the less mobile Al and Si accumulate and form a protective layer on mineral surfaces (Harley and Gilkes, 2000). Mobile cations, further from the mineral surface are released at a slower rate; because the protective layer limits further diffusion. As the protective layer thickens, diffusion of cations slows down further. Consequently, there is relative depletion of Mg and Ca and K towards the surface, while Fe, Si and Al show a relative enrichment towards the surface of weathering rock (Harley and Gilkes, 2000).

Changes that occur during transformation of primary minerals to secondary minerals are of chemical nature, as a result of which nutrients are released to the soil, as simple ions, complex ions or colloids (Harley and Gilkes, 2000). Chemical reactions range from simple solution reactions, where $Cl^-$ and $SO_4^{2-}$ of $Na^+$, $K^+$, $Ca^{2+}$ and $Mg^{2+}$ dissolve in soil solution, to hydration reactions involved in transformation of feldspars to secondary clay minerals (Amerijckx, 1985). Weathering rate and direction is initially determined by pH of soil solution, which is about 5.7 (slightly acid), due to dissolved $CO_2$ (Harley and Gilkes, 2000).

Chemical weathering occurs as a result of various chemical reactions between the soil solution and mineral surfaces. The reactions include oxidation, which is important in minerals that contain Fe (II) and Mn (II) (ferromagnesian silicates and biotites), which are oxidized to higher valencies, thus causing a loss of negative charge and loss of K (Stucki and Huo, 1997). Reduction of Fe can also occur in illites and vermiculites, which increases the negative charge, and reverses the gains made from weathering, by increasing K fixation in soils (Stucki and Huo, 1997). Other minerals affected by cyclic redox events include S and N.

Hydration (taking in of water); is common in phyllosilicates that expand and thus creating tensional forces (De'Conninck, 1987). Anhydrite (white) takes in water to form gypsum (blue), and haematite (red) to form lemonite (yellow). Hydration results in increase in volume, which leads to rock disintegration.

$$\text{Anhydrite: } CaSO_4 + H_2O \longrightarrow CaSO_4.\,2H_2O \text{ (gypsum)}$$

$$\text{Haematite: } Fe_2O_3 + H_2O \longrightarrow Fe_2O_3.\,2H_2O \text{ (lemonite)}$$

Hydrolysis is partial decomposition by water (Amerijckx, 1985), and is best demonstrated by hydrolysis of a salt from a strong base and a weak acid, e.g. $CH_3COONa$. In the presence of water, the salt is hydrolysed to form a strong base (NaOH) and a weak acid ($CH_3COOH$), suggesting that $H^+$ ions have replaced $Na^+$ in the salt. A similar reaction is expected with orthoclase ($KAlSi_3O_8$), which is a salt of a strong base (KOH) and a weak acid ($H_2SiO_3$). The reaction goes in stages and for a long time. The products of hydrolysis of feldspar are the ions ($K^+$ and $OH^-$), silicic acid and aluminosilicates. Aluminosilicates may be hydrolysed further to form kaolinite, and still further to form gibbsite; $Al(OH)_3$ . In both ferromagnesian and aluminosilicate minerals, reactions involve loss of exchangeable cations ($Ca^{2+}$, $Mg^{2+}$, $K^+$ and $Na^+$), followed by gradual loss of Si, and an accumulation of Al and Fe as oxides and hydroxides (sesquioxides). The events are characteristic of formation of an oxic horizon in soils, and dependent on drainage conditions (Mohr *et al.*, 1972).

Parent rocks weather to soils of different properties, depending on their mineralogy and chemical composition (Tenning *et al.*, 1995). Rocks rich in alkali feldspars and micas are more likely to weather into soils that are rich in K. Amount of K in soils is dependent on extent of weathering, losses (leaching, runoff, erosion and crop uptake), and addition through organic and mineral fertilizers (Khan and Fenton, 1996). Chemical composition of rocks is determined by laboratory analysis of the constituent elements expressed as % weight of oxide.

Depending on $SiO_2$ content by weight, igneous rocks are classified as acid (> 66 %), intermediate (52 – 66 %), basic (45 - 52 %) or ultrabasic (< 45 %), (Marechal *et al.*, 1983). Acid rocks, like granite are rich in alkalis (K and Na), but low in alkaline earths (Mg, Ca, Fe and Mn). The reverse is true for basic igneous rocks, like basalt. According to Sparks (1987), granites and syenites contain 46 – 54 g K $kg^{-1}$, basalts 7 g K $kg^{-1}$, and peridotites 2 g K $kg^{-1}$ of rock. Rock characterization is done by examination of thin sections and geo-chemical analysis of rock specimens. In petrographic classification, therefore, increased acidity of parent materials refers to increase in the silica content and decrease in alkaline earths (Mohr *et al.*, 1972).

The relative proportion of each of the four pools of K will differ among soils and will normally depend on type of parent material and stage reached on the advancement of weathering (Smith, 1954). In Virginian Coastal Plain soils, Sparks (1980) reported exchangeable K concentrations in soils that were lower than 0.2 cmol $(p^+)$ $kg^{-1}$ with 94 % of the total K in an Ap horizon occurring in structural form. Total K content in soils is affected by soil forming factors, which include parent materials, climate, relief, time and human activities (Amerijckx, 1985). Climate and relief influences the amount of K in soil through weathering and losses through leaching and runoff. Time determines the period to which parent materials have been exposed to weathering agents and extent of losses that have taken place in the soil. Human factors influence K status in the soil mainly through addition of fertilizers, soil conservation and intensity of cropping.

### *2.9.6: Soil biological activity and mineral weathering*

Biological activity due to plants and microorganisms influences the chemical and physical conditions in the soil (Harley and Gilkes, 2000). The part of the soil most influenced by biological activity is the rhizosphere (root environment). Conditions in the rhizosphere can differ greatly from those in the bulk soil (Marschner, 1995). Uptake of $K^+$ and P in rhizosphere results in development of very low solution concentrations, which creates a diffusion gradient and release of interlayer K in micas, and dissolution of P salts. Rye grass depleted K in soil solution within the rhizosphere to approximately 3 mg $L^{-1}$, which resulted in release of interlayer K from phlogopite and formation of vermiculite (Harley and Gilkes, 2000). Root activity changes the concentration of gases ($CO_2$ and

$O_2$), in rhizosphere, and weathering conditions (Harley and Gilkes, 2000).

Rhizosphere can differ from the bulk soil by two pH units due to efflux of $H^+$ (causing low pH) or $HCO_3^-$ (causing high pH). Efflux of ions by the roots occurs as a means of maintaining the charge balance or electroneutrality (Marschner, 1995). Both high and low pH values enhance the rate of mineral weathering, a procss that is lowest at neutral pH values. Low pH increases the release of micronutrients Mn, Fe, Zn and Cu (Marschner, 1995), and solubilizes soil P (Kirk, 1999).

Plants and microflora secrete organic acids to the rhizosphere, which triggers dissolution of minerals (Harley and Gilkes, 2000). Organic acids are more effective in the dissolution of minerals than mineral acids at comparable concentrations. Organic acids are able to dissolve silicate minerals at near neutral pH where simple proton- promoted dissolution is limited. Complexing properties of organic acids reduce concentration of cations in solution and trigger further release (Harley and Gilkes, 2000). Among the organic acids, bi-dentate ligands, like oxalate, have a greater influence on dissolution than mono-dentate ligands like acetate. Mafic minerals are more susceptible to dissolution in the presence of organic solutes than felsic minerals (Harley and Gilkes, 2000; Raulund – Rasmussen *et al.,* 1998); as a result of which there is limited effects of organic ligands on feldspars. Divalent and trivalent cations suppress the effects of organic matter due to the formation of organic ligand – metal cation complexes (Raulund – Rasmussen *et al.,* 1998).

Organic acids are particularly important in speeding up the dissolution of Ca- and Mg- containing minerals (Raulund – Rasmussen *et al.,* 1998). Calcium is precipitated in solution as Ca-oxalate and Ca- citrate salts, which lower the concentration of Ca in solution and trigger further release. Al dissolves preferentially or equally to Si in strongly complexing organic acids. Immobile Al and Fe are easily transported as complexes in solution (Harley and Gilkes, 2000). Aluminium released during dissolution in soils above pH 5 is precipitated as secondary aluminosilicates (e.g.. kaolinite, allophanes), or as oxides and hydroxides (Harley and Gilkes, 2000). The $Al^{3+}$ ion is dominant below pH 5, but may not inflict significant toxicity to plant roots, due to its complexation with organic ligands between pH 3.8 and 5.0 (pH range for organic acid deprotonation). Complexed, soluble forms of Al; were found dominant in organic horizons of spodosols (Harley and Gilkes, 2000). Plants that are efficient in extraction of P from soils were found superior in secretion of organic anions (Kirk, 1999). Solubilization of P may be improved by either formation of soluble complexes with P via metal ions, or chelation of metal ions (Fe, Al, Ca), that would otherwise immobilize P.

Soluble complexes of metal cations and low molecular weight organic ligands are known to migrate down the profile and precipitate in the spodic horizon of podzolic soils (Mohr et al., 1972). Complexes with $Al^{3+}$ ions are less toxic, and do not interfere with proliferation of plant roots (Sumner and Yamada, 2002), and healthy plant growth in otherwise acid soils. High organic matter results in increased microbial activity and production of $NH_4^+$ ions. Ammonium ions displace $K^+$ from wedge zones of decomposing micas to weaker adsorption sites where it is easily available to crops (Rao et al., 1997).

Low organic matter content results in dispersion of clay particles on impact of rain- drops, which seal the soil pores and lowers infiltration rates. Dispersed clay may lead to excessive runoff, soil erosion and poor availability of water to crops (Sumner and Yamada, 2002). Liming of such soils does not improve the physical status. Instead, liming results in increased negative charges (pH-dependent charges), icreased repulsion of particles, and further dispersion of clay (see Coulomb's law).

Micro-organisms increase nutrient availability by directly solubilizing minerals, increasing mobility of trace elements through formation of complexes and chelates, or providing a sink for ions in solution through absorption for their own nutrition plant (Harley and Gilkes, 2000). Mycorrhizal fungi increase the volume of soil explored by plant roots. Mycorrhizal hyphae explore pores in crystals of feldspars, secrete exudates including acids, which digest the minerals and transport nutrients directly to the host plant (Harley and Gilkes, 2000). Minerals tend to dissolve faster as temperature increases due to activation energy considerations.

# CHAPTER 3: MATERIALS AND METHODS

## 3.1: Mapping and characterization of areas with emerging K deficiency

### *3.1.1: Mapping*

Soil K status was modeled by the universal soil forming equation, given by H. Jenny in 1941, and quoted by Ahn (1970) and Amerijckx (1985):

$Ks = f(Cl), PM, Rel, Veg, Ti. Man, \ldots$ Equation 1

Where *Ks* = K status in soils, *Cl* = environmental climate, *PM* = parent material, *Rel* = relief, *Veg*= natural vegetation, *Ti* = absolute period of soil formation, *Man* = man's activities and the dots, (….), imply additional unspecified factors. The *(Cl*), in brackets indicates that, if other independent variables were to be constant, K status would vary with climate, to form a *climo-sequence* (Amerijckx, 1985). Of course, such situations seldom exist (Amerijckx, 1985).

Important climatic parameters are temperature and precipitation, which have been used to map agro-ecological zones (AEZs) in Kenya (Jaetzold and Schmidt, 1982). Temperatures fall with increase in elevation, and, thereby, define temperature belts. Precipitation exerts its effects through the moisture availability index, *r/Eo* where *r* = average annual precipitation and *Eo* = average annual potential evaporation. The *Eo* is a function of temperature, and, therefore, decreases with rise in elevation. All the three: rainfall, temperature and relief, influence the type of natural vegetation. Relief and natural vegetation variables in equation 1 are, therefore, factored in the *r/Eo* variable. Time, a geological parameter, is closely linked to the *PM*. Equation 1 was, simplified thus:

$Ks = f\,(r/Eo), PM, hu\text{--------}.\,,$ Equation 2

Potassium status in soils would, therefore, vary with the moisture availability index (*r/Eo)*, parent materials *(PM)* and human factors *(hu)*. This agrees with Issaka *et al.* (1996) who singled out climate, geology and anthropogenic factors as major contributors to soil characteristics. The variables *r/Eo* and *PM* form part of the climatic and edaphic databases respectively for Kenya in the Almanac Characterization Tool (ACT) (Corbett *et al.*, 1999). Humid and sub-humid areas, which are characterized by *r/Eo* values > 0.75 (FURP, 1987), in Fig. 2 were considered to have K deficiency and mapped by the database in ACT (Corbett *et al.*, 1999). Databases for administrative divisions, *r/Eo* and underlying geology (details shown later), were accessed using the access and query commands. Each map layer from ACT was then exported to Archview GIS (ESRI, 1999), as different data layers, for merging and map printout.

### *3.1.2 Administrative coverage of mapped area*

The areas mapped in Fig 2 are located in Western and Nyanza provinces, parts of the Rift Valley province, and Central, Eastern and Coast provinces of Kenya, and the districts within these provinces are shown in Table 1.

Table 1: Districts in Kenya with a potential for potassium deficiency

| Province | Districts |
|---|---|
| Western: | Bungoma, Busia, Vihiga, Kakamega |
| Nyanza: | Siaya, Homabay, Kisumu, Nyamira and Kisii |
| Rift Valley: | Nandi, Kericho, Bomet and parts of Baringo, Uasin Gishu and Trans Nzoia |
| Central: | Parts of Nyandarua, Kiambu, Muranga, Nyeri and Kirinyaga |
| Eastern: | Parts of Embu and Meru |
| Coast: | Kwale, Taita Taveta |

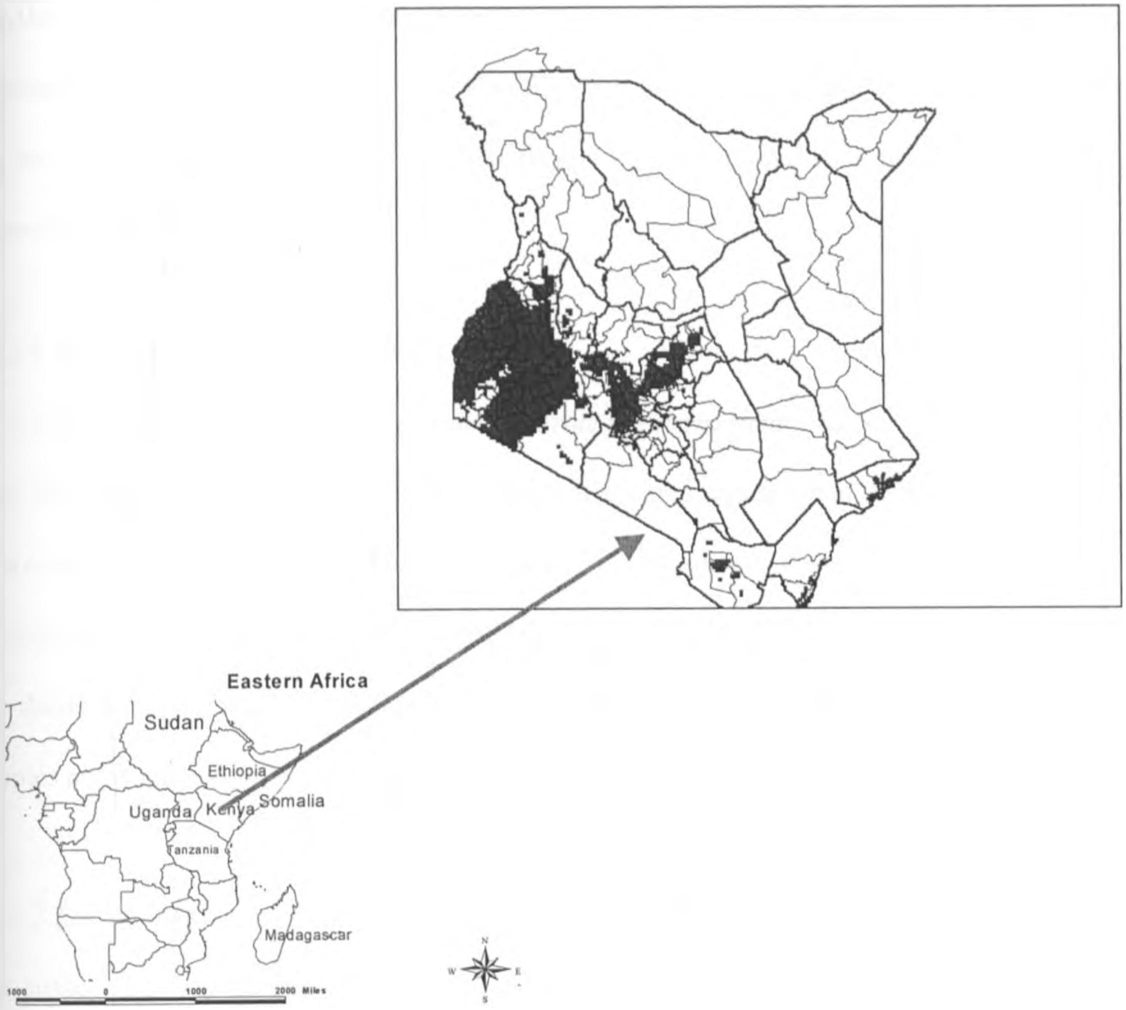

Fig 2: A GIS – based map of Kenya showing areas (shaded) with moisture availability index (*r/Eo*) values > 0.75 that are considered to have a higher likelihood of potassium deficiency

The districts are clustered in Lake Victoria Basin to the west of the country, slopes of Mt. Kenya and the Aberdare Range in central Kenya, and a few regions at the Coast. The mapped area falls in what is referred to as "high and medium rainfall area" of Kenya, where intensive cash and food cropping has been taking place for decades. It covers about 13 % of the total land area in the country, or approximately 7.5 million hectares.

### *3.1.3 Characterization of mapped areas*

#### *3.1.3.1 Selection of study area and data taking strategies in the field*

From the mapped region (Fig 2), a representative study area was selected to the west of the country, where an emerging K deficiency had been reported (Kanyanjua & Buresh, 1999). In the study area, (i) information from farmers and stakeholders, and secondary data relevant to the hypothesis tested in this thesis were collected and collated, and (ii) experimental sites were selected, from which soil samples and hand specimens of rocks were collected for laboratory analysis.

#### *3.1.3.2 Location of study area*

The study area was located in western Kenya, to the west of the Great Rift Valley (GRV); a geological feature formed during the last 30 million years (Nyamweru, 1980), and running in a North – South direction along the longitude 35° 30' E. The area also extends to the north and south of the equator, to about 1° 10' N and 1° 10' S respectively (Fig 2).

#### *3.1.3.3Climate and natural vegetation*

Average annual precipitation (*r)* ranges from 1000 – 1700 mm year$^{-1}$, and increases with elevation (Corbett *et al.,* 1999). Highest rainfall occurs around Mt Elgon in Bungoma district, to the north; districts neighboring the Western Wall of the Great Rift Valley (GRV) in the east, that include

Nandi and Kericho; and districts in the Kisii highlands, to the south, that include Gucha, Kisii and Nyamira. Around the lake, rainfall averages about 1000 mm year$^{-1}$. Mean maximum temperatures range from about 18 - 30 ° C and decrease with altitude, while *Eo* values range from 1300 –1600 mm (Corbett *et al.,* 1999). Natural vegetation types include grasslands, bushy- grasslands, bush land and forests (Corbett *et al.,* 1999). The high rainfall and temperatures in mapped region favours a high turnover of biomass and a high rate of rock weathering (Tisdale & Nelson, 1975).

#### *3.1.3.4 Parent materials, relief and soils*

The geology consists of igneous rocks of intrusive (granites) and extrusive (basalts, rhyolites and trachytes) origin (Corbett *et al.,* 1999), that differ widely in age (Nyamweru, 1980). To the east are volcanic rocks of various ages that were formed during the time of formation of the Grteat Rift Valley (GRV). Soils developed from volcanic rocks are younger, in line with the age of the parent volcanic material. They are more fertile but dependent on the chemical composition of parent magma (Nyamweru, 1980). To the west are older basement rocks, perhaps of Tertiary times (Nyamweru, 1980; Corbett *et al.,* 1999). The soils are poorer, classified in Udox and Udult suborders (Corbett *et al.,* 1999), of Pleistocene or earlier. Oxisols and Ultisols are the predominant soils of humid tropics (Vilela & Ritchey, 1985). The great diversity in type and age of parent materials may have a big impact on the ease and extent of weathering of parent rocks, and amount of K released for plant uptake in western Kenya (Harley and Gilkes, 2000; Haby *et al.,* 1990).

Elevation ranges from 1160 m above sea level (asl) around Lake Victoria to 2800 m asl around the foot slopes of Mt. Elgon in Bungoma, 1800 m asl in parts of Kisii and 2700 m asl in Kericho (Corbett *et al.,* 1999), (Fig 3). Major rivers, with their source in Mau Escarpment to the east, have cut deep valleys and steep slopes on their way, westwards, to Lake Victoria (Nyamweru, 1980).

The common land forms are uplands, but minor bottomlands, valleys, plateaus, hills and piedmont plains occur, due to the influence of rivers. Due to magma pile up and the characteristic "rise to the rift" in a west – east direction (Nyamweru, 1980), volcanic soils to the east are in higher elevations than the rest of the region.

The difference in elevation, and resultant differences in moisture availability index (*r/Eo*), may result in equally wide range in soil properties, and perhaps K status in soils (Amerijckx, 1985; Ahn, 1970). Some workers (Gachene, 1986; Khan & Fenton, 1996); reported appreciable losses of plant nutrients including K through surface runoff and soil erosion, from cropped regions with similar variations in relief. Excess rainwater also results in some of it percolating down the profile under the influence of gravity. Results by Shepherd *et al.* (2001), showed that as water percolates down the profile, it leaches the cations and anions released by weathering and mineralization of organic residues, beyond reach of shallow rooted crops. Davis *et al.* (1996), found higher leaching in sand and loam sandy textures but low leaching in fine textured soils.

The severity of surface runoff as a nutrient loss pathway is dependent upon many factors that include: amount of rainfall and intensity, amount and type of vegetation cover, slope, and soil texture (Loes and Ogaard, 2003). Fine soil may loose the immunity to leaching losses, due to macro- aggregation, as found in acid tropical soils dominated by kaolinite, sesquioxides and organic matter (Shepherd *et al.*, 2001). Such soils may hold a lot of water due to the high clay content, but remain highly porous and fast draining, due to the macro-pores (Shepherd *et al.*, 2001). Excessive loss of nutrients from surface soils through leaching interferes with microbial nutrition at surface horizons of soils, slows down the mineralization process, and leads to accumulation of intermediary decomposition products as organic C in soils (Mohr et al., 1972).

### 3.1.3.5 *Human activities*

The area has high population densities, ranging from 100 – 200 persons km $^{-2}$ (Niang *et al.*, 1998). Farm sizes have dwindled over the last 30 years due to subdivision, with majority of farms at the moment ranging between 0.5 – 2.0 ha (Jama *et al.*, 1997). There was wide variation in eating habits of the inhabitants in western Kenya, and type of farming methods used. Majority of farmers used a hand hoe to till their land, while some used oxen, where topography is ideal. Common soil conservation structures were terraces, grass- strips, trash- lines or stone- lines, which differ remarkably in their effects on control of soil erosion and surface runoff. Scarcity of conservation materials and necessary tillage tools was a common problem. A number of farms were poorly tilled and conserved, leading to soil erosion, excessive runoff, and perhaps severe nutrient losses, as reported by other workers in similar environments (Khan & Fenton, 1996; Gachene, 1986).

Tea (*Cammellia sinensis*), coffee (*Coffea sp.*) and pyrethrum (*Crysenthemum cinerariaefolium*), were common cash crops in cooler areas, and sugarcane in the warmer, lower regions; which form the western Kenya sugar belt. The mid-altitudes were reserved for food crops such as maize (*Zea mays*); the staple food, as well as vegetable (cabbages, kales, other traditional vegetables) and pulse (beans, peas) crops. The land has been farmed for a long time with very low or no external inputs, due to widespread poverty (Jama *et al.*, 1997). The available land has been cropped continuously, to meet the food demand for the people and their livestock. The number of farm animals was small, mainly shoats and cows, and some indigenous birds. It was a common feature to see cows and shoats tethered outside homesteads and fed through the cut- and – carry system of Napier grass (*Pennisetum purpureum*), and other crop residues. The farm animals did not provide sufficient manure (Recke *et al.*, 1997); yet consumed most of the crop residues as feeds, which would otherwise be recycled. In some cases, residues were used as fuel (Jama *et al.*, 1997; Nandwa and Bekunda, 1998).

Crops grown in the area, therefore, have different root/shoot ratios and K uptake kinetics, as reported by Meyer and Jungk (1993). Crops of the grass family with fibrous root systems deplete the soils more (Grimme, 1979), while deep-rooted crops exploit larger soil volume than shallow-rooted crops. For any crop variety, higher population densities remove more K per unit area than thinly planted plant populations, while high yielding varieties have a higher demand for K than traditional, low yielding cultivars (Okalebo, 1979). Extent of depletion may, therefore, depend on the intensification of cropping and extent to which the soils have been exploited. Western Kenya enjoys two cropping seasons in a year, and has potentially high nutrient mining, particularly when no external inputs are applied (Stoorvogel *et al.*, 1993).

Use of crop residues for feeding livestock and a source of fuel has denied the land much needed recycling of nutrients, a practice recommended by some workers (Okalebo, 1979; Kaboneka and Sobbe, 1995). Potassium occurs in high concentration in above ground plant tissues (Tisdale and Nelson, 1975; Okalebo, 1979), and is easily released during residue decomposition (Kaboneka and Sobbe, 1995). There were reports of some use of N and P fertilizers, but use of K fertilizers in food crops was rare. Sole application of N and P fertilizers without K may accelerate the rate of depletion of K and other nutrients in soils (Anderson, 1973). Imbalanced fertilizer programs employed by farmers may help to explain the reasons behind reduced impact of N and P fertilizers in successive croppings (ICRAF, 1995), and emergence of deficiencies of nutrients like K, not applied through fertilizers (Kemmler and Hobt, 1986). In cases where nutrient outputs are greater than nutrient inputs, the result is a negative nutrient balance, and a deficit of the nutrients in question, as reported by Loes and Ogaard (2003).

There was ample evidence to show that pressure on land reserved for food crops was real and intense, and emergence of K deficiency in such agro- ecological systems should not be surprising. As reported by Jama *et al.* (1997), there is limited use of industrial fertilizers in many regions of tropical Africa. The same workers found that lack of cash was the reason for not using mineral fertilizers, forcing many farmers to rely on alternative sources of nutrients like farmyard manure and composts. In western Kenya, some K fertilizers were applied in cash crops like coffee and tea, where K forms part of the fertilizer formulation of specific crops, usually sourced and distributed by cooperative societies through a check-off system. Human activities may, therefore, influence the K status in soils through: (i) efficiency of soil conservation measures employed, (ii) choice of type and intensification levels of crops grown, (iii) the amount of N and P, and organic fertilizers used, and (iv), crop residue management. No efforts were made to collect data related to any of these activities.

### *3.1.4 Selection of study sites*

Six study sites were selected in groups of three, from each of two geomorphic areas (Fig 3). The southern geomorphic area (SGA) is on volcanic rocks (Corbett *et al.,* 1999), and located in Kisii highlands, to the south-east of lake Victoria, while northern geomorphic area (NGA), is to the north of Lake Victoria, on basement rocks (Corbett *et al.,* 1999). Sites were selected on contrasting parent materials, to provide variation in mineralogy, geo-chemical properties and age of rocks, all of which may influence soil properties and K status in overlying soils differently.

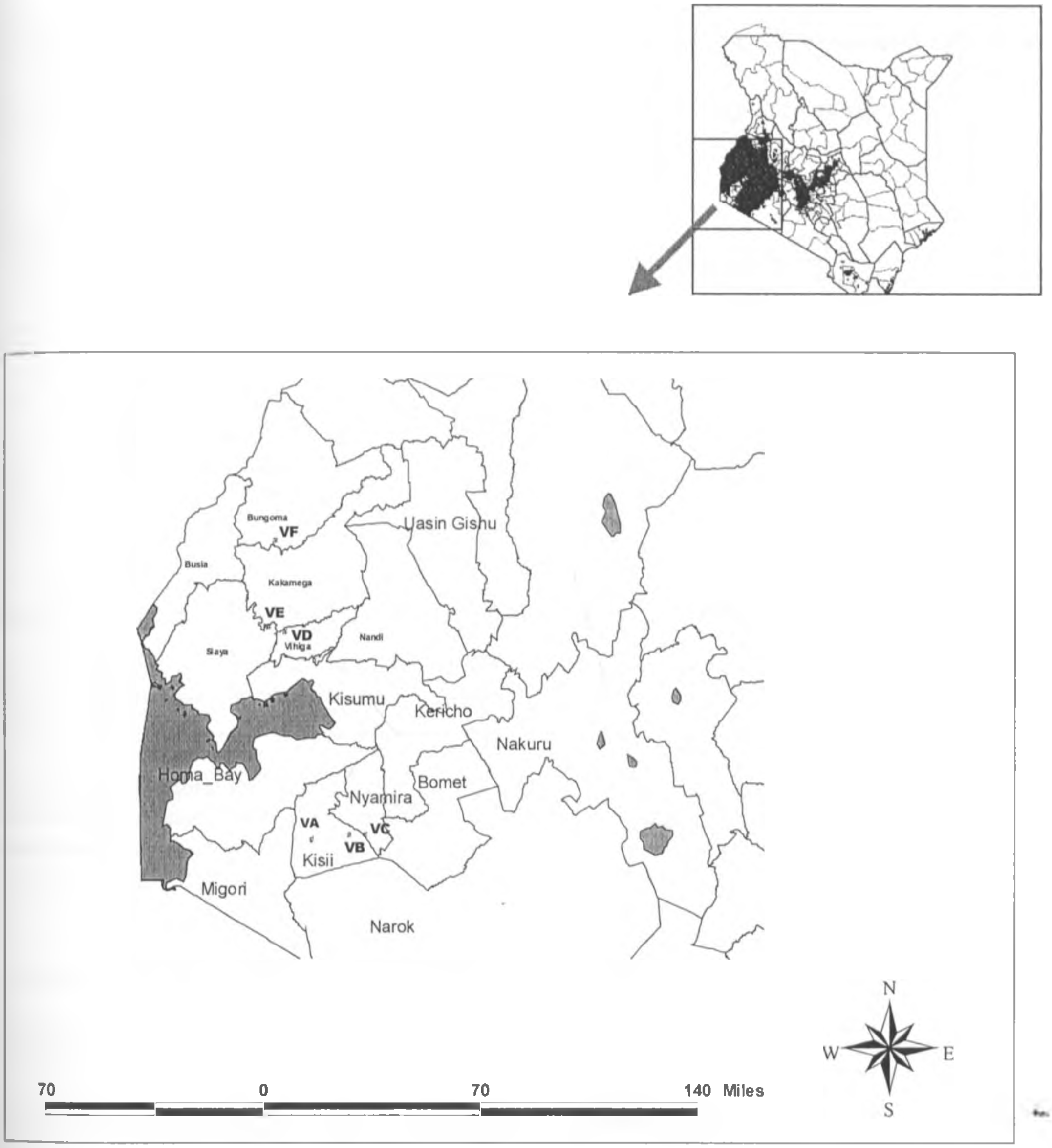

**Fig 3: Location of study sites in western Kenya**
VA = Itare, VB = Keumbu, VC =Ndanai, VD = Ebukanga, VE = Yala and VF = Kabula. (Exact location shown in red balls), Irregular lines marking the district boundaries, Blue shadings represent the lakes

Location and other important characteristics are shown in Table 2. Global Positioning System (GPS) was used to take coordinates and altitude data (Table 2), during site characterization. In all these study sites, no K fertilizers had been applied since opening the land from natural fallow, while soils that had received manures within two years to the date of sampling were avoided.

Table 2: Location and selected agro-climatic characteristics of study sites

| Site | District | Location[1] | MAI[2] (r/Eo) | Land form, Slope | Alt[3] (masl) | Parent rock[4] | Soil Classification[5] |
|---|---|---|---|---|---|---|---|
| | | | Southern geomorphic area (SGA) | | | | |
| Itare | Gucha | 0° 49′ S 34°43′ E | 0.928 | Upland, 12% | 1617 | Basalt | Typic Paleudoll |
| Keumbu | Kisii | 0° 48′ S 34°54′ E | 1.312 | Upland, 13% | 1986 | Trachyte | Typic Palehumult |
| Ndanai | Nyamira | 0° 48′ S 34°58′ E | 1.293 | Upland, 19% | 1930 | Rhyolite | Ultic Paleudoll |
| | | | Northern geomorphic area (NGA) | | | | |
| Ebukanga | Vihiga | 0° 05′ N 34°36′ E | 1.066 | Upland, 16% | 1440 | Granite | Haplohumic Eutrorthox |
| Yala | Siaya | 0° 07′ N 34°31′ E | 1.039 | Upland, 04% | 1439 | Rhyolite | Typic Rhodudalf |
| Kabula | Bungoma | 0° 29′ N 34°33′ E | 0.908 | Upland, 03% | 1373 | Granite | Plinthaquic Tropudult |

[1] Location, south (S), north (N), east (E), [2] MAI = moisture availability index, expressed as the ratio, average annual precipitation (r) / average annual potential evaporation ($E_o$), [3] Alt = altitude in meters above sea level (masl). Data on MAI and Landform obtained from Corbett *et al.* (1999), [4] Rock naming and characterization done at the Department of Mines and Geology, Kenya. [5] Soil classification by FURP (1987), after Soil Survey Staff (1975).

Among the sites in southern geomorphic area (SGA), i.e Itare, Keumbu and Ndanai, Itare soils developed on basalts are farthest from the great rift valley (GRV), lower in elevation and in a drier climate (Table 2). The sites in SGA, on volcanic outflows, have been cultivated for a relatively shorter period since clearance from natural fallow. On average, sites in northern geomorphic area (NGA), i.e. Ebukanga, Yala and Kabula; are at a lower elevation and drier climate than sites in the SGA. Within the NGA, the site in Kabula is more to the north, lower in elevation and in a drier environment than other sites (Table 2).

When compared to SGA, the NGA has been under a crop for a much longer period. The grouping of study sites in NGA and SGA was meant to capture differences that may arise in K supply of soils, as a result of differences in age of parent rocks, weathering environment, and period since the area was put under cultivation. The two geomorphic areas are, therefore, located in very contrasting environments and their influence on K status in soils may feature significantly after analysis.

### *3.1.5 Soil sampling from farmers' fields*

Soil samples were collected from farmers' fields in five of the six sites selected, where field experiments were later conducted. Two sites (Itare and Keumbu) were in the SGA and three (Ebukanga, Yala and Kabula), in the NGA. The site at Ndanai in SGA was left out, because it is a predominantly tea growing area, and food crops were considered of minor importance there. From each of the five sites, a cluster of about 25 farms was selected. Representative surface (0 – 25 cm) samples were collected by augering, and taken to the laboratory for analysis. Study sites were referred to as clusters, in recognition of the number of participating farmers living together, and their common interests. The large number of farms involved was meant to take care of differences that may arise in management among the farmers.

### *3.1.6 Analysis of rock and soil samples*

#### *3.1.6.1 Rock samples*

Samples of rock outcrops, representing the parent rocks in Table 2, were analyzed at the Department of Mines and Geology, Kenya, for mineralogy and geo-chemical composition. The relative mineral composition was estimated on thin sections, under a petrographic microscope, before putting minerals in the wider mafic (ferromagnesian silicates and trioctahedral micas), and felsic groups (feldspars, muscovite, quartz) (De'Conninck, 1987). Results were expressed as mafic – to – felsic mineral ratios.

Geochemical analysis was done by grinding the rock samples and sieving through a No. 100 (150 μ–size) mesh. A weighed sample was then digested with Aqua regia ($HNO_3$ + HCl, ratio, 1: 3) + HF, and kept overnight before adding boric acid (Sridhar and Jackson, 1974). Mineral cations were then read in Atomic Absorption Spectrophotometer (AAS), against certified geologically- referenced standards expressed in percent oxides. The geo-chemical data of rocks was then used to calculate molecular values of metal oxides, as was done by Niggli in 1923 (Mohr *et al.*, 1972), and grouped under *si* for $SiO_2$, *al* for $Al_2O_3$, *fm* for ($FeO + Fe_2O_3 + MnO + MgO$), *ca* for CaO and *alk* for the alkalies ($Na_2O + K_2O$). Free silica (*qz*) was calculated from *si-*, combined silica (*si'*) and *alk*-values, using formulae after Mohr *et al.* (1972), thus:

$$si' = 100 + 4\,alk;\ and\ qz = si - si'$$

### *3.1.6.2 Detailed soil sampling and analysis*

Four replicates of pits were dug to about 200 cm, in each of the six sites. The pits were assumed to overlay the corresponding rock types in Table 2. The replicates were widely distributed in the site to cover as much as possible of the soil associated with a targeted parent rock. In each pit, soil samples were collected at 30 cm intervals from the surface to a depth of 180 cm, and packed separately for laboratory analysis. A second surface soil sample was dug from each of the six sites (Table 2), on a particular spot measuring 1x 2 sq meters, to a depth of 20 cm and placed in gunny bags for greenhouse experiments. If the soil from one spot was not enough, a second spot was marked and sampled, and the two samples mixed in the bag. Due to the variation in topography, some of the pits were dug from low- lying grounds and possibilities of surface contamination with deposits from higher ground could not be ruled out. The Kabula pit had features of seasonally restricted drainage and plinthite in subsurface layers (Table 2).

### *3.1.6.3 General laboratory procedures*

#### *3.1.6.3.1 Sample preparation before analysis*

Soil samples were oven dried at 40° C, and ground gently by hand in a mortar to pass through a 2-mm sieve. Samples for organic carbon determination, were ground further to pass through 0.5- mm sieve.

#### *3.1.6.3.2 Particle size analysis*

Particle size analysis was determined by the hydrometer method (Bouyoucos, 1962). The < 2mm sample was dispersed with water and sodium hexametaphosphate (calgon) and shaken overnight (Hinga *et al.,* 1980), followed by sedimentation in 1L measuring cylinder, and emersion of a hydrometer. Particle size ranges used were sand (2mm-50 μm), silt (50– 2 μm) and clay (< 2 μm).

#### *3.1.6.3.3 pH, organic carbon, and extractable P*

Soil pH was measured in a digital pH meter after immersion of a glass electrode in a 1:2.5 soil/ solution ratio (Hinga *et al.,* 1980). Soil organic carbon was determined on the 0.5 mm sieved soil samples, by the Walkley & Black (1934) method, with modifications given by Nelson & Sommers (1982). Extractable P was determined by the double acid: 0.1 N HCl + 0.025 N $H_2SO_4$ (Mehlich, 1953) method.

#### *3.1.6.3.4 Cation exchange capacity (CEC)*

##### *(i) Total exchangeable bases (TEB)*

Cation exchange capacity (CEC) was determined by summation of Total Exchangeable Bases (TEB), and Total Exchangeable Acidity (TEA); described as Effective Cation Exchangeable Capacity (ECEC), by Rhoades (1982), and Kamprath (1984). Two grams (2g) of the oven - dry sample were saturated with $NH_4^+$ from two successive aliquots of 25mL, 1 N $NH_4OAc$- pH 7, shaking for 30 min and centrifuging for 10 min at 2000 rpm. The supernatant was collected in a 50mL volumetric flask and made to volume with neutral 1 N $NH_4OAc$. Concentration of $K^+$ was determined by Flame Emission Spectrophotometer (FES), while $Ca^{2+}$ and $Mg^{2+}$ were determined in the Atomic Absorption Spectrophotometer (AAS). Interpretation of results for the exchangeable cations ($Ca^{2+}$, $Mg^{2+}$ and $K^+$), extracted by $NH_4OAc$ $pH_7$ followed the Soil Test Interpretation Guidelines published by Oregon State University Extension service (Marx *et al.,* 1999). The total amount of $Ca^{2+}$, $Mg^{2+}$, and $K^+$ in cmol ($p^+$) $kg^{-1}$ was expressed as TEB (Kamprath, 1984).

##### *(ii) Total exchangeable acidity (TEA)*

Total exchangeable acidity was determined by displacement of the exchangeable acidity with 1 M KCl, followed by titration with 0.01 M NaOH as described by Cottenie (1980). Five grams of soil were weighed into 100 mL Erlenmeyer flask, into which 40 mL 1M KCl was added and put in a reciprocating shaker for 30 minutes. After sedimentation was complete, the clear supernatant was filtered into a 100 mL volumetric flask. Another 20 mL of 1M KCl was added to the sample in Erlenmeyer flask, shaken manually and allowed to equilibrate for 10 minutes, before filtering into the same 100 mL volumetric flask. The treatment with 20 mL 1M KCl was repeated up to three times and final extract made to the 100 mL mark with 1M KCl. To determine the H and Al concentration (TEA), 50 mLs of the extract was put in a 100 mL beaker and titrated with 0.01 M

NaOH to a permanent pink end point with phenolphthalein indicator. Cation exchange capacity (CEC), and base saturation were calculated from the formulae

CEC = TEB + TEA (cmol $(p^+)$ $kg^{-1}$)

BS = TEB/CEC*100 (%)

### *3.1.6.3.5 Soil mineralogy*

Soil mineralogy studies were done on the four replicates of soil samples collected from surface horizons (0 – 20 cm) only. Analysis was done separately in the sand and clay fractions following recommendations given by Stoops (1987). Pseudo particles were destroyed (dispersed) by removal of organic matter with 30 % $H_2O_2$ and iron (hydro) oxides by the dithionite –citrate ($Na_2S_2O_4$ + $Na_3C_6H_5O_7$ .2 $H_2O$) method (SCS, 1972). Calcium carbonate was not considered a serious cementing agent because the soils had an acid reaction. Particle size fractions in the organic matter- and iron- free samples were separated by the usual sedimentation and sieving procedures (Mackenzie, 1956). Sand fraction was separated by wet sieving the sample through a 300-size (53 µ)- mesh sieve and collecting of clay and silt in the cylinder. Clay was pipetted out after silt had settled, seven hours after disturbance (USDA, 1992).

The sand and clay samples were oven-dried and analysed at the Department of Mines and Geology (DMG), Kenya, for total elemental analysis by Aqua regia ($HNO_3$ + HCl, ratio, 1: 3) + HF method (Sridhar and Jackson, 1974). Chemical data was used to perform the normative classification of the mineral suite, using the protocol of Cross, Iddings, Pirsson and Washington (CIPW) norms (Zehetners *et al.*, 2003, Marechal *et al.,* 1983). In calculations, it was assumed that primary minerals in parent rocks weathered along the scheme shown in Fig 4. Upon rock decomposition, the alkaline and alkaline earth metals were assumed to have completely leached (Mohr *et al.*, 1972, Aide and Smith-Aide, 2003), such that their occurrence in the clay fraction must be in the crystal lattice of calculated minerals.

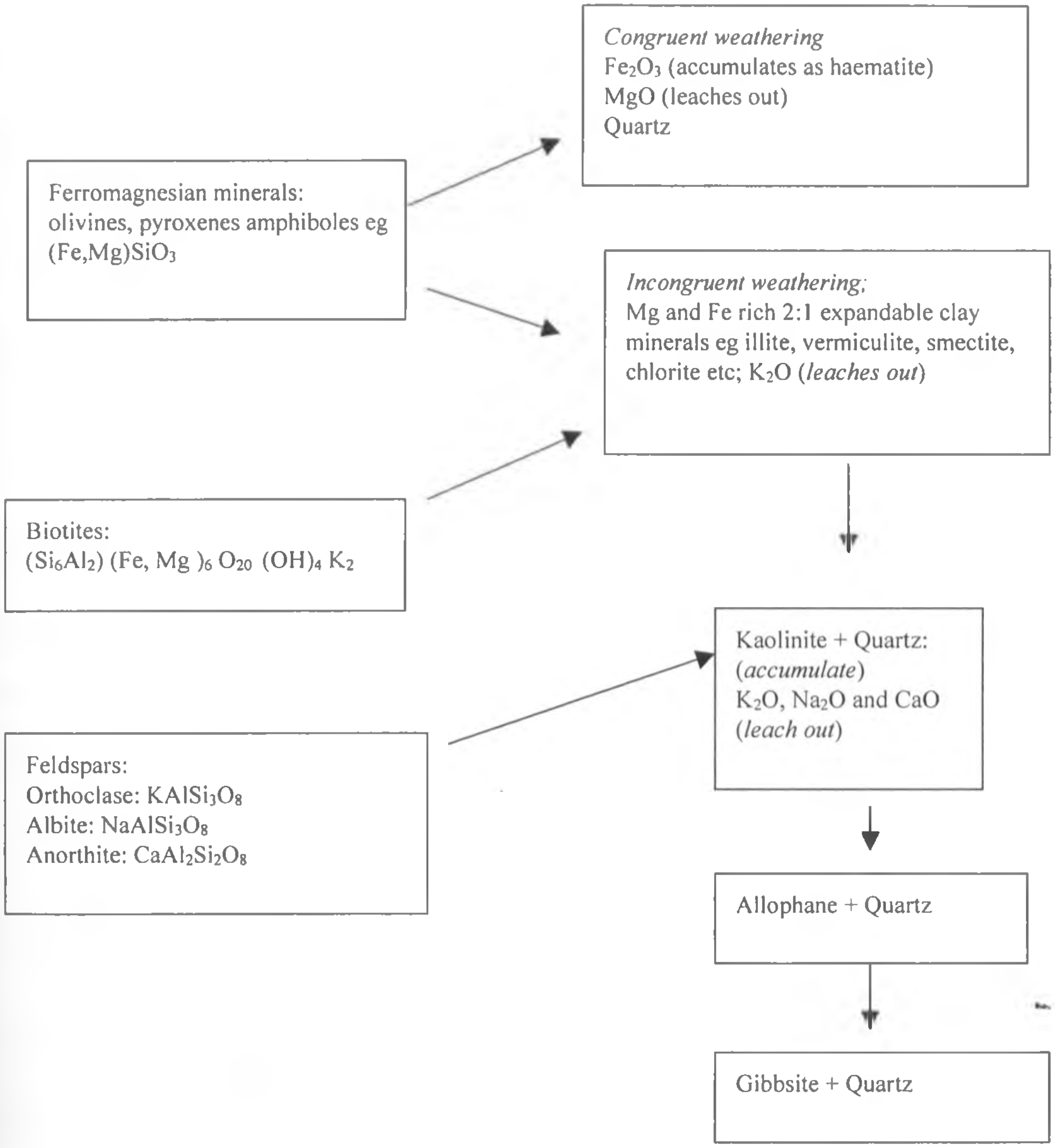

Fig 4: Schematic representation of the weathering pathways for primary silicate minerals. Adopted from Harley and Gilkes (2000)

In this regard; K, Ca, Na, Mn and Mg, may only exist in the tri-octahedral micas (illites), either due to isomorphic substitution, or after entrapment between phyllosilicate layers, as the mica weathers to illite and other 2:1 minerals (De'Conninck, 1987).

Iron can be found in biotite or as free haematite, while Al combines with Si to form kaolinite, or allophanes, depending on extent of leaching of $SiO_2$. Both Al and Si may exist as free gibbsite or $SiO_2$ (amorphous opal or chalsedony), respectively. Limits were set by the extent to which metal oxide ratios are able to satisfy the structural formulae in turn (Marechal *et al.,* 1983); starting with the least stable (first to crystalize from magma), as shown in the Bowens reaction series (Fig 1). Primary minerals in sand fraction were recalculated to 100%.

#### *3.1.6.3.6 Distribution of K in various pools and K availability to maize*

#### *(i) Solution K*

Solution K was determined in a 1: 2 soil: water ratio (Sonnevelt and Van den Ende, 1971). Twenty grams (20g) of air- dry soil were weighed into a shaking bottle and 40 mL of distilled water added, stoppered and placed in a reciprocating shaker for 1 hr. The residue was filtered using Whatman filter paper No. 44 of slow filter speed and fine crystalline retention. When the filtrate was turbid, a repeat filtration was done. The concentration of Ca and Mg was determined in the AAS and K in a flame photometer. Potassium activity ratio ($AR_K$) was calculated by the equation after Greenwood and Karpinets (1997), with modifications after Verloo (1990). Important equations used in the calculations were:

(i) $AR_K = (K)/\{(Ca) + (Mg)\}^{0.5}$

(ii) $a = c.\ f$

(iii) $\text{Log } f = -\ 0.5\ n^2\ (\mu)^{0.5}$

(iv) $\mu = 0.5.\ \Sigma\ c\ n^2$

Where $AR_K$ = potassium activity ratio and (K), (Ca) and (Mg) respective activities. The individual activity (a) for the cations was calculated as the product of corresponding concentration (c) and activity coefficient (f). Activity coefficient (f) for each cation was estimated by the Debye-Huckel equation (equation iii), where n = valency of cation, and $\mu$= ionic strength of the solution. Ionic strength was calculated from the Ca, Mg and K concentrations and cation valency (equation iv).

*(ii) Exchangeable K*

Exchangeable K was extracted as one the exchangeable bases in 1 N $NH_4OAc$- pH 7 during CEC determination, as described in *3.1.3.4,* above.

*(iii)Non- exchangeable K*

Non-exchangeable K was determined by boiling $HNO_3$ (Knudsen and Peterson, 1982, Loes and Ogaard, 2003). Two and a half grams (2.5 g) of finely ground soil were put in a 125-mL Erlenmeyer flask. Twenty- five (25) mL of 1 M $HNO_3$ were added and placed under a gas burner. When boiling started, the flame was reduced and gentle boiling continued for 10 min. The flask was then removed and the contents filtered into a 100-mL volumetric flask. The soil was washed with four 15-mL portions of 0.1 M $HNO_3$. The solution was then cooled diluted to volume with $HNO_3$ and mixed thoroughly. Potassium concentration was determined by a flame photometer using K standards made in the same $HNO_3$ concentration as in the samples. Non-exchangeable K was determined by the formula after Horra *et al.* (2000):

*Non-exchangeable K = 0.1 M* $HNO_3$*-K – exchangeable K (NH4OAc- K)*

*(iv) Total K*

Total K was determined at the Department of Mines and Geology by digestion with Aqua regia ($HNO_3$ + HCl, ratio, 1: 3) + HF, and kept overnight before adding boric acid (Sridhar and Jackson, 1974). Potassium content in the digest was determined by AAS and expressed in cmol ($p^+$) $kg^{-1}$.

### 3.2 Greenhouse studies

The K supplying power was investigated by exhaustive cropping and harvesting of maize plants (data to complement results from farmers fields) in a greenhouse at the National Agricultural Research laboratories (NARL). Four and a half kg of 2mm- sieved, dry soil, whose lime requirement had been determined by the method described by Allen *et al.* (1976), were placed in 6-L cylindrical metal pots. The pots were arranged in randomized complete blocks of three replications. Maize, *Zea mays (L.)*, var. H513 plants were grown in soils fertilized with minus-K nutrient combinations at rates given by Allen *et al.* (1976) in successive cycles of eight weeks each. The minus-K macro- and micro- nutrient applications were applied in every cycle but lime was applied at the beginning of the experiment, to lower the pH and correct Ca and Mg deficiencies. Soils were limed with the equivalent of 2.5 Mg $ha^{-1}$ of dolomitic lime prior to initiation of the greenhouse study.

Seven seeds were planted in each pot and seedlings thinned to five after emergence which were allowed to grow to harvesting at eight weeks. During growth, the pots were watered daily with deionized water to about 80% of the field capacity. Other husbandry practices were kept optimal. The above ground biomass was harvested and oven-dried at 70°C for 48 hours; before dry matter and nutrient uptake determinations. Dried plant samples were ground through a 1- mm screen and later digested in conc. Sulfuric acid ($H_2SO_4$) – salicyclic acid – $H_2O_2$ – selenium mixture (Walinga *et al.,* 1989). The digested samples were analyzed for K. Potassium uptake was calculated as the product of the percent concentration of K in the plant tissue and the dry matter yield. About 5 g of soil samples were also collected from the pot at each harvest for analysis. Changes in exchangeable K were determined for correlation with crop uptake.

### 3.3 Field experiments

Field experiments were conducted during the period 2000 – 2002, for at least three seasons in each site. Experiments were conducted in the participatory learning and research (PLAR), approach (Defoer *et al.,* 2000), in which farmers were empowered to manage the trials. Supervisory role was left in the hands of an elected; and initially trained village committee. Extension staff from the Ministry of Agriculture and researchers from KARI worked very closely with the committee members. These interactions were meant to enhance the rate of adoption of superior results as research work progressed.

Participating farmers were selected to represent a geographical area, hereafter referred to as a cluster under the supervision of a committee. The number of participating farmers varied from cluster to cluster, and from season to season, because some of the farmers dropped out before any data could be obtained. In each farm, plots measuring 9m x 30m, were measured, and divided into five sub-plots measuring 9m x 6m ($54m^2$) on to which treatments were applied. All the farmers implemented the same design of five treatments (Table 3).

Nitrogen (N) and phosphate ($P_2O_5$) were applied at 75 kg ha $^{-1}$ each, the rates considered optimal for the soils of these regions (KARI, 1995). Treatments were randomized within the blocks (farms) while farmers formed replicates. Phosphate and K fertilizers were basal applied while N was applied at two levels, 30 kg ha$^{-1}$ at planting and 45 kg ha$^{-1}$ as a side dress when the crop was 30 cm tall. Maize (Hybrid 614) was then planted at a spacing of 0.75m x 0.60m, two plants per hill, and a population density of 44,444 plants ha$^{-1}$. Management practices were left at farm level; and only the yield data was collected at harvest.

Table 3: Treatments employed at the potassium experimental sites

| Plot No | Treatment code | Treatment details[1] |
|---|---|---|
| 1 | Control | No fertilizer |
| 2 | NPK0 | N and $P_2O_5$ at 75 kg ha$^{-1}$of each, respectively, and zero K |
| 3 | NPK25 | As plot 2 + 25 kg K ha$^{-1}$ |
| 4 | NPK50 | As plot 2 + 50 kg K ha$^{-1}$ |
| 5 | NPK75 | As plot 2 + 75 kg K ha$^{-1}$ |

[1] Nitrogen (N) was applied in form of calcium ammonium nitrate, CAN (26-0-0), phosphate ($P_2O_5$) as diammonium phosphate, DAP (18-46-0), and potassium (K) as muriate of potash (KCl) (0-0-60), respectively

## 3.4 Data analysis

All statistical analysis was done using GENSTAT 5 software (Lawes Agricultural Trust, 1996), or in conjunction with the Excel worksheet of Windows 85. Severally, data was organized in Excel, before exporting to GENSTAT for analysis. Statistical significance was determined by Least

Significant Difference, (LSD), at $P \leq 0.05$, unless otherwise stated. Standard errors of the differences of means (s.e.d.) were reported for comparison of treatment means.

### *3.4.1 Laboratory data*

One- way analysis of variance (ANOVA), for soil data was conducted separately for each soil parameter, the variate, and study sites as the treatments, replicated in farms. Where some sites had fewer farmers (replicates), the equalizing number was taken as missing values. Interpretation of data for pH, organic C and extractable P levels was done by laboratory standards set at the National Agricultural Research Laboratories (NARL) (unpublished). Data for extractable bases was interpreted using the standards set by Marx *et al.* (1999), unless otherwise stated. To illustrate the statistical significance, both the probability level (P) and standard errors of the differences of means (s.e.d) were quoted.

From the data of rock analysis, the Ma: Fe ratios (De'Conninck, 1987), and Niggli values (Mohr *et al.,* 1972); were plotted against $SiO_2$ content in rocks to demonstrate the variation of ease of weathering (De'Conninck, 1987, Scott and Smith, 1987), and chemical composition, respectively, in rocks of increasing $SiO_2$. From the CIPW norms of soils, proportionate content of soil minerals in sand and clay fraction of soils were determined. Correlations were done between clay content as an index for extent of weathering (Zahetner *et al.,* 2003), and the Illite/Kaolinite ratio, as an index for possible selective adsorption of K and release of non-exchangeable K (NEK). Interesting relationships between parameters were investigated by regression analysis. Relationship between rock and soil data was investigated by running linear or polynomial regressions, with strength of regressions judged by the regression coefficients and sometimes the probability (P). Relationship between clay and clay mineralogy, and amount of K in various pools was treated in a similar way.

### 3.4.2 *Agronomic data from greenhouse and field experiments*

The data collected from greenhouse were dry matter yields (g/pot) and K concentrations in above-ground tissues of maize plants, for every of the five growth cycles grown in a particular soil type. Potassium uptake was calculated as a product of dry matter yields and K concentrations. For each type of data, results were analysed in a Two-way (growth cycle and soil type), analysis of variance (ANOVA) – of Randomized Complete Blocks.

Only yield data was obtained from field experiments. As in soil data, grain yields were analysed in a one-way ANOVA, separately for each site and season. There were four fertilizer treatments (NPK0, NPK25, NPK50 and NPK75), as shown in Table 3, and replicates equal to the number of participating farmers. Potassium fertilizer effects on maize yields were also analyzed by comparing the treatment without K fertilizer (NPK0 treatment) with the agronomic optimum (Recke *et al.,* 1997). To test the effects of NP and K fertilizers in field experiments, datasets for the unfertilised plots were compared with datasets from fertilized treatments, in a *t*- test for paired samples. Relationships between soil K, soil properties and and maize growth were examined by plotting graphs of all combinations of variables and looking for patterns in the data. Linear regression was used to test the strength of the relationship between soil K and soil properties.

### 3.4.3 *Economic analysis of yield data from field experiments*

Economic evaluation was aimed at assisting the farmer to make decisions on what maize yield level to produce under prevailing economic conditions, and incorporated aspects of costs and returns. The economic optimum was estimated as that level of production where net returns (difference between Total Returns (TR) and Total Costs (TC)), were highest. Returns were the market value of produced grain, while costs involved purchased N-P-K fertilizers, from the local market. Market prices used in the calculation for N, $P_2O_5$ and $K_2O$ nutrients, and maize-grain; were: 80, 60, 50 and 11 Kenya shillings (KES), $kg^{-1}$, respectively (equivalents in US$: 1.067, 0.800, 0.667, 0.147, respectively $kg^{-1}$). Seasonal means for each treatment were used in the calculation.

# CHAPTER 4: RESULTS AND DISCUSSIONS

## 4.1 Soil analysis results for samples from farmers' fields

Physico- chemical data of surface (0- 20 cm) soils, from the five clusters are given in Annex 1, and average values for all the samples collected and analysed from each cluster in Table 4.

Table 4: Particle size distribution and chemical characteristics of soils from farmers' fields[1]

| Soil Parameter[3] | Trial sites[2] | | | | | LSD (P< 0.001) |
|---|---|---|---|---|---|---|
| | Itare | Keumbu | Ebukanga | Yala | Kabula | |
| Sand (%) | $18.2^{a}$ | $25.0^{b}$ | $37.6^{c}$ | $32.8^{c}$ | $68.2^{d}$ | 5.437 |
| Silt (%) | $31.5^{c}$ | $29.8^{c}$ | $18.3^{b}$ | $17.5^{b}$ | $5.2^{a}$ | 4.465 |
| Clay (%) | $50.3^{b}$ | $45.2^{b}$ | $44.1^{b}$ | $49.7^{b}$ | $26.6^{a}$ | 6.820 |
| pH (1:2.5 $_{H2O}$) | $5.9^{c}$ | $5.7^{c}$ | $4.8^{b}$ | $4.5^{a}$ | $4.9^{b}$ | 0.25 |
| Org C, g $kg^{-1}$ | $20.0^{b}$ | $18.2^{b}$ | $11.5^{a}$ | $9.3^{a}$ | $9.3^{a}$ | 2.35 |
| Exch $Ca^{2+}$[cmol ($p^{+}$) $kg^{-1}$] | $8.8^{d}$ | $5.8^{c}$ | $4.5^{b}$ | $4.5^{b}$ | $2.4^{a}$ | 1.240 |
| Exch $Mg^{2+}$[cmol ($p^{+}$) $kg^{-1}$] | $2.5^{d}$ | $1.8^{c}$ | $1.2^{b}$ | $1.4^{b}$ | $0.7^{a}$ | 0.313 |
| Exch $K^{+}$[cmol ($p^{+}$) $kg^{-1}$] | $1.6^{c}$ | $1.1^{b}$ | $0.2^{a}$ | $0.4^{a}$ | $0.3^{a}$ | 0.223 |
| Ca/K | $4.7^{a}$ | $5.0^{a}$ | $28.9^{d}$ | $18.9^{c}$ | $11.2^{b}$ | 6.061 |
| Mg/K | $1.5^{a}$ | $1.7^{a}$ | $7.5^{b}$ | $5.9^{b}$ | $3.1^{a}$ | 1.799 |
| P Meh (mg $kg^{-1}$) | $15.4^{b}$ | $10.4^{ab}$ | $9.5^{ab}$ | $13.0^{b}$ | $6.6^{a}$ | 4.542 |

[1] Values in the table are averages of all the samples from each cluster [2] Superscripts: Same letter = no significant differences ($P \leq 0.05$) between parameter means along the rows [3] Exchangeable cations $Ca^{2+}$, $Mg^{2+}$ and $K^{+}$ extracted using 1N $NH_4OAc$, pH 7.0. Meh = Mehlich (1953) extractant (0.1N HCl + 0.025N $H_2SO_4$)

### 4.1.1 *Textural characteristics of soils*

Surface soils from study sites ranged from clay to sandy clay loams. Sand content increased significantly in the order: Itare < Keumbu < Ebukanga = Yala < Kabula (Table 4). Silt content decreased significantly ($P < 0.001$), in the order: Itare = Keumbu > Ebukanga = Yala > Kabula. Clay content decreased in the order: Itare = Keumbu = Ebukanga = Yala > Kabula. Itare soil was, therefore, the finest and Kabula soil most coarse, with Keumbu, Ebukanga and Yala soils having textural properties, mid-way between the two extremes. In the absence of excessive macro-aggregation, as suggested by Shepherd *et al.* (2001), leaching of $K^{+}$ and other cations, and anions, would be highest in Kabula, lowest in Itare, and moderate in Keumbu, Ebukanga and Yala soils.

Some workers (Sparks, 1987; Davis *et al.*, 1996) reported higher leaching of exchangeable cations in coarse textured soils, which they ascribed to the increased macro- porosity.

### 4.1.2 *Chemical characteristics of soils*

The pH of soils ranged from 4.5 – 5.7 (Table 4), which was strong to moderately acid, according to standards set at the National Agricultural Research Laboratories (NARL). The pH was low, particularly in soils from the northern geomorphic area (NGA). Results are in agreement with the findings by Kamprath (1984), who reported low pH and base status in soils from humid and sub-humid areas of the world, because, according to him, they are highly weathered and leached. Results were also in agreement with the findings from study sites in similar regions and reported by FURP (1987).

Kamprath (1984), singled out the following soils for being acid, as judged by base saturation in sub-surface horizon: (i) the Order of Ultisols; (ii) the Great groups of Inceptisols and Oxisols carrying the prefixes "Dystr" and "Hapl", respectively; (iii) Ultic groups of the Alfisols, and (iv) the "Acr" great groups of the Oxisols. Soils under current study were classified as Typic Palehumult (Keumbu), and Plinthaquic Tropudult (Kabula), and Haplohumic Eutrorthox (Ebukanga) (FURP, 1987), which, therefore, fall in the acidic Ultisol and Oxisol groups. Other soils were classified as Typic Paleudoll (Itare), and Typic Rhodudalf (Yala) (FURP, 1987), and do not, therefore fall in the category of acid soils singled out by Kamprath (1984).

Soil pH decreased significantly ($P < 0.001$), in the order: Itare = Keumbu > Ebukanga = Kabula > Yala, but did not reflect the grouping of acid soils given by Kamprath (1984), perhaps because the pH was determined on the surface soils, as opposed to the sub-surface horizons used by Kamprath

(1984). Keryn *et al.* (2003) reported pH values lower by up to 1.5 units in sub-surface horizons (5 – 15 cm) under a crop than in surface soils, which they attributed to root activity. A drop in pH is greater when form of N taken up by the crop is > 17 % $NH_4^+$ (due to efflux of $H^+$ by roots). Conversely, the pH in rhizosphere may rise if form of N taken up by a crop is > 83 % $NO_3^-$, due to efflux of $OH^-$, $HCO_3^-$ or $RCOO^-$ through the roots (Keryn *et al.*, 2003). Non-legumes have a preference for anion form of N and legumes the cation form (Keryn *et al.*, 2003), implying that legumes are more likely to lower soil pH than non-legumes. The sparingly acid soils from southern geomorphic area (SGA) were unexpected in a region where tea (*Camellia sinensis L.*), a crop adapted to acid soils, is widely grown.

There was a tendency for soil acidity (Table 4), to increase with increase in $SiO_2$ content of parent materials, in the order: basalts < trachytes < granites < rhyolites (Table 1). This was possibly due to higher contents of clay, organic C, and exchangeable cations Ca and Mg in Itare and Keumbu soils, formed from basalts and trachytes respectively, than in the other soils (Table 4). Mohr *et al.* (1972), reported low pH in soil samples sieved to < 2 mm where sand particles were excluded, but much higher values in samples of whole soils, which, according to them was due to a concentration effect in the sieved soil.

Organic rich surface soils, as found in the SGA, have high pH because of organic anion association (mopping up of protons), in soils of moderate pH (pKa values of organic acids are higher than pH of soils), and oxidation by microorganisms (Keryn *et al.*, 2003). Organic anions may also lower the acidity in soils, after complexing with aluminium ions, and therefore, reduce the $H^+$ activity in soil solution (Keryn *et al.*, 2003). The benefit resulting from organic matter may only affect the surface horizons of soils, while sub-surface layers remain acidic. When the organic part of the complex is mineralised, as often happens in sub-surface layers, Al is set loose and soils become acid (Keryn *et al.,* 2003). The $NH_4^+$ formed after mineralization of organic matter, may also result in high acidification in rhizosphere (after nitrification, and due to efflux of $H^+$ during crop uptake), at the same time when low acidity is maintained in surface soils (Keryn *et al.,* 2003). Low pH in soils from the northern geomorphic area (NGA) was, therefore, attributed to a likely occurrence of sub-surface characteristics at the surface, due to low organic matter content (Table 4). Using the same arguments, high pH in soils from the SGA was attributed to the high organic matter content in soils. No efforts were made to monitor the variation of soil pH with depth.

The SGA had significantly ($P< 0.001$), higher organic C content than NGA (Table 4). Organic C levels in the SGA were within the 10 – 20 g $kg^{-1}$ (modarate) range, and in the 5 – 10 g $kg^{-1}$ (low) range in the NGA, according to NARL standards (unpublished). Nizeyimana (1997) attributed the presence of high organic matter in highland soils to the formation of stable complexes of organic matter with Al, Fe and amorphous soil constituents (e.g. allophane), which protect the organic matter from attack by microorganisms.

According to Simpson (1969), basalts and trachytes, as found in SGA, are rich in plagioclase feldspars, and soils developed from them, if strongly weathered and leached may form Al and allophanes. Nizeyimana (1997) also attributed the presence of high organic matter to high biomass production as a result of high rainfall and high fertility levels in soils, and slow mineralization due to low temperatures. Low organic matter content in soils of the NGA was, therefore, attributed to low biomass production (low nutrient status in soils), and high mineralization rates (warm and wet climatic conditions).

High organic matter content in the soils from SGA was attributed to lower mineralization rates due to lower average annual temperatures (Corbett *et al.*, 1999), than in NGA. Organic residues play an important role in K dynamics due to the high K content in above ground tissues (Kaboneka and Sobbe, 1995). On mineralization, organic matter releases much higher amounts of K than Ca and Mg. Soils from the NGA have been under cultivation for a much longer period, and have lost more carbon during the many years of cropping in humid and warm environmental conditions, which agrees with the findings by Tisdale and Nelson (1975) in similar soils across the world.

The relative mineral and organic composition of soils, therefore, has a direct effect on K dynamics in soils. Soils from SGA with high organic C content may release high amounts of K on decomposition. Results from Rao *et al.* (1997) on Indian soils shows that the K in soils from SGA may similarly be held more loosely because of the effects of $NH_4^+$ ions released during mineralization. According to Kamprath (1984), there is reduced $H^+$ and $Al^{3+}$ activity in soils rich in organic matter due to Al complexation with organic ligands and, therefore, healthier root development and enhanced nutrient uptake from such soils. Organic matter improves soil structure leading to improved gaseous, water and nutrient diffusion in soils, and faster crop growth.

Mean exchangeable $Ca^{2+}$ and $Mg^{2+}$ levels decreased significantly ($P < 0.001$), in the order: Itare > Keumbu > Ebukanga = Yala = Kabula (Table 4). According to the neutral $NH_4OAc$- soil test interpretation guidelines (Marx *et al.,* 1999), mean $Ca^{2+}$ levels in the samples were in the 5 – 10 cmol $(p^+)$ $kg^{-1}$ (medium) range in Itare and Keumbu soils, and in the < 5 cmol $(p^+)$ $kg^{-1}$ (low), range in Ebukanga, Yala and Kabula soils. Exchangeable $Mg^{2+}$ levels were in the 0.5 – 1.5 cmol $(p^+)$ $kg^{-1}$ (medium), in Ebukanga, Yala and Kabula soils, and in the > 1.5 cmol $(p^+)$ $kg^{-1}$ (high), range in Itare and Keumbu soils.

There was a tendency for soils to have lower exchangeable Ca and Mg as the parent materials became more silicious (Tables 1 and 4). In addition, the sum ($Ca^{2+}$ + $Mg^{2+}$); was influenced significantly by sand, silt and organic C content, given by equations in Table 5, but effects of % clay and pH were not significant at $P < 0.05$. Results conformed to a decrease in Ca and Mg oxides, and increase in Al oxide as parent rocks become more silicious (Simpson, 1969), suggesting that the exchangeable base content in studied soils was influenced by chemical composition of parent materials.

Table 5: Simple regression equations between the sum (Ca + Mg), (Y), and soil parameters

| Fitted term | Regression equation | $R^2$ | SE | P |
|---|---|---|---|---|
| Sand (%) | Y = 11.78 – 0.1391 % sand | 0.715 | 1.61 | 0.045 |
| Silt (%) | Y = 1.81 + 0.2440 % silt | 0.779 | 1.42 | 0.030 |
| Organic C (g kg $^{-1}$) | Y = - 0. 49 + 0.528 org C | 0.717 | 1.61 | 0.045 |

P = probability level, SE = standard error, Y in cmol (p+) $kg^{-1}$

The positive correlation between exchangeable Ca and Mg, and organic matter was expected and associated with increased CEC. Organic CEC is pH- dependent (soils from SGA have higher pH, Table 4), and has a preference for higher valency, and smaller (non-hydrated) cations (Barber, 1995). The positive correlation with silt was perhaps due to the presence of weatherable Ca and Mg rich primary minerals. Though not significant, exchangeable cations decreased as soil acidity increased. Present results are in agreement with the findings by Kamprath (1984), who found increased $Ca^{2+}$ and $Mg^{2+}$ deficiency in coarse textured soils, due to leaching of the base cations.

Exchangeable $K^+$ levels in soils decreased significantly ($P < 0.001$) in the order: Itare > Keumbu >

Ebukanga = Yala = Kabula (Table 4). According to the $NH_4OAc$- soil test interpretation guidelines by Marx *et al.* (1999), exchangeable K was in the 0.6 – 2.0 cmol ($p^+$) $kg^{-1}$ (high), range, in Itare and Keumbu, and in the < 0.4 cmol ($p^+$) $kg^{-1}$ (low) range, in Ebukanga, Yala and Kabula soils. Studies by Sparks (1987) and Mohr *et al.* (1972), showed high K content with increase in Si of parent materials. In the present study, however, rocks high in silica did not result in soils that are rich in K, suggesting that the K in rocks was either locked up in unavailable form in intermediary products or had been released and lost through leaching.

After running exchangeable K as a response variable in multiple regression, and organic C, sand, silt, clay and pH as fitted terms, no two or more terms fitted significantly ($P< 0.05$) into a model after stepwise regression. Simple regressions were alternatively tested and results are shown in Table 6.

Table 6: Simple regressions of exchangeable K (Y) on selected soil parameters

| Fitted term | Regression equation | $R^2$ | SE | P |
|---|---|---|---|---|
| pH | $Y = -4.06 + 0.927$ pH | 0.815 | 0.261 | 0.023 |
| Organic C (g $kg^{-1}$) | $Y = - 0.818 + 0.1126$ org C | 0.859 | 0.228 | 0.015 |
| (Ca +Mg) | $Y = -0.507 + 0.1826 (Ca + Mg)$ | 0.774 | 0.288 | 0.031 |

P = probability level, SE = standard error

Sand, silt and clay were not significantly correlated with exchangeable K content. Exchangeable K correlated strongly and positively with pH, organic C, and (Ca + Mg) (Table 6), implying lower exchangeable $K^+$ in acid, low organic C containing soils. The results are in conformity with possible release of K from decomposing organic matter (Kaboneka and Sobbe, 1995), and higher K activity due to desorption from interlayers of clay minerals by $NH_4^+$ resulting from organic matter decomposition (Rao *et al.*, 1997). Lack of a significant correlation with clay content is contradictory to the findings by Singh and Agrawal (1995), perhaps because clay content did not vary widely among the soils (Table 4). Fig 5 shows the relative exchangeable cation content.

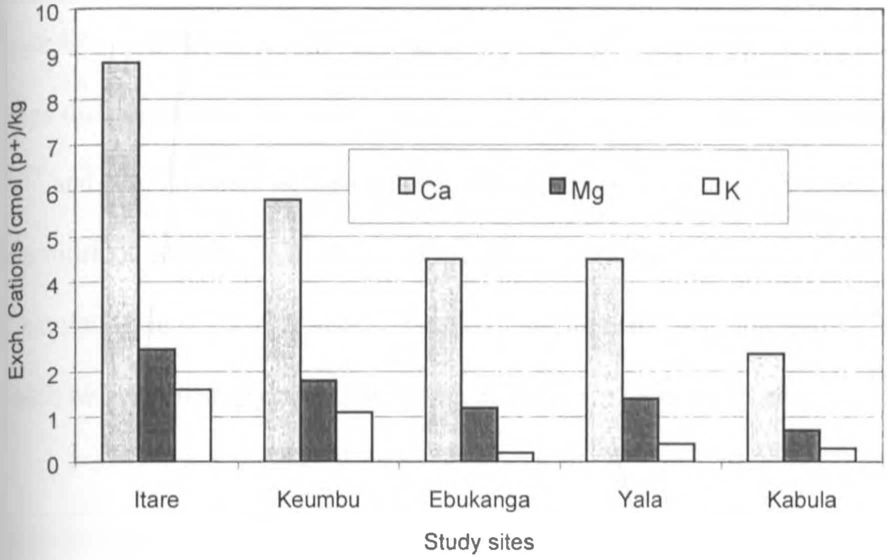

Fig 5: Variation of exch. Ca, Mg and K in farmers' fields

The relationship between exchangeable cations in soils was further assessed by Ca: K and Mg: K ratios (Table 4). These basic cation saturation ratios (BCSR), (Uribe and Fox, 1988), were in the 1940s believed to influence K availability in soils. The BCSR is no longer considered an important index in modern agriculture (Uribe and Fox, 1988; Rehm, 2003). The conclusions by Rehm (2003); were drawn after trials at a site in Wisconsin, USA, where Ca, Mg and K levels in soils were high. In the present study, Ca: K ratios increased in the order: Itare = Keumbu < Kabula < Yala < Ebukanga. In Itare and Keumbu, the Ca: K ratios were < 10, the limit set by Mehlich (1964) for healthy soils. Ratios were > 10 in Ebukanga, Yala and Kabula.

Magnesium: K ratios increased significantly (P < 0.001), in the order: Itare = Keumbu = Kabula <

Ebukanga = Yala (Table 4). Ratios were smaller in Itare, Keumbu and Kabula, and higher in Ebukanga and Yala, than 4.0, the limit set by Mehlich (1964). Results show higher BCSR in northern geomorphic area (NGA), than southern geomorphic area (SGA). There might have been higher $K^+$ and possibly $NH_4^+$ (from mineralization) activity in soils from the SGA, which according to Marschner (1995) and Barber (1995), may result in $Ca^{2+}$ and $Mg^{2+}$ deficiency in crops due to competition during uptake. Indeed, Barber (1995), reported 17 and 25 % decrease in $Ca^{2+}$ and $Mg^{2+}$ content in corn plants, respectvely, when K levels increased from 0 to 100 mg $kg^{-1}$ in a nutrient solution. Wapakala (1976), when working on various crops managed to increase the K saturation in soils after adding farmyard manure, but also realized deficiencies of Ca and Mg, which he attributed to disruption of Mg: K and Ca: K ratios in soils.

Considering that soils from the NGA, which are low in base status are the same with high Ca: K and Mg: K ratios, yet low pH, implies that the available CEC had extremely low exchangeable and solution K. Soils with high Ca: K and high Mg: K may have most of the negative charges occupied by $Ca^{2+}$ and $Mg^{2+}$ due to the strong binding energy of divalent, relative to monovalent cations (Barber, 1995). In fact, the high exchangeable K in SGA relative to Ca and Mg may also be attributed to the high Ca and Mg levels in the soils, which consequently displaces the weakly binding monovalent K to equlibrium solution, a phenomenon called Viets effect (Marschner, 1995).

In general, results from current study show a significantly positive correlation between organic matter content, and to some extent the silt content, and base status of soils. According to Barber (1995), this could be attributed to increased cation exchange capacity associated with organic matter, which holds cations against leaching. Asadu *et al.* (1997) found strong correlations between effective cation exchange capacity (ECEC) and soil organic matter, which he associated with negative charges arising from dissociation of weakly acidic functional groups in organic matter. In addition, organic residues form important sources of nutrients, which are released to the soil after decomposition (Okalebo, 1979; Grewal and Sud, 1995). Good management of organic residues can sustainably remain a dependable source of plant available K in the SGA. This system may, however, not be sustainable because of increased export of K from the farms, through crop harvests, soil erosion and runoff. Scarcity of land is not favourable to a sustainable system, because residues are increasingly fed to livestock or used as fuel (Jama *et al.,* 1997).

Extractable P levels increased in the order: Kabula < Ebukanga = Keumbu < Yala = Itare (Table 4). Extractable P increased with increase in Ca + Mg ($r^2 = 0.677$, $P = 0.055$). High contents of $Ca^{2+}$ may promote retention of P from fertilization and organic sources, as Ca- phosphates (Posse and Mendoza, 1995). In all the sites, however, average P values were lower than the critical values set at the NARL, and crops were expected to respond well to applied P fertilizers. After soil analysis in clusters, there were more P-deficient, than K- deficient samples. Out of the farms sampled, 0, 0, 100, 65 and 90 (mean = 51) %, were deficient in K, while 57, 89, 83, 84 and 95 (mean = 82) %, were deficient in P in Itare, Keumbu, Ebukanga, Yala and Kabula respectively. Soils from the NGA were deficient in both P and K, while soils from the SGA were deficient in P only.

Results from the SGA demonstrate how soil analysis has contributed to the belief that Kenyan soils have adequate K for crop growth. Using such results, fertilizer programs of food crops have been formulated, which rarely include K. This also partly explains why Kenya has a domestic fertilizer market with only N and P fertilizers stocked for use by farmers (Mwaura and Woomer, 1999). Mamo and Haque (1988) blamed routine soil K determinations that often showed adequate levels of exchangeable K for the poor attention that had been given to K status of Ethiopian soils. They recommend determination of all forms of K for a critical appraisal of K supplying power of soils.

Soils from the NGA were high in sand, but low in silt, pH, organic C and the exchangeable cations, $Ca^{2+}$, $Mg^{2+}$ and $K^{+}$, than soils from the SGA. Observed differences affirm the importance of the geological history of an area, as a major contributing factor in fertility status of soils. Older parent materials form soils that have weathered to greater extents, and have lost more of the exchangeable cations, due to prolonged exposure to the weathering forces. The results are in agreement with the findings by Anderson (1973), who reported higher K deficiencies in sandy acid soils. Greater K losses were reported in sandy soils due to leaching (Davis *et al.,* 1996). Among the exchangeable cations, $K^{+}$ is leached out of the soil profile much easily than $Ca^{2+}$ and $Mg^{2+}$ because of the low $K^{+}$ binding energy on exchange sites in clay and organic matter (Barber, 1995).

### *4.1.3 Results obtained and opinion on soil K status in Kenya*

Mapping of humid and sub-humid areas gave an indication of where K deficiency is likely to occur due to greater losses through soil erosion, surface runoff, leaching and excessive crop uptake, than gains through organic matter mineralisation, and weathering of parent materials, in situations where external inputs are limited. That not all samples in mapped region were deficient in K disapproves hypothesis 1, and suggests a need to incorporate data on parent materials and human activities in the mapping model; as shown by Issaka *et al.* (1996).

In situations where *r/Eo* > 0.75, K deficiency may not necessarily be evident from the exchangeable K soil test because of past and current human activities, and unique geological history of the area. There is need to characterize the soils further, to get a better picture of the long-term K supply potential of soils. Mapping of areas that are prone to K deficiency market an important step in K research in Kenyan soils, by delineating the areas where studies should be confined, but the map is subject to improvement when more data is collected.

## 4.2 Rock characteristics

### *4.2.1 Mineralogy of rocks*

The type and proportionate composition of mafic and felsic mineral components among rock samples are shown in Table 7.

Table 7: Mineral characteristics* of rock samples from study sites

| Site | Rock name | Color | Texture | Approximate mineral composition by volume | | |
|---|---|---|---|---|---|---|
| | | | | Mafic (Ma) | Felsic (Fe) | Ma:Fe |
| Itare | Nyanzian Basalt[a] | Dark grey | Fine grained | 70% (olivine, pyroxene, magnetite) | 30% (feldspars-labradorite, plagioclase) | 2.33 |
| Keumbu | Weathered trachyte[b] | Pink | Medium grained | < 10% (indistinct) | > 90% (quartz and feldspars) | 0.11 |
| Ndanai | Quartzite[c] | Light | Fine-medium | 5% (red garnets) | 95% (mainly quartz, minor feldspars) | 0.05 |
| Ebukanga | Weathered granite[d] | Light grey | Coarse[d] grained | < 25% (hornblende, biotite, magnetite | >75% (quartz, feldspars) | 0.33 |
| Yala | Rhyolite[e] | Grey + white veins | Fine[e] grained | 15% (hornblende, biotite, magnetite) | 85% (quartz and feldspars) | 0.18 |
| Kabula | Mumias granite[f] | Light grey | Medium[f] - coarse | 20% (biotite, hornblende) | 80% (quartz, feldspars-plagioclase + K feldspars) | 0.25 |

*Structure: [a]uniform grain distribution; weathering visible in outer surface, otherwise fresh, [b]uniform grain distribution, with fine kaolinitic veins cutting it, heavily weathered, [c]uniform grain distibution, fresh sample, [d] uniform grain distribution, weathered, [e] uniform grain distribution + cutting quartz veins, fairly weathered, [f] random mineral distribution- near uniform grain size, sample not weathered

Textural characteristics of hand specimens varied from fine – coarse. Textural characteristics influence the rate of weathering among rocks of similar chemical composition (Smith, 1962).

Technology limitation would not allow quantitative determination of the proportion of micas and feldspars, and type of micas or feldspars in hand specimens.

The mafic – to – felsic (Ma: Fe) ratio ranged from 0.05 – 2.33, and increased in the order: Ndanai < Keumbu < Yala < Kabula < Ebukanga < Itare. Apart from Itare, all the other rocks had higher felsic than mafic minerals (Ma: Fe ratios < 1), as expected of acid rocks. Ease of rock weathering, and clay content in associated soils is expected to increase in the same order, because mafic minerals are more weatherable than felsic minerals (De'Conninck, 1987; Scott and Smith, 1987; Harley and Gilkes, 2000), and easily weatherable rocks give more clayey soils under similar circumstances (Zahetner *et al.*, 2003).

The mafic minerals present were hornblende and biotite (Table 7). With respect to mafic minerals, therefore, K content in soils would increase with increase in biotite content in rocks, while weatherability of rocks will decrease with rise in biotite: hornblende ratio, because hornblend is more weatherable than biotite (Harley and Gilkes, 2000). Hornblendes are rich in Fe, Mg and Ca, while biotites have K in addition to Fe and Mg (De'Conninck, 1987). Felsic minerals present were quartz, and plagioclase and alkali feldspars (Table 7). Felsic contribution to soil K, therefore, increases with increase in K - feldspar in the rocks, while weatherability decreases with increase in quartz: feldspar ratio, and nature of feldspar; amongst orthoclase, albite and anorthite, as arranged in the Bowen's Reaction Series (Harley and Gilkes, 2000), (Fig 1). Details on proportionate composition of each of these minerals could not be obtained from the analysis that was done.

Among the K- containing minerals, biotite is more weatherable than orthoclase, suggesting that the relative orthoclase: biotite ratio in rocks of similar $K_2O$ content is an important index for determining the rate of K release from structural pool of the soil, as described by Haby *et al.* (1990). Soil Ca and Mg contents would also depend on the amount of minerals containing the cations and ease of weathering. Accordingly, granites and rhyolites, that are rich in orthoclase and biotite (Simpson, 1969), are likely to give more K to the soil than trachytes and basalts. Rocks from the northern geomorphic area (NGA), may weather into soils that have more K than rocks from the southern geomorphic area (SGA), because they are predominantly granites and rhyolites (Table 7). In contrast, the bedrock geology of SGA is more variable, with rhyolites, trachytes and basalts (Table 7). In the SGA, no biotites were identified, and K – feldspars may be the only sources of K (Table 7). Potassium feldspars are resistant to weathering and may not contribute much K to soils (Khan and Fenton, 1996).

### *4.2.2 Geo-chemical properties of rocks*

Geo-chemical analytical data for rock samples is given in Table 8, and Niggli values in Table 9.

Table 8: Chemical composition (% oxide) of rock samples[1] from study sites

| Sample | $SiO_2$ | $Al_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $TiO_2$ | MnO | $Fe_2O_3$ | LOI |
|---|---|---|---|---|---|---|---|---|---|---|
| Itare | 50.08 | 16.10 | 5.30 | 5.10 | 1.75 | 1.87 | 1.32 | 0.19 | 10.80 | 5.50 |
| Keumbu | 67.60 | 12.70 | 0.10 | 0.38 | 0.04 | 1.48 | 1.18 | 0.00 | 2.92 | 5.30 |
| Ndanai | 95.96 | 02.03 | 0.08 | 0.05 | 0.03 | 0.09 | 0.05 | 0.00 | 0.55 | 1.90 |
| Ebukanga | 60.81 | 17.40 | 2.42 | 4.08 | 4.70 | 3.61 | 1.06 | 0.04 | 3.61 | 2.30 |
| Yala | 69.71 | 12.44 | 0.09 | 2.21 | 0.09 | 2.64 | 1.65 | 0.01 | 4.78 | 5.20 |
| Kabula | 68.28 | 14.20 | 1.42 | 0.47 | 4.31 | 4.34 | 0.40 | 0.00 | 1.11 | 4.70 |

[1] No of replicates = 3 per rock sample, LOI = Loss on Ignition

According to silica content, there were basic (Itare), intermediate (Ebukanga) and acid rocks, where acidity increased in the order: Keumbu < Kabula < Yala < Ndanai (Table 8). Chemical analysis did not place Keumbu rock in intermediate (trachyte), and Ebukanga rock in acid (granite), classes, as was done by Corbett *et al.* (1999).

Table 9: Niggli values[1] for rock samples from study sites

| Parent rock | Calculated Niggli values[2] | | | | | |
|---|---|---|---|---|---|---|
| | *si* | *al* | *fm* | *ca* | *alk* | *qz* |
| Itare | 147 | 28 | 47 | 17 | 8 | 13 |
| Keumbu | 596 | 66 | 24 | 1 | 9 | 462 |
| Ndanai | 5171 | 64 | 26 | 5 | 5 | 5052 |
| Ebukanga | 212 | 36 | 31 | 9 | 24 | 16 |
| Yala | 431 | 45 | 43 | 1 | 11 | 287 |
| Kabula | 372 | 45 | 8 | 8 | 38 | 121 |

[1] Molecular values of metal oxides (Mohr *et al.*, 1972)

[2] *si* = $SiO_2$, *al* = $Al_2O_3$, *fm* = $Fe_2O_3$ + MnO + MgO, *ca* = CaO, *alk* = $K_2O$ + $Na_2O$, *qz* = free $SiO_2$

The relatively high silica content in Keumbu specimen (Table 8) was perhaps due to alteration of weatherable mafic minerals in the rock, resulting in a relative accumulation of resistant felsic minerals. Smith (1962) had observed such trends in the weathering sequence of Scottish basic igneous rocks. Trachytes are rich in hornblende (Simpson, 1969), which may decompose and result in the relative accumulation of quartz and orthoclase. The medium grained texture of Keumbu rocks (Table 7) is suited to high rates of weathering, as was reported of similar rocks by Smith (1962). Ebukanga sample had less silica, suggesting limited residual accumulation of resistant felsic minerals. Perhaps the felsic mineral emphasized by Corbett *et al.* (1999) in classifying the rock from Ebukanga was plagioclase feldspar, which had preferentially weathered at the time of analysis, resulting in enhanced accumulition of less silicious biotite and hornblende. Plagioclase feldspar was found to be more weatherable than augite (Smith, 1962), and should, therefore, be more weatherable than hornblende, because augite is higher in the Bowen's reaction series than hornblende (Fig 1). As the $SiO_2$ content increased in rock samples, Ma: Fe ratio decreased as shown in Fig 6.

Niggli *si*-values varied widely, within a range of 147 – 5171, and increased in the order: Itare <

Ebukanga < Kabula < Yala < Keumbu < Ndanai. The *si*-values were inversely related to Ma: Fe ratios and, therefore, conformed to the plot in Fig 6. A graph, (Fig 7), was plotted with increasing *si*- values on the abscissa, and Niggli values for *al, fm, ca* and *alk* (Table 9), on the ordinate, to compare with a similar plot by Mohr *et al.* (1972). It was observed from the graph that *al* – values increased with increase in *si*-values, which agreed with results from Mohr *et al.* (1972), and was perhaps due to the increase in feldspars. In addition, *alk* –values increased as *si*- values increased in the range < 372, but decreased in the upper range as *si*- values increased further. Mohr *et al.* (1972) operated within the *si*- values range < 463 and results reported here for the range < 372 are consistent with their findings, and those reported by Sparks (1987).

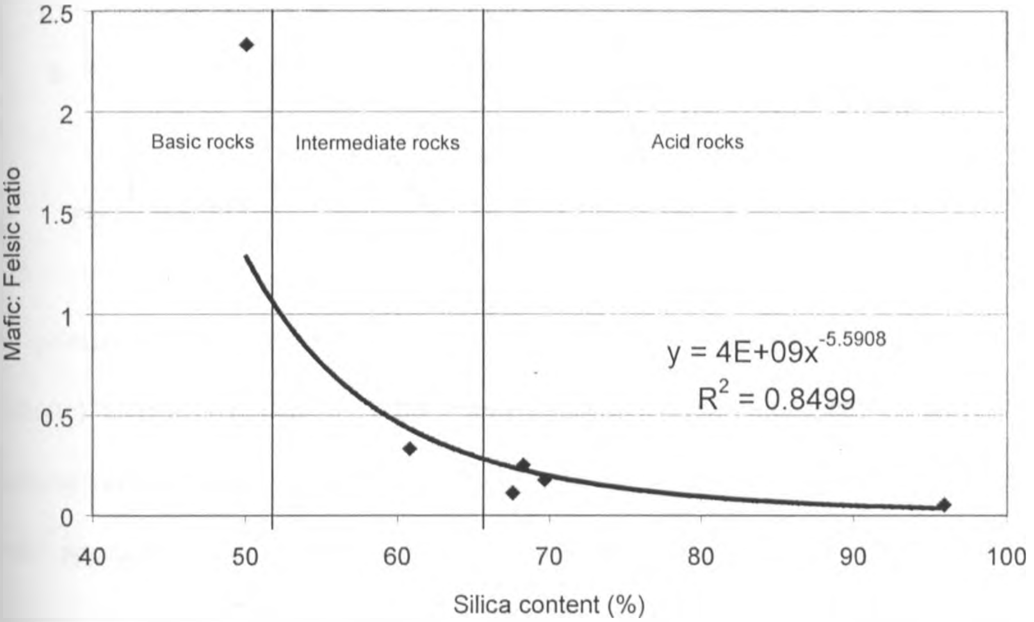

Fig 6: Variation of mafic: felsic ratio as $SiO_2$ content increased in parent rocks

Mafic (e.g. augite, hornblende, biotite): felsic (feldspars, quartz) ratios as in Table 7, and $SiO_2$ values in Table 8

A positive correlation between *alk* –values and *si*- values, was attributed to the high presence of biotites and alkali feldspars in acid rocks, as reported by Simpson (1966). In si- value range > 372, high Si and Al in Yala, Keumbu and Ndanai rocks (rock samples with lowest Ma: Fe ratios), did not result in higher *alk* –values. We expect a positive correlation between *combined silica (si)* and *alk*-values (Mohr *et al.*, 1972), but differences may arise when secondary silica (*qz*), and aluminosilicates occur in the weathered rocks.

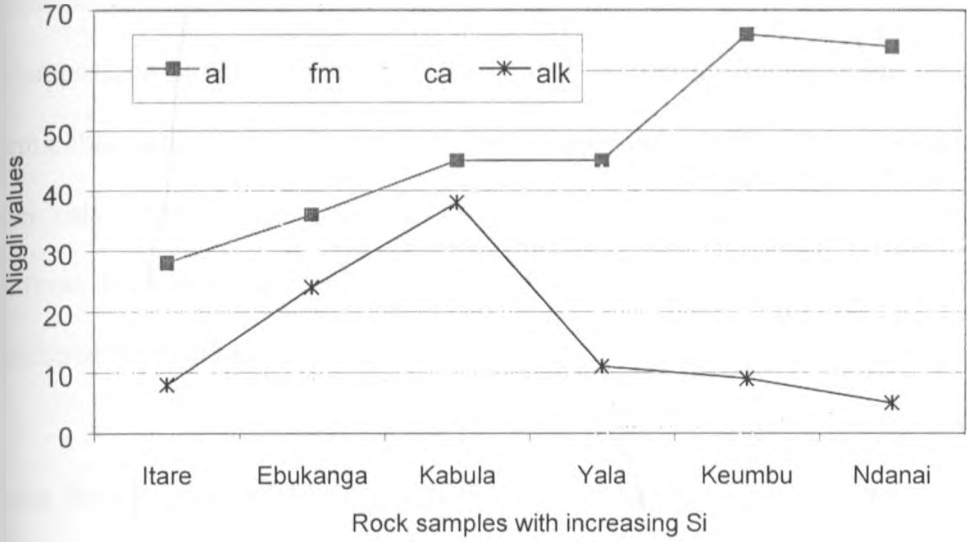

Fig 7: A plot of Niggli values against increasing si-values in studied rocks

The primary *alk*- rich minerals may have decomposed and formed secondary minerals (e.g. kaolinite), after loss of alkalis. All the three rock samples had high contents of *qz* (Table 9), while kaolinite veins were observed in Keumbu sample. In outcrop, the trachyte from Keumbu had an earthy appearance, due to advanced weathering and crumbled easily in the hand due to high friability. Weathered and unweathered (difficult to find during characterization), hand specimens of Keumbu rock are compared in Plate 1.

In the graph (Fig 7), *ca*-values decreased as *si*- values increased, which is consistent with the findings by Mohr *et al.* (1972), and was attributed to the decrease in hornblende and plagioclase feldspars (Simpson, 1969). In general, *fm*-values decreased with increase in *si*-values as reported by Mohr *et al.* (1972) and Sparks (1987), but anomalies were noted in rock samples from Kabula and Yala. Kabula rock, though low in *si*-value was also low in *fm*-value. The biotite could have decomposed, as quartz and orthoclase accumulated. High *alk*-value in Kabula sample was, therefore, ascribed to primary or secondary illites, and K-feldspars. Yala rock, though high in silica was also high in *fm*-value. High silica was ascribed to the free quartz, and high *fm* -value to decomposition products from mica. Biotite and phlogopites are known to co-exist with illites, vermiculites and chlorites in regolith (Harley and Gilkes, 2000). The magnetite in rock samples from Yala (Table 7), suggests strong weathering of biotite and loss of $SiO_2$, while low *alk* –value confirms that biotite had indeed lost the alkalis *in situ*. Smith (1962) reported similar findings in weathered Scottish basic igneous rocks.

Rocks from Kabula and Ebukanga (both granites), had K contents > 3.1 % $K_2O$ (Table 8), the average given for igneous rocks (Mohr *et al.,* 1972), while all the other rocks had lower K contents. Rocks from the northern geomorphic area (NGA) had significantly higher K contents ($P = 0.029$) than rocks from the southern geomorphic area (SGA), which was attributed to accumulation of orthoclase and biotite (or illites) in granites and rhyolites, as the rocks weathered. Rock samples analyzed had altered incongruently and their value in predicting soil characteristics from mineralogical and geo-chemical data was doubtful.

## 4.3: Soil samples for detailed characterization

### *4.3.1: Clay content*

The variation of clay content with depth among the soils is shown in Table 10. There was a significant difference ($P < 0.001$), in clay content among soils, which increased in the order: Kabula < Ndanai < Keumbu < Ebukanga < Yala < Itare. The correlation between, Ma: Fe ratio in rock samples, and clay content in soils was not significant (P = 0.653). Poor correlations were attributed to three reasons, (i) rock samples had weathered incongruently at the time of analysis, by losing the weatherable minerals, and a relative accumulation of resistant minerals, leading to erroneous Ma: Fe ratios; (ii) clay in soils may not necessarily have originated from the parent rock, but deposited as a surface contaminant from higher ground, e.g. Ndanai, and; (iii) clay in soils may be cemented together as occurs in plinthite, leading to erroneous results, e.g. Kabula.

Table 10: Clay content$^{*}$ (%) at different depths of studied soils

| Site | Soil depths (cm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-30 | 30-60 | 60-90 | 90-120 | 120-150 | >150 | Mean¶ |
| Itare | 65.5 | 70.0 | 71.5 | 75.5 | 76.0 | 75.5 | $72.33^{f}$ |
| Keumbu | 48.5 | 56.5 | 55.0 | 50.5 | 49.5 | 43.5 | $50.58^{c}$ |
| Ndanai | 40.0 | 42.00 | 40.00 | 45.50 | 47.50 | 44.00 | $43.17^{b}$ |
| Ebukanga | 53.00 | 57.50 | 56.00 | 56.00 | 54.50 | 62.50 | $56.58^{d}$ |
| Yala | 59.00 | 66.50 | 70.50 | 68.50 | 67.00 | 64.00 | $65.92^{e}$ |
| Kabula | 35.50 | 43.00 | 42.00 | 35.50 | 36.50 | 34.00 | $37.75^{a}$ |
| Mean | 50.25 | 55.92 | 55.83 | 55.25 | 55.17 | 53.92 | 54.39 |

$^{*}$Each value represents an average of four replicate samples. ¶ Superscripts: Same letter = no significant difference between means. None = P for treatment in ANOVA > 0.05. LSD among sites = 4.946 (P < 0.001)

It may be difficult to compare the characteristics of soils formed from parent materials of different ages, and which have weathered in different environments as found in the two geomorphic areas of western Kenya. Zehtners *et al.* (2003), studied volcanic ash soils from Ecuador, and found that old soils were highly indurated, had high clay content, and small amounts of primary minerals as compared with recent soils, due to prolonged exposure of older soils to processes of weathering. Due to the differences associated with weathering of parent materials in dissimilar environments, our hypothesis: that the amount of clay in soils is a function of the extent of weathering was not proved true.

### *4.3.2 Soil mineralogy*

#### *4.3.2.1 Sand fraction*

Results for the total elemental analysis of sand fraction of soils are summarized in Table 11, and CIPW norms (Zehetners *et al.*, 2003), in Table 12.

Table 11: Chemical composition (% oxide) of sand sized soil particles in soils from study sites [1]

| Sample | $SiO_2$ | $Al_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | MnO | $Fe_2O_3$ |
|---|---|---|---|---|---|---|---|---|
| Itare | 82.9 | 8.6 | 0.2 | 0.1 | 0.1 | 1.5 | 0.0 | 2.2 |
| Keumbu | 85.2 | 6.0 | 0.1 | 0.1 | 0.1 | 2.2 | 0.0 | 1.7 |
| Ndanai | 91.2 | 7.3 | 0.1 | 0.1 | 0.1 | 1.9 | 0.0 | 0.9 |
| Ebukanga | 76.2 | 6.2 | 0.2 | 0.1 | 0.1 | 4.6 | 0.0 | 0.2 |
| Yala | 62.5 | 0.9 | 0.5 | 0.1 | 0.1 | 0.3 | 0.0 | 0.6 |
| Kabula | 99.6 | 1.4 | 0.0 | 0.0 | 0.1 | 1.1 | 0.0 | 0.2 |
| Mean | 82.9 | 5.1 | 0.2 | 0.1 | 0.1 | 1.9 | 0.0 | 1.0 |
| SDev | 12.8 | 3.2 | 0.2 | 0.0 | 0.0 | 1.5 | 0.0 | 0.8 |

[1] Figures shown are averages of three replicates per sample

Table 12: Sand mineralogy (w/w %) of soil samples from study sites[1]

| Sample | Feldspars | | | | FM minerals[2] | Quartz | Haematite | F+Q[3] |
|---|---|---|---|---|---|---|---|---|
| | Orthoclase | Albite | Anorthite | Total | | | | |
| Itare | 9.0 | 34.2 | 1.0 | 44.2 | 3.9 | 51.9 | 0.7 | 96.1 |
| Keumbu | 13.4 | 18.2 | 0.5 | 32.1 | 3.2 | 64.7 | 2.7 | 96.8 |
| Ndanai | 10.7 | 24.8 | 0.5 | 36.0 | 1.6 | 62.0 | 0 | 98.0 |
| Ebukanga | 30.9 | 5.0 | 1.1 | 37.0 | 0.7 | 62.3 | 12.0 | 99.3 |
| Yala | 2.8 | 0 | 2.5 | 5.2 | 2.5 | 92.3 | 35.1 | 97.5 |
| Kabula | 6.3 | 1.1 | 0.0 | 7.4 | 0.3 | 92.3 | 0 | 99.7 |
| Mean | 12.2 | 13.9 | 0.9 | 27.0 | 2.0 | 70.9 | 8.4 | 97.9 |
| SDev | 9.9 | 14.0 | 0.9 | 16.5 | 1.4 | 17.1 | 13.8 | 1.4 |

[1] Each value is an average of three replicates of a sample. Primary minerals have been re-calculated to 100%. [2]FM minerals = pyroxenes and amphiboles, [3]F+Q = Feldspars + Quartz

Silica was the dominant oxide in all the samples, with contents ranging from 62.5 – 99.6 %, and a mean of 82.9 %. Oxide content decreased in the order: $SiO_2 > Al_2O_3 > K_2O > Fe_2O_3 >$ CaO (Table 11). Contents of MgO and $Na_2O$ were considered trace. The proportionate oxide content in sand fraction is probably a reflection of the abundance of the oxide in parent rocks, resistance of the corresponding oxide-rich minerals to weathering, and weathering intensity. The proportionate composition of primary minerals decreased in the order: quartz > feldspars > ferromagnesian silicates (Table 12). Also, alkali feldspars were in higher concentration than plagioclase feldspars (Table 12). This pattern is consistent with decreasing resistance to mineral weathering as indicated in the Bowen's reaction series (Harley and Gilkes, 2000), (Fig 1).

Quartz and feldspars accounted for between 96.1 – 99.7 % (mean = 97.9 %), of calculated mineral content in sand fraction of soils. In Kabula and Ebukanga soils, for example, ferromagnesian minerals formed < 1 % of the mineral content, suggesting that biotite and hornblende in parent rocks (Table 7) had decomposed completely. Both Yala and Kabula samples had > 90 % $SiO_2$ and may be considered mono-mineralic, quartz. The apparently high haematite in Ebukanga and Yala soils (Table 12), corresponded with the magnetite identified in rock samples (Table 7), and strengthened the argument of possible *in situ* weathering of iron- rich biotite.

Feldspar content ranged from 5.2 – 44.2 %, and increased in the order: Yala < Kabula < Keumbu < Ndanai < Ebukanga < Itare. It is possible to group Yala and Kabula together, as soils with low (< 10 %) feldspar content, and the other soils with high (> 30 %) feldspar content in the sand fraction. Kabula soil had surprisingly low feldspar content, yet the parent rock had highest $K_2O$ and *alk*-values (Tables 8 and 9, respectively). Since the rock samples were also rich in MgO (Table 8), it can be concluded that the K containing minerals in Yala and Kabula rock samples was predominantly biotite, and a combination of both biotite and orthoclase in Ebukanga sample. Soils from Yala and Kabula depict extreme weathering and are unlikely to release more K and other nutrients as weathering progresses, because the sand fraction is dominated by quartz.

Itare, Keumbu and Ndanai rocks in southern geomorphic area (SGA), and Ebukanga in northern geomorphic area (NGA) were rich in orthoclase (Table 12). These results are supported by the chemical analysis results of rock samples in Table 8, which show comparatively low MgO content in rock samples from SGA, indicating that the main form of K is orthoclase. Since orthoclase is resistant to weathering (Khan and Fenton, 1996), these soils may not gain much in terms of K from further weathering of sand fraction.

Mafic minerals were rare in the sand fraction and ranged from 0.3 – 3.9 %, increasing in the order: Kabula < Ebukanga < Yala < Ndanai < Keumbu < Itare. By arbitrarily considering < 2 % as low, only Keumbu and Itare had high contents. Mafic minerals were perhaps augites and hornblende in Keumbu, and augites in Itare, which were inherited from parent rocks (Table 7). The relatively high content of weatherable ferromagnesian minerals in sand fraction of soils from SGA is consistent with the young age of volcanic soils closer to the Great Rift Valley (GRV). Other workers (Nyamweru, 1980; Zehetner *et al.*, 2003) reported the presence of such minerals in younger volcanic soils. Their presence was regarded to be transitory due to their high weatherability. They decompose to release the Mg and Ca they contain, to the soil, as Fe and Si accumulate in clay fraction.

Soils from NGA had low levels of mafic minerals in sand fraction, possibly due to great weathering, as a result of advanced age. Zehetner *et al.* (2003) reported similar results from the volcanic ash soils of Equador. Results from current studies confirmed the comparatively high weatherability of mafic minerals in soils as reported by various workers (De'Conninck, 1987; Scott and Smith, 1987), and the relatively young geological age of rocks from SGA, because they still contained unweathered mafic minerals. Results were also in conformity with the findings by Vilela and Ritchey (1985), that Ultisols and Oxisols; the predominant soils of the tropics are characterised by near absence of weatherable minerals in the sand and silt fractions.

Among the feldspars, orthoclase occurred in the sand fraction in concentrations between 2.8 – 30.9 %, and decreased in the order: Ebukanga > Keumbu > Ndanai > Itare > Kabula > Yala. Orthoclase may form an important source of reserve K that buffers up the K adsorbed on exchange sites and in soil solution (Sparks, 1980), and an important long- term source of K in soils (Khan and Fenton, 1996). According to Sparks (1987), mineral K may form an important source of K when the readily available K is depleted, as happens in intensively cropped systems. Potassium feldspars, however, weather slowly and do not contribute significantly to the overall K uptake to crops (Harley & Gilkes, 2000; Khan and Fenton, 1996). Since micas were rare, sand mineralogy may not offer short- term solution to K deficiency in studied soils.

Soils may have been dominated by orthoclase and quartz in sand fraction (e.g. Kabula and Ndanai), either because they are highly weathered, resulting in complete decomposition of other primary minerals, or the parent rocks were very siliceous, resulting in quartz accumulating residually. High K content in soils may, therefore, be partly accounted for by the resistance of orthoclase and biotite to weathering. Due to high stability of orthoclase, K content in soils is usually higher than other cations, yet K is only the seventh in abundance in the earth's crust (Csatho, 2002). The other cations (Ca, Mg and Na), occur in more weatherable minerals, and disappear faster through leaching, and other processes. Sand grains may persist for long in soils without any benefit to crops because the K in them becomes available very slowly.

#### *4.3.2.2 Clay fraction*

Chemical analysis results of the clay fraction of soil samples is given in Table 13, which was used to perform the normative classification of the mineral suite, using the protocol of Cross, Iddings, Pirsson and Washington (CIPW) norms (Zehetner *et al.*, 2003; Marechal *et al.*, 1983), (Table 14).

Table 13: Chemical composition (% oxide) of clay fraction of soils from study sites

| Sample | $SiO_2$ | $Al_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | MnO | $Fe_2O_3$ |
|---|---|---|---|---|---|---|---|---|
| Itare | 25.70 | 19.90 | 0.02 | 0.23 | 0.05 | 0.41 | 0.00 | 5.85 |
| Keumbu | 36.10 | 25.40 | 0.05 | 0.35 | 0.05 | 0.87 | 0.01 | 13.21 |
| Ndanai | 36.41 | 22.48 | 0.05 | 0.35 | 0.05 | 1.08 | 0.00 | 2.32 |
| Ebukanga | 33.04 | 24.78 | 0.10 | 0.31 | 0.05 | 0.89 | 0.00 | 1.43 |
| Yala | 36.90 | 26.60 | 0.05 | 0.29 | 0.05 | 0.65 | 0.00 | 1.49 |
| Kabula | 35.17 | 27.50 | 0.00 | 0.39 | 0.05 | 0.89 | 0.00 | 1.73 |

Clay fraction of all soils was dominated by kaolinite, which accounted for between 89.7 – 96 (mean = 93.6) % of the dry weight. The presence of kaolinite was anticipated because of large amounts of Si and Al released from decomposition of mafic and felsic minerals, and good drainage in soils. Illites accounted for between 4.5 – 10.6 % of the dry weight. There were trace amounts of residual $SiO_2$ in most soils, and haematite in Itare and Keumbu soils. The results conformed to the findings by Sparks (1987), who reported that pure kaolinite rarely exists in soils, but is often associated with small amounts of 2: 1 clay minerals, Al- interlayered 2: 1 clays and mixed layer silicates.

Table 14: Clay mineralogy, expressed as CIPW[**] norms of soil samples from study sites

| Sample | Illites | | | Kaolinite | Illite: Kaol[¶] | Silica | Haematite |
|---|---|---|---|---|---|---|---|
| | Tri- oct | Di- oct | Total | | | | |
| Itare | 4.5 | 0 | 4.5 | 98.5 | 4.6 | 1.2 | 3.8 |
| Keumbu | 9.5 | 0 | 9.5 | 96.0 | 9.9 | 0 | 8.6 |
| Ndanai | 6.6 | 4.0 | 10.6 | 89.7 | 11.8 | 0.7 | 0 |
| Ebukanga | 4.7 | 3.9 | 8.6 | 90.9 | 9.5 | 1.1 | 0 |
| Yala | 4.6 | 1.9 | 6.5 | 94.7 | 6.9 | 1.2 | 0 |
| Kabula | 5.3 | 3.4 | 8.7 | 91.5 | 9.5 | 1.0 | 0 |

[**] CIPW = Cross, Iddings, Pirsson and Washington (Zehetner *et al.*, 2003) [¶] Illite: kaolinite ratio * 100

Muchena (1974) studied the mineralogy of several soils from Central and Eastern Kenya, and found predominantly kaolinite and smaller amounts of illite. Mohr *et al.* (1972), when studying the genesis of Oxisols, obtained similar results. They found that the new, clay sized minerals, formed alongside soluble salts, after alteration process, are kaolinite and hydrated oxides of Fe and Al. They also found that illite and montmorillonite can crystallize, albeit temporarily. According to De'Conninck (1987), kaolinite is the dominant clay mineral in humid tropical soils. Harley and Gilkes (2000) reported that mature soils from warm and humid environments are dominated by kaolinite and sesquioxides. Presence of free Si suggests the unlikely presence of allophanes and other poorly crystallized alumino-silicates found in Andisols (Ecudey *et al.,* 2004). Halloysite may form under conditions of impeded drainage, while allophanes form under excessive rainfall and leaching (Zehetner *et al.,* 2003).

The illite: kaolinite ratio ranged from 4.6 – 11.8 x $10^{-2}$, and correlated negatively with Ma: Fe ratio in parent rocks ($r^2 = 0.577$, $P = 0.049$). The results, therefore, show that rocks that weather more easily (high Ma: Fe ratio); have lower amounts of 2: 1 clay minerals and a predominance of kaolinite. At the same time, the illite: kaolinite ratio was negatively correlated to % clay in soils ($r^2 = 0.678$, $P = 0.027$), (Fig 8), confirming the absence of 2: 1 clays, and presence of kaolinite in increasingly more clayey soils. The results are consistent with recognized theory that kaolin belongs to an advanced stage in the weathering sequence (Smith, 1962). Results also agreed with the view that 2:1 clay minerals decompose to kaolinite in extreme weathering (Smith, 1962). According to the current study, therefore, silicious (acid) parent materials, which normally have low mafic: felsic ratio (Fig 6), are likely to have low clay content, but high illite: kaolinite ratio.

Illites and other 2:1 clay minerals may originate from biotites, which are relatively more abundant in the acid than basic rocks (Simpson, 1966). Also, tri-octahedral 2: 1 clays may form from ferromagnesian silicates (Harley and Gilkes, 2003). The 2: 1 clays may decompose to form kaolinite, and further again to form hydrous oxides, e.g. haematite and gibbsite. Following this argument, therefore, it was assumed that the illites from ferromagnesian silicates in basic rocks, and in rocks from NGA where biotite is the major K- containing mineral had weathered to kaolinite, and thus explaining the low illite: kaolinite ratio.

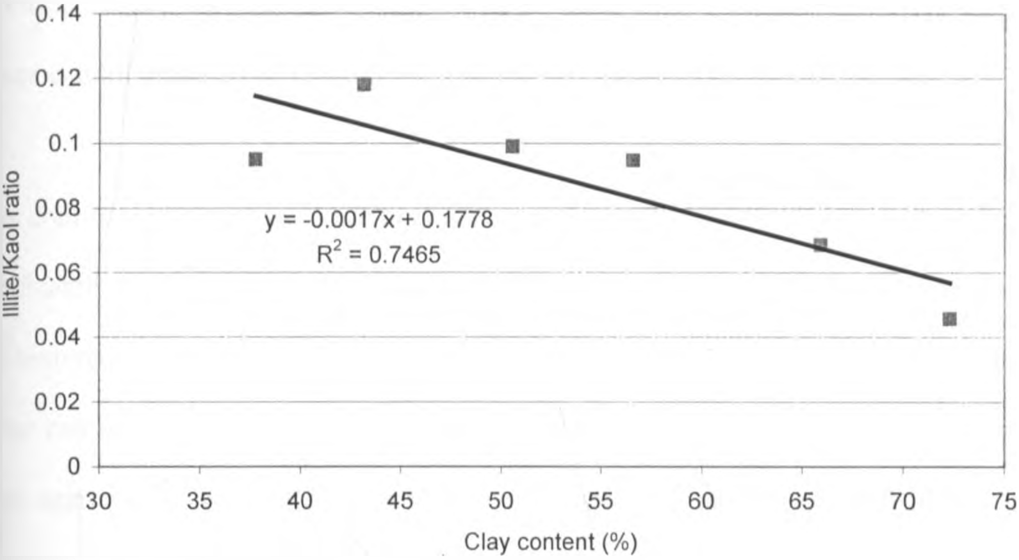

Fig 8: A plot of Illite/Kaol ratio against clay content of studied soils

Since illite was higher in the coarse than fine textured soils, it was concluded that illites from acid rocks were probably still being formed from biotite as the rocks take long to decompose. Illites are either decomposition products from primary minerals, or secondary minerals synthesized in the soil, depending on the $H^+$ / $K^+$ ratio (Mohr *et al.*, 1972). Secondary illites are more likely to form in soils from acid rocks, because they contain more K in biotites and orthoclase, than basic rocks (Simpson, 1969). Illites are also formed as a result of slow internal drainage, but are limited in strongly acid conditions (Mohr *et al.*, 1972).

With regard to K dynamics in soils, kaolinitic soils have poor selectivity for K, when compared with soils dominated by 2: 1 clays like illite and vermiculites (Singh and Agrawal, 1995; Parfitt *et al.*, 1995). Kaolinitic soils are characterized by pH- dependent charges on broken bonds (edges, surfaces), which bind cations very weakly (Barber, 1995). Such soils may test high in plant available K, but the long- term supply potential is doubtful. The 2: 1 clays, Al- interlayered chlorites, and vermiculites, and mixed layer silicates in kaolinitic Oxisols and Ultisols of the tropics exhibit pronounced fixation and specific adsorption of K (Sanchez & Buol, 1974).

Soils dominated by kaolinite have limited non-exchangeable K, the form of K that may contribute significantly to plant K uptake in soils dominated by 2: 1 clays (Richards and Bates, 1989). Also, fine textured acid tropical soils dominated by kaolinite and sesquioxides, and if rich in organic matter can be highly porous and fast draining (Shepherd *et al.,* 2001). Organic matter results in micro aggregation, and such soils may give way to speedy leaching of exchangeable bases formed during the alteration stage, though still holding a lot of water.

### *4.3.3: Organic carbon content and variation with depth*

Levels of organic C content in soils were significantly different among soils ($P < 0.001$), and increased in the order: Kabula = Ebukanga = Yala < Keumbu = Itare < Ndanai (Table 15).

Table 15: Organic C$^{*}$ (g kg$^{-1}$) content at different depths of soils from study sites

| Site | Soil depths (cm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-30 | 30-60 | 60-90 | 90-120 | 120-150 | >150 | Mean¶ |
| Itare | 16.53 | 14.88 | 8.98 | 6.23 | 4.65 | 3.08 | $9.05^{b}$ |
| Keumbu | 18.97 | 14.55 | 8.13 | 4.90 | 3.70 | 3.28 | $8.92^{b}$ |
| Ndanai | 24.80 | 20.10 | 11.28 | 6.55 | 5.60 | 5.20 | $12.25^{c}$ |
| Ebukanga | 13.45 | 7.53 | 4.70 | 4.55 | 4.35 | 3.93 | $6.42^{a}$ |
| Yala | 14.50 | 9.50 | 7.20 | 4.70 | 4.95 | 4.40 | $7.50^{ab}$ |
| Kabula | 10.65 | 7.23 | 4.98 | 3.68 | 3.33 | 2.63 | $5.41^{a}$ |
| Mean | $16.48^{d}$ | $12.30^{c}$ | $7.54^{b}$ | $5.10^{a}$ | $4.43^{a}$ | $3.75^{a}$ | 8.27 |

*Each value represents an average of four samples. ¶ Superscripts: Same letter = no significant difference between means. None = P for treatment in ANOVA > 0.05. LSD: Sites = 2.135 ($P < 0.001$), Depths: = 2.135 ($P < 0.001$)

This order divides the two geomorphic areas in terms of C content, which was significantly ($P = 0.043$) higher in the southern geomorphic area (SGA) (mean = 10.07, SD = 1.89), than the northern geomorphic area (NGA) (mean = 6.44, SD = 1.04). As was suggested for the samples collected from farmers' fields, high organic C in SGA was perhaps due to stabilization of organic matter after complexation with Al, and other amorphous weathering products, and cooler climatic conditions that lower the rate of organic mineralization. Allophanes, Al and imogolite are active amorphous weathering products, normally found in volcanic soils (Parfitt *et al.*, 1999, Zehetners *et al.*, 2003). Al-humus complexes are active below pH 5.0, and allophanes in pH > 5.0 (Zehetners *et al.*, 2003). Aluminium suppresses enzyme activity and, therefore, substrate degradation rates, resulting in accumulation of organic C (Zehetners *et al.*, 2003).

Organic C decreased significantly ($P < 0.001$) with depth. Surface C accumulations were expected as most of the organic residues are deposited, and decompose at the surface. In the SGA, organic C increased in the order: Itare < Keumbu < Ndanai, which conforms to increased organic matter with altitude and the likely Ultisol – Andisol transition in the Kisii toposequence. Other workers (Escudey *et al.*, 2004, Zehetners *et al.*, 2003) reported such transitions along similar topo-sequences. Organic matter plays an important role in regulating the selectivity of cations in volcanic soils (Escudey *et al.*, 2004).

### *4.3.4 Cation exchange capacity and base saturation*

The Effective Cation Exchange Capacity (ECEC), of soils and other data are shown in Table 16. The values of ECEC; ranging from 5.48 – 8.65 cmol $(p^+)$ $kg^{-1}$ were low, but conformed to low Cation Exchange Capacity (CEC) values of acid soils in the tropics. Kamprath (1984) ascribed such low CEC values to high $Al^{3+}$ saturation, which countered a large part of the negative charge.

Mohr *et al.* (1972), found ECEC values of similar magnitude in surface samples of kaolinite dominated soils but higher values in lower horizons where illite/kaolinite ratio was in favor of illite.

Table 16: Exchangeable bases and cation exchange capacity of soil samples from study sites[¶]

| Site | Ca | Mg | K | TEB | TEA | ECEC | CKSL | BS | KS |
|---|---|---|---|---|---|---|---|---|---|
| | cmol (p+) kg$^{-1}$ | | | | | | | % | |
| Itare | 5.25 | 2.08 | 0.28 | 7.61 | 1.04 | 8.65 | 0.3 | 88.0 | 3.2 |
| Keumbu | 3.53 | 1.43 | 0.18 | 5.14 | 1.57 | 6.71 | 0.3 | 76.6 | 2.7 |
| Ndanai | 4.03 | 1.30 | 0.30 | 5.63 | 1.35 | 6.98 | 0.3 | 80.7 | 4.3 |
| Ebukanga | 5.15 | 1.98 | 0.18 | 7.31 | 0.57 | 7.88 | 0.3 | 92.8 | 2.3 |
| Yala | 3.58 | 1.40 | 0.10 | 5.08 | 0.60 | 5.68 | 0.3 | 89.4 | 1.8 |
| Kabula | 2.88 | 1.33 | 0.35 | 4.56 | 0.92 | 5.48 | 0.3 | 83.2 | 6.4 |

TEB = Total exchangeable bases, TEA= Total exchangeable acidity, ECEC = effective cation exchange capacity, CKSL = Critical potassium sufficiency level (Fisher, 1974), BS = Base saturation, KS = exch K/ECEC *100. [¶] Each of the values represents an average of four samples.

According to Kamprath (1984) and Khan and Fenton (1996), low CEC of old tropical soils is due to extreme weathering. The colloids of highly weathered soils have a constant surface potential, which is characteristic of kaolinite, Al-interlayered chlorites, hydrous oxides of Fe and Al, and Al-organic matter complexes, which is pH- dependent (Kamprath, 1984).

The total exchangeable bases (TEB) were in low concentrations, possibly due to extensive leaching. Apart from Itare and Ebukanga, all the other samples were deficient in $Ca^{2+}$. High Ca content in soils from Ebukanga and Itare was attributed to the high mafic: felsic ratio (Table 7) and CaO contents (Tables 8 and 9) in parent rocks. Exchangeable $Mg^{2+}$ was well supplied in all the soils probably because Mg minerals are well spread across the rock classification scale from basic (ferromagnesian silicates) to acid (biotites) rocks. Exchangeable K contents ranged from 0.10 – 0.35 cmol ($p^+$) $kg^{-1}$, and were, therefore, in the low range (Marx *et al.*, 1999) in all samples.

Critical exchangeable K levels were calculated from Fisher's formula (Fisher, 1974), and gave a constant value of 0.3cmol $(p^+)$ $kg^{-1}$. Only the soil from Kabula had a value above the critical level and, therefore, may not have severe K limitation. High K deficiency was attributed to extensive leaching, possibly because of weak K adsorption on soil colloids, relative to Ca and Mg (Barber, 1995). Potassium saturation levels of CEC ranged from 1.7 – 6.3 %, which was higher than the lower limit of 2 % given by Anderson (1973) in all soils, but the soil from Yala. Yala soils were found to have the lowest feldspar and orthoclase content in sand fraction (Table 12). It has been inferred from this research that Yala and Kabula soils are dominated by biotite as the main K-containing mineral. Consequently, biotite had probably weathered completely, and K had been lost through leaching and other pathways.

The soil from Kabula, though formed from biotite rich rocks was high in exchangeable K. The location of this site is in a plain frequented by runoff water from higher rocky grounds to the east. Considering that both the higher ground and the plain have similar parent materials, the runoff is bound to have a lot of dissolved K. Khan and Fenton (1996) reported significantly high content of K in surface soils of western Iowa, USA, that had suffered perpetual flooding from Missouri River, before flood control structures were installed in 1952. They concluded that surface horizons of soils may benefit from fixation of K from flood waters. The relationship between % K in ECEC and exchangeable K, though significant ($P = 0.01$), was not linear (Fig 9), suggesting that some K in adsorption sites is not readily exchangeable. Khan and Fenton (1996) attributed this phenomenen to the differences in selective adsorption of K by constituent soil colloids.

Some of the K extracted with neutral $NH_4OAc$ is in soil solution, and may be substancial, particularly in sandy soils (Grimme, 1979). Considering that exchange sites have a preference for divalent cations (Barber, 1995), soils of high % K must have a high K activity ratio and a likely deficiency of divalent cations. Such is a likely occurrence in soils from Kabula formed on granites; which are low in Ca and Mg but rich in K which was assumed to have been deposited colluvially from higher grounds.

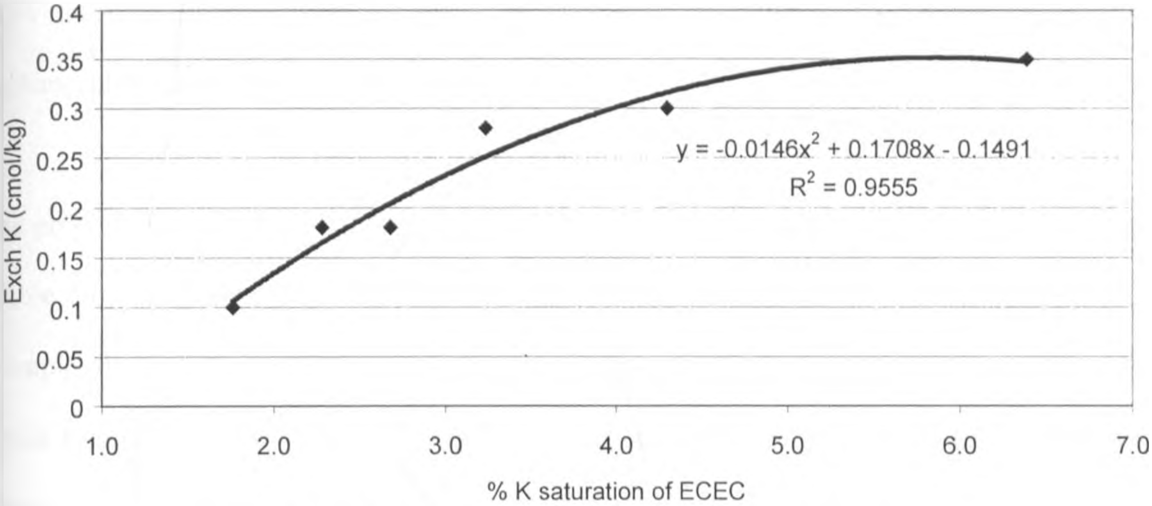

Fig 9: A plot of exch K against K saturation of ECEC in studied soils

Stepwise regression did not reveal a significant relationship between ECEC and either clay or organic C content in surface soils, or between ECEC and illite or kaolinite composition of the clay fraction of soils. Relationships between TEB and the soil parameters were not significant at $P \leq 0.05$, either. Escudey *et al.* (2004); did not find significant correlation between ECEC and organic matter in volcanic ash derived soils of Chile. They however observed a direct relationship between $CEC_{pH = 8 2}$ and organic C, which indicated the importance of organic matter in CEC of Andisols and Ultisols that have crystalline clay minerals (e.g. kaolinite), and lower organic matter contents. Organic matter accounted for 10 – 85 % of the CEC in such soils (Escudey *et al.*, 2004). In the current study, therefore, poor correlations were explained by low dissociation of pH-dependent charges at pH 7.0, resulting in underestimate of the CEC.

The TEA values ranged from 0.60 – 1.57, and were higher in soils from the SGA (mean = 1.32 cmol ($p^+$) $kg^{-1}$), than soils from NGA (mean = 0.70 cmol ($p^+$) $kg^{-1}$). As found in this research study, soils from the SGA were formed from parent materials, where major K – containing minerals were K-feldspars (Table 12). Consequently, the high TEA was attributed to the high Al formed after weathering of orthoclase. Also, it has been postulated that the high organic matter in SGA forms complexes with Al, which though stable still has a potential to increase the exchangeable acidity.

The proportion of TEA in ECEC ranged from 7.2 – 23.4 % (data not shown). Results for TEA (Table 16), have been used as an indicator for lime requirements in soils. In South Africa, for example, liming is recommended if the acid saturation of CEC is > 20 % (Sumner and Yamada, 2002). Using the same criterion, therefore, liming is recommended in Keumbu and Ndanai soils, where % TEA is about 20 %. Because of their very low CECs, highly weathered soils may be very low in exchangeable acidity, and crop response to liming would be primarily due to additions of Ca and Mg, rather than pH changes (Kamprath, 1984).

## 4.4: Parent rocks and exchangeable bases

### *4.4.1 Exchangeable potassium and parent rocks*

The exchangeable K status among soils and variation with depth is given in Table 17. There was a significant difference ($P < 0.001$) among sites, but depth effects were not significant at $P \leq 0.05$. Exchangeable K decreased in the order: Kabula > Itare > Keumbu = Ndanai > Ebukanga > Yala. Apart from the high K status in Kabula soils, a similar order was obtained in samples from farmers' fields (Table 4); where soils from SGA had significantly higher K content than soils in the NGA. As argued earlier (section 4.3.4), analysed samples from Kabula may have been contaminated with soluble K in runoff water from higher grounds. Correlation between rock- K and exchangeable soil –K was not significant at $P \leq 0.05$.

Table 17: Average[1] exchangeable potassium content at different depths of studied soils.

| Site | Soil depths (cm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-30 | 30-60 | 60-90 | 90-120 | 120-150 | >150 | Mean[2] |
| | Potassium, cmol $(p^+)$ $kg^{-1}$ | | | | | | |
| Itare | 0.170 | 0.150 | 0.200 | 0.295 | 0.220 | 0.250 | $0.2142^{c}$ |
| Keumbu | 0.205 | 0.165 | 0.175 | 0.215 | 0.225 | 0.205 | $0.1983^{bc}$ |
| Ndanai | 0.265 | 0.165 | 0.140 | 0.140 | 0.175 | 0.212 | $0.1829^{bc}$ |
| Ebukanga | 0.175 | 0.175 | 0.125 | 0.125 | 0.150 | 0.175 | $0.1542^{b}$ |
| Yala | 0.100 | 0.100 | 0.075 | 0.075 | 0.075 | 0.100 | $0.0875^{a}$ |
| Kabula | 0.350 | 0.300 | 0.200 | 0.275 | 0.300 | 0.375 | $0.3000^{d}$ |
| Mean | 0.2108 | 0.1758 | 0.1525 | 0.1875 | 0.1908 | 0.2196 | 0.1895 |

[1]Figures shown are averages of four replicate samples. [2]Superscripts: Same letter = no significant difference between means. None = P for treatment in ANOVA > 0.05. LSD among sites was 0.05971 ($P < 0.001$).

The efficiency of rock K conversion to exchangeable soil K was calculated as a rock K: soil K ratio depicted in Table 18.

Table 18: Potassium content in rocks and exchangeable K in soils, and the rock K: soil K ratio

| Site | Potassium content[1] (%) | | Rock: Soil ratio[2] | |
|---|---|---|---|---|
| | Rock K | Soil K (x $10^{-3}$) | Absolute | Relative |
| Ndanai | 0.09 | 10.34 | 9 | 0.01 |
| Keumbu | 1.48 | 8.00 | 185 | 0.27 |
| Itare | 1.87 | 6.63 | 282 | 0.42 |
| Kabula | 4.34 | 13.65 | 318 | 0.47 |
| Ebukanga | 3.61 | 6.83 | 529 | 0.78 |
| Yala | 2.64 | 3.90 | 677 | 1.00 |

[1] Values for rocks are borrowed from Table 8, and soil K (exchangeable K values from 0 –30 cm depth) from Table 17, recalculated to a percent. Table components sorted in ascending order downwards according to relative values (column 5).

Generally, rocks from the SGA (Ndanai, Keumbu and Itare); had lower rock K: soil K ratios (mean = 159 ± 139), than soils from NGA (Kabula, Ebukanga, Yala); (mean = 508 ± 180). There were four possible explanations to this: First, soils from SGA had higher organic matter content than soils from the NGA (Table 15). Mineralization of organic matter, releases organic ligands, which are strong weathering agents, that speeds up the decomposition of particularly mafic minerals (Harley and Gilkes, 2000), releasing K and other cations to the soil. Second, due to the high organic matter contents, organic contribution of K after mineralization is likely to be higher in SGA than NGA, thereby lowering the ratios. Thirdly, rocks from NGA had significantly higher K contents (P = 0.031), and lower exchangeable K content in surface horizon (Table 18). Soils from the NGA are older and have, therefore, been exposed to weathering forces for a longer period, and have probably lost more K through leaching. Fourthly, the form of K in parent rocks, whether biotite or orthoclase determines the ease of weatherability, and amount of nutrients released to the soil. The main K- bearing minerals in NGA are biotites, while K-bearing minerals in SGA are K – feldspars. Biotites have apparently weathered completely, K released, and lost from the solum.

The ratio for Ndanai soil was very low (Table 18), and exchangeable K levels could not be attributed to the K content in rocks. Potassium in Ndanai soils was perhaps deposited as a contaminant through runoff from higher grounds. Smaling *et al.* (1997), when working in western Kenya, identified runoff as the second most important nutrient loss pathway in Kisii highlands after crop uptake. Naturally, then, low-lying areas, which are net recipients of runoff, may get enrichment of nutrients washed out of adjecent lands higher up. Gachene (1986) recorded 1.05 to 2.23 times as much K in eroded soil material than in un-eroded material.

Potassium content in parent material may be a good indicator of the likely content of K in overlying soils, but inability to derive predictive models emphasizes the multiplicity of factors that determine exchangeable K status in soils. Current soil K status is a balance between losses through leaching, erosion, runoff and uptake, and gains through weathering of parent materials, plant residue mineralization, deposition and addition of manures or fertilizers. No efforts were made to determine the rate of release of rock K to the soil pool, or amount of K deposited through runoff and colluvial material (Plate 2). Comparisons between parent materials can, therefore, only be done if corrections are done for K from organic sources, colluvial contamination, nature of primary minerals, and age of parent materials. The variation of exchangeable K with depth is plotted in Fig 10.

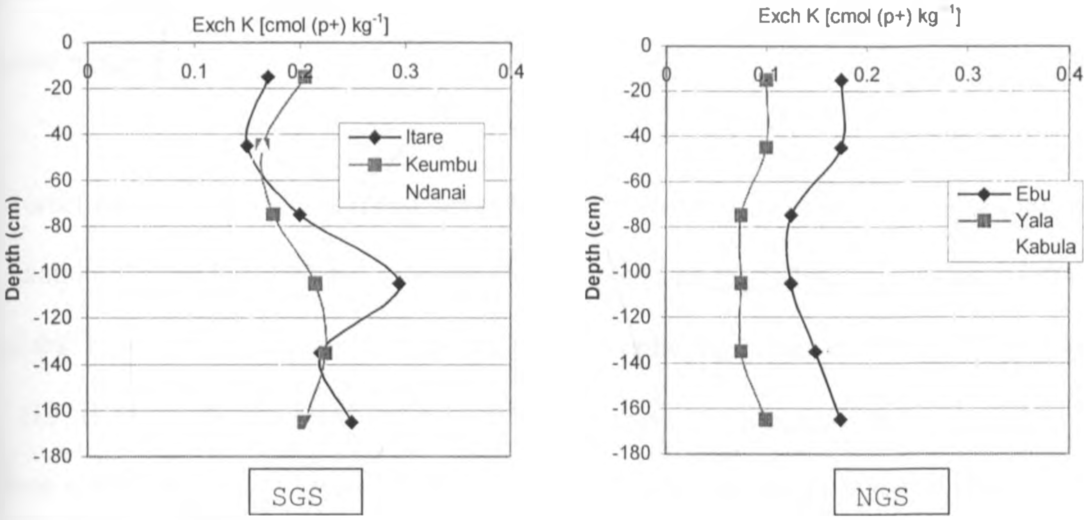

Fig 10: Variation of exchangeable K with depth in soils from southern (SGA) and northern (NGA) geomorphic areas

There was $K^+$ accumulation at the surface 0 - 30 cm in soils from the SGA, and 0 - 60 cm in soils from the NGA. Potassium accumulation in surface horizons was attributed to the continuous release from decomposing organic materials. Potassium content in above ground parts of most plants is much higher than that of Ca and Mg, and decomposition of plant residues releases more K than other cations (Haby *et al.,* 1990; Kaboneka and Sobbe, 1995). Kaboneka and Sobbe (1995) reported that K release from organic materials is sometimes due to non-biological processes, such as leaching of residues; due to irrigation or rainfall, and that organic residues compare well with inorganic fertilizers in efficiency of K recovery.

Surface soil horizons may have high exchangeable K values than sub-surface horizons because there is higher organic matter at the surface, yet K bonding energy to organic matter is weaker than to mineral fractions of soils. Uribe and Cox (1988), and Haby *et al.* (1990), reported that, due to the weak bond between $K^+$ ions and organic matter, organic rich soils have a higher K concentration in the equilibrium solution than soils of equivalent exchangeable K but low in organic matter.

The other possible source of K found in surface horizons of soils is the dynamic reversible process of fixation and release of K due to seasonal wetting and drying (Khan and Fenton, 1996). Also, available K is higher in surface soils due to intense weathering (Khan and Fenton, 1996). Mohr *et al.*, (1972) reported a decrease of kaolinite and increase of illite down the soil profile, due to intense weathering at the surface. There was a second accumulation of K below 100 cm depth in Itare, Keumbu, Ndanai and Kabula soils, which was ascribed to leaching. No such accumulations occurred in soils from Ebukanga and Yala, which have been found to contain lowest exchangeable K (Tables 16 and 17), lowest in soil K: rock K (Table 18), and lowest % K in CEC (Table 16).

High leaching, therefore, occurs where K occurs in large amounts in labile form, and is loosely bound. Yala soils were inherently low in K due to the great weathering of plagioclase and biotite, leading to low reserve K, in sand fraction. Ebukanga soils have high orthoclase content in the sand fraction, which, unfortunately, is resistant to weathering (Table 12). Considering that the two soils are low in organic matter, little K is being released from inherent sources, and none is being leached at the moment. The K released during alteration has perhaps been leached deeper or washed out of the solum in drainage water.

Alternatively, soils from Ebukanga and Yala where no leaching was identified, may, by virtue of their high clay but low organic matter content (Table 10), have a problem of surface sealing. Clay particles in the absence of organic matter are easily dispersed by rain - drops, clog up the soil pores, reduce infiltration; and increase surface runnoff and soil erosion (Sumner and Yamada, 2002). Surface sealing reduces circulation of air, and hence root respiration, which in turn affect the rate of root growth and nutrient uptake (Grimme, 1979). Leached K under such circumstances can only be accessible to deep- rooted crops.

Potassium may also be selectively adsorbed or fixed at the surface layers, to an extent that no leaching occurs. Fixation of K in surface horizon, and the resulting possibilities of denying subsurface horizons of plant available K can cause K deficiency in deep- rooted crops (Keryn *et al.*, 2003). The K bulge in profiles was increasingly shallow in the order: Itare > Keumbu > Ndanai = Kabula, and is shallow where moisture availability index (r/Eo) is lower. In SGA, depth of accumulation increases with increase in elevation, possibly because of increased leaching in wetter, cooler highlands. Similar observations were made in volcanic ash soils of Equador (Zahetner *et al.,* 2003).

### *4.4.2 Exchangeable calcium and magnesium content in soils*

The level of exchangeable Ca and Mg in soils and variation with depth are shown in Table 19. Calcium levels in the surface horizon decreased in the order: Itare > Ebukanga > Ndanai > Yala > Keumbu > Kabula. Magnesium levels decreased in the order: Itare > Ebukanga > Keumbu > Yala > Kabula > Ndanai. Soil- Mg contents were significantly influenced by the rock- Mg contents (P =

0.018, $r^2 = 0.739$), but correlations between soil – Ca and rock-Ca were not significant at $P \leq 0.05$.

Table 19: Average[1] calcium and magnesium contents at different depths of studied soils

| Site | Soil depths (cm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-30 | 30-60 | 60-90 | 90-120 | 120-150 | >150 | Mean[2] |
| | | | Calcium, cmol ($p^+$) $kg^{-1}$ | | | | |
| Itare | 5.25 | 4.33 | 3.70 | 2.75 | 2.38 | 1.93 | $3.39^{b}$ |
| Keumbu | 3.53 | 2.08 | 2.43 | 2.08 | 1.95 | 1.85 | $2.32^{ab}$ |
| Ndanai | 4.03 | 2.70 | 1.45 | 1.08 | 1.05 | 1.15 | $1.91^{a}$ |
| Ebukanga | 5.15 | 3.85 | 3.58 | 3.40 | 3.25 | 3.10 | $3.72^{b}$ |
| Yala | 3.58 | 3.75 | 3.93 | 3.28 | 2.88 | 2.75 | $3.36^{b}$ |
| Kabula | 2.88 | 2.63 | 2.65 | 2.73 | 2.78 | 2.60 | $2.71^{ab}$ |
| Mean | $4.07^{b}$ | $3.22^{ab}$ | $2.95^{a}$ | $2.55^{a}$ | $2.38^{a}$ | $2.23^{a}$ | 2.90 |
| | | | Magnesium, cmol ($p^+$) $kg^{-1}$ | | | | |
| Itare | 2.075 | 1.975 | 2.125 | 1.775 | 1.800 | 1.525 | $1.879^{c}$ |
| Keumbu | 1.425 | 1.450 | 1.050 | 1.000 | 1.125 | 1.175 | $1.204^{b}$ |
| Ndanai | 1.300 | 0.900 | 0.600 | 0.450 | 0.450 | 0.525 | $0.704^{a}$ |
| Ebukanga | 1.975 | 1.500 | 1.350 | 1.325 | 1.475 | 1.425 | $1.508^{bc}$ |
| Yala | 1.400 | 1.275 | 1.175 | 1.100 | 1.075 | 1.100 | $1.188^{ab}$ |
| Kabula | 1.325 | 1.100 | 1.125 | 1.175 | 1.275 | 1.075 | $1.179^{ab}$ |
| Mean | 1.583 | 1.367 | 1.238 | 1.138 | 1.200 | 1.138 | 1.277 |

[1]Figures shown are averages of four replicate samples. [2]Superscripts: Same letter = no significant difference between means. None = P for treatment in ANOVA > 0.05. LSD for calcium and magnesium among sites were 1.090 ($P = 0.009$) and 0.4930 ($P < 0.001$), respectively. LSD for calcium among depths was 1.090 at $P = 0.013$.

Table 20 shows the results for the rock Ca: soil Ca, and rock Mg: soil Mg ratios (absolute values). The ratio for Ca ranged from 1 - 49, and increased in the order: Ndanai < Keumbu < Kabula < Yala < Ebukanga < Itare. The ratio for Mg ranged from 3 – 205, and increased in the order as that of Ca (Table 20). Highest ratios were obtained in soils formed from rocks that had the highest mafic: felsic ratios (Table 7), and soils with highest clay content (Table 10), and lowest illite: kaolinite ratios (Table 14). Since clayey soils are normally regarded to have weathered more strongly than coarse textured soils (Smith, 1962), it is reasonable to argue that soils with high rock: soil ratios had had greater losses of the cations from labile pools. Alternatively, rocks with high mafic: felsic mineral ratios, being more endowed with ferromagnesian minerals have had greater losses from soils than the primary minerals have disintegrated.

Small rock: soil cation ratios were attributed to high adsorption energy of Ca and Mg to illitic soils (Barber, 1995). Plagioclase, biotite and ferromagnesian silicates in rocks may have altered greatly at the time of analysis, thus underestimating the Ca and/ or Mg content in rocks. After weathering, the cations had remained adsorbed in exchange sites due to their high binding energy (Barber, 1995), thus lowering the ratios. The possibility of deposition of cations by runoff from higher grounds to the soils from Kabula and Ndanai was not ruled out, which would effectively lower the ratios.

Table 20: Ratio[1] of rock contents of calcium and magnesium (% oxide) to the corresponding exchangeable levels (%) in surface soil layers of studied soils (absolute values), and their relative values.

| | Calcium | | Magnesium | |
|---|---|---|---|---|
| Site | Absolute | Relative | Absolute | Relative |
| Ndanai | 1 | 0.02 | 3 | 0.01 |
| Keumbu | 5 | 0.10 | 22 | 0.11 |
| Kabula | 8 | 0.16 | 30 | 0.15 |
| Yala | 31 | 0.63 | 132 | 0.64 |
| Ebukanga | 40 | 0.82 | 172 | 0.84 |
| Itare | 49 | 1.00 | 205 | 1.00 |

[1] Exchangeable Ca and Mg expressed in % are calculated from 0 – 30 cm depths in Table 19. Table components sorted in ascending order downwards according to relative values of calcium.

The relative values for each of Ca and Mg ratios between rocks and soils (Table 20); were not significantly different ($P = 0.989$), suggesting that both Ca and Mg suffered the same fate in the weathering environment. This result was expected because both Ca and Mg originate from primary minerals of high weatherability (augites, hornblende, anorthite and biotite), are subjected to the same soil environment, being divalent.

The variations of exchangeable $Ca^{2+}$ and $Mg^{2+}$ with depth are shown in Table 19. Calcium levels decreased significantly ($P = 0.013$) with depth. Surface accumulations were ascribed to release from decomposing organic residues and intense weathering of parent rocks, and the low $Ca^{2+}$ mobility in soils. There was greater decrease in exchangeable Ca with depth in the SGA than in the NGA ($P = 0.019$), perhaps due to the greater influence of organic matter in SGA than NGA. Organic acids complex with $Ca^{2+}$ ions in soil solution, and form precipitates of oxalate and citrate salts (Harley and Gilkes, 2000), which may accumulate at the surface where organic matter is high. Variation of exchangeable $Mg^{2+}$ with depth was not significant, and Mg was assumed to have leached out of the soil in drainage water. Magnesium mobility in soils is higher than that of $Ca^{2+}$ (Barber, 1995), and hence the cation may be easily leached.

The anomalies discussed not withstanding, it was concluded that basic rocks (higher Mafic: Felsic mineral ratios), are more likely to weather into soils richer in $Ca^{2+}$ and $Mg^{2+}$, because ferromagnesian silicates and plagioclase feldspars are more prevalent in basic rocks, than acid rocks (Simpson, 1969; Hunt, 1972), and that Niggli values for *ca* and *fm* were inversely related to *si*-values (Fig 7). Conversely, acid rocks are more likely to weather into soils that are poor in exchangeable $Ca^{2+}$ and $Mg^{2+}$. Shepherd *et al.* (2001), found higher levels of $Ca^{2+}$ and $Mg^{2+}$ in top- and sub-soil layers of soils developed from basic igneous parent materials than in soils developed from acid igneous rocks.

Itare soil showed a small bulge of $Mg^{2+}$ at around 80 cm depth, and Yala soil a $Ca^{2+}$ bulge at the same depth. Other soils did not show a net accumulation of $Ca^{2+}$ and $Mg^{2+}$, relative to the surface. Soils from Yala and Itare, which showed a bulge, did not have surface accumulations of corresponding nutrients, and had the highest proportion of kaolinite in clay fraction (Table 9). Soils that lack 2:1 clay minerals may not hold cations strongly, leading to leaching (Barber, 1995). Alternatively, since the two soils contained the highest clay, they were least permeable.

Consequently, the cations may have leached to the 80 cm depth in Itare and Yala, but out of the solum in less clayey soils. Itare soils are located in a comparatively drier region, relative to Keumbu and Ndanai (Table 2), and may explain the limited leaching of cations in Itare, but complete flushing out in Keumbu and Ndanai. Other workers, (Sparks, 1987, Davis *et al.,* 1996), reported increased leaching of basic cations, as soil texture gets coarse.

Leaching of cations in the fine textured soils from Itare and Yala was not expected. Shepherd *et al.* (2001), however, reported high leaching of N in agricultural systems in the humid and subhumid tropics with high rainfall and porous soils. They attributed the enhanced porosity in soils to stable aggregation characteristic of acid tropical soils with variable charge, due to high contents of kaolinite and sesquioxides. Kaolinite and sesquioxides have high anion exchange capacity (AEC), which results in loss of cation adsorptive power of soils and enhanced leaching. High porosity leads to rapid drainage and leaching of cations. Yala and Itare soils had the lowest illite: kaolinite ratios (Table 14).

A rough indicator of the stability of aggregates was expressed in terms of the % fine fraction, determined as a proportion of dry soil sample; which was easily ground by hand to pass through a 2- mm sieve (Fig 11). The % fine fraction was significantly different among sites ($P = 0.039$) and depths ($P = 0.044$). In the less clayey soils from Ndanai and Kabula of SGA and NGA, respectively (Table 10), variation of stability in aggregates with depth was greatest (Fig 11). The greatly reduced % fine fraction with depth, in Kabula soils, was expected due to plinthite formation in these soils. In both geomorphic areas, the % fine fraction was lowest in the fine-textured soils of Itare and Yala. Soils with stable micro-aggregates retain large quantities of water in the micropores, yet drain rapidly through the macro (between aggregates) pores ($\varnothing > 0.06$ mm), and thus favor leaching (Shepherd *et al.*, 2001).

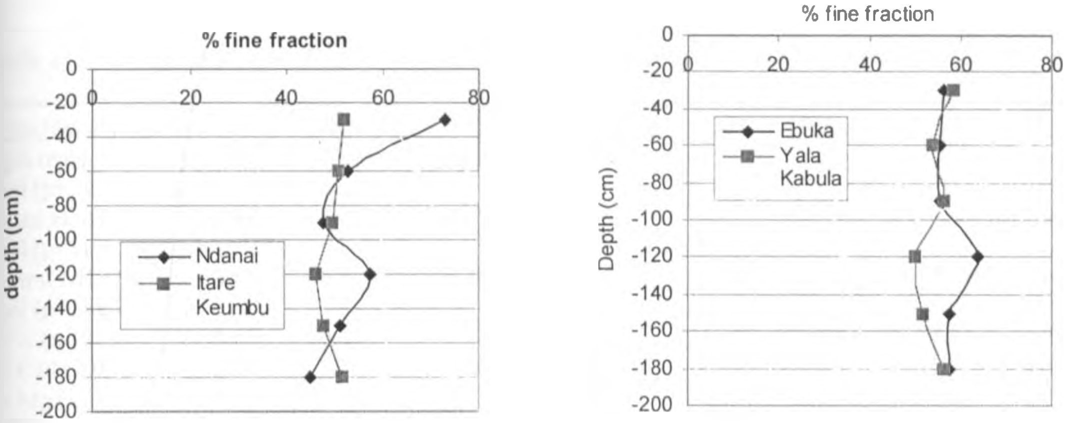

Fig 11: Percent fine fraction at different depths of studied soils

### 4.5: Distribution of soil K in various pools

Results for Aqua regia (total), boiling $HNO_3$ (exchangeable + non- exchangeable); neutral $NH_4OAc$ (exchangeable), and water (solution)- K extracts, from surface soils are given in Table 21. Extracted K increased with increasing strength of extracting reagent; in the order: water < neutral $NH_4OAc$ < boiling $HNO_3$ < Aqua regia.

Total K ranged from 10.7 – 48.5 cmol ($p^+$) $kg^{-1}$, and increased in the order: Yala < Itare < Kabula < Keumbu < Ndanai < Ebukanga. The range was wide, but inclusive of 43.6 cmol ($p^+$) $kg^{-1}$, (1.7 %); the average for natural soils given by Sparks (1980). The correlation between total K in soils and % K in parent rocks was not significant at $P \leq 0.05$. Total K, however, correlated positively and significantly (P = 0.013, SE = 6.55), with orthoclase content in sand fraction (Table 12, Fig 12). The results are in agreement with increase in *alk* – Niggli values as parent rocks become more acid (Fig 7), because orthoclase is the dominant mineral in acid rocks (Simpson, 1969). Results also illustrate the influence of K- mineral resistance to weathering on total K contents in soils.

Table 21: Average amounts of potassium in surface soils from study sites, by different extractants[1]

| Extraction method[2] | Itare | Keumbu | Ndanai | Ebukanga | Yala | Kabula | LSD | P[4] |
|---|---|---|---|---|---|---|---|---|
| Aqua regia cmol (p+) $kg^{-1}$ | $13.2^{a}$ | $27.9^{b}$ | $31.4^{b}$ | $48.5^{c}$ | $10.7^{a}$ | $26.2^{b}$ | 12.51 | <0.001 |
| Boiled $HNO_3$ cmol (p+) $kg^{-1}$ | $0.750^{a}$ | $0.875^{a}$ | $0.675^{a}$ | $0.625^{a}$ | $0.725^{a}$ | $1.350^{b}$ | 0.3225 | 0.003 |
| Neutral $NH_4OAc$ cmol (p+) $kg^{-1}$ | $0.170^{ab}$ | $0.205^{ab}$ | $0.265^{b}$ | $0.175^{ab}$ | $0.100^{a}$ | $0.350^{b}$ | 0.1333 | 0.019 |
| Sol K (x $10^{-2}$) | 0.92 | 0.48 | 1.72 | 1.43 | 1.82 | 1.53 | 2.16 | $0.759^{ns}$ |
| Sol Ca (x $10^{-2}$) | 3.58 | 1.13 | 3.80 | 1.53 | 1.23 | 0.45 | 3.54 | $0.279^{ns}$ |
| Sol Mg (x $10^{-2}$) | 1.61 | 1.53 | 3.85 | 1.33 | 0.93 | 0.33 | 1.94 | $0.027^{*}$ |
| KAR[5] | 0.59 | 0.74 | 0.90 | 0.73 | 0.71 | 0.65 | NA | NA |
| NEK[1] cmol (p+) $kg^{-1}$ | 0.580 | 0.670 | 0.410 | 0.450 | 0.625 | 1.000 | NA | NA |
| Buffer power (Φ)[3] | 18.5 | 42.7 | 15.4 | 12.2 | 5.5 | 22.9 | NA | NA |

[1]Superscripts (a.b.c): different letters indicate significant differences between soils, [2]Aqua regia = HCl + $HNO_3$ in ratio 3:1 + HF; Dist. water = distilled water; NEK = Non- exchangeable K. (boiled $HNO_3$ – neutral $NH_4OAc$). [3]Buffer power (Φ) = $NH_4OAc$ $pH_7$ – K/ distilled $H_2O$ - K. [4] P = level of probability, [5]KAR= Potassium Activity Ratio, calculated from activities of Ca, Mg and K, in each of the solution extracts (Greenwood and Karpinets, 1997), i.e. activity (a) = c.f., where c= concentration as in table, and f= activity coefficient, from Debye-Huckel equation (Verloo, 1990). NA = not applicable

Total K appeared to decrease with increase in clay content, and increase with increase in illite/ kaolinite ratio, but the correlations were not significant at $P \leq 0.05$. The result was not surprising because high clay soils are more weathered, presumably because they are low in orthoclase as postulated in this research work. The converse is true for soils with higher illite: kaolinite ratio (Fig 8). Mohr *et al.* (1972) reported higher illite: kaolinite ratio in sub-surface horizons of soils where advancement in weathering was low.

Total contents of K in soils, serves as a good indicator of potential reserves in soils but show little information on K availability to crops (Sparks, 1980). Among the soils from northern geomorphic area (NGA), total K was higher in Ebukanga than Yala and Kabula, possibly due to the high orthoclase content in sand fraction of Ebukanga soil (Table 12). Soils from Yala, Kabula and Itare, which are construed in this study to contain biotite as the main K-containing mineral had low total K contents. In this research work, high clay content and low illite: kaolinite mineral ratios have been found to depict a high degree of weathering in soils.

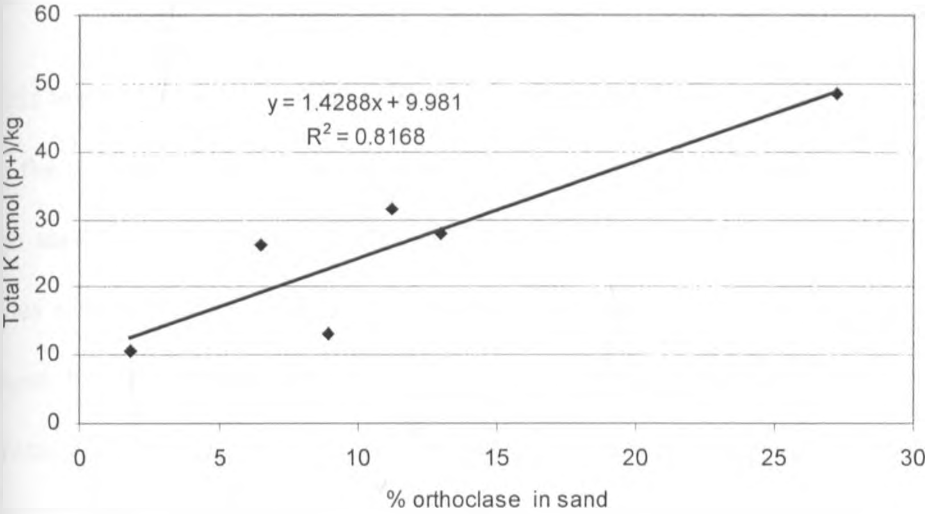

Fig 12: Relationship between total potassium of whole soil and orthoclase content in sand fraction of studied soils

Ebukanga soil had 53 % clay (Table 10) and highest total K because of high orthoclase content in the sand fraction (Table 14). The parent rock from Ebukanga had about 25 % mafic minerals (Table 7), which may have weathered quickly and formed clay alongside the sand. The result shows that high clay soils may not necessarily be low in total K, particularly when orthoclase forms a major component of the sand fraction.

Nitric acid extractable K ranged from, 0.625 – 1.350 cmol ($p^+$) $kg^{-1}$, (Table 21), which represented 1.3 – 6.8 % of the total K in soils. The correlation between $HNO_3$-extractable K and clay content in soils, and between $HNO_3$-extractable K and illite/ kaolinite ratio was not significant at $P \leq 0.05$. The relationship between total K and $HNO_3$-extractable K was not significant at $P \leq 0.05$, but the percent of total K extracted with $HNO_3$ (Y), was inversely proportional to total soil K (TK), as defined by the derived equation below:

$$Y = 7.88 - 0.1465\ TK\ (r^2 = 0.802,\ P = 0.01)$$

This relationship suggests that soils with high total K contents contribute proportionately less of it to the slowly and readily available pools. This is probably because most of the total K occurs in the sand fraction, where it is tied in orthoclase (Table 12). According to Barber (1995), $HNO_3$ does not decompose sand-sized particles, but decomposes the clay-sized particles releasing K in them. Nitric acid extractable K is a summation of K on the surface of exchange sites, and that entrapped between the interlayers of phyllosilicate minerals (Barber, 1995). According to this research work, the dominant clay minerals in studied soils are illites and kaolinite (Table 14). Since clay soils have higher surface area for adsorption than sandy soils, it is not surprising that a higher proportion of $HNO_3$ – extractable K in clayey soils is in the labile pool. In deed, this work has shown that high clay soils have less illitic minerals (Fig 8), and thus, only a small amount of the K would be selectively adsorbed.

Neutral $NH_4OAc$- extractable (exchangeable) - K ranged from 0.1 – 0.35 cmol (p+) $kg^{-1}$, (Table 21), and was in the low range (Marx *et al.,* 1999) in all soils. Exchangeable K was negatively and significantly ($P = 0.031$), correlated with clay content in soils. The result is in contrast to the findings by Singh and Agrawal (1995), who reported a positive correlation between available K and clay content in Indian soils. Further analysis showed that neutral $NH_4OAc$ extracted between

14 – 39 % of the $HNO_3$- extractable K in the different soils. The relationship between $NH_4OAc$- K and $HNO_3$- K was not significant at $P \leq 0.05$.

The relationship between $NH_4OAc$- K: $HNO_3$- K ratio (% labile K), and illite/kaolinite ratio is shown in Fig 13. It has been found in this research work that soils with a low illite: kaolinite ratio are the more weathered, and have lower sand content. Since hot $HNO_3$ does not decompose sand sized particles (Barber, 1995), the proportion of labile pool in coarse textured soils may be exaggerated if compared with soils of fine texture. In a similar study by Grimme (1979), it was found that sandy soils have a greater part of their readily extractable K in labile form than clayey soils, which agrees with the current results plotted in Fig 13. Sparks (1980), singled out sand and silt fractions of the soil as home for reserve K that buffers up the K adsorbed in clays.

Nitric acid extractable K increased in the order: Ebukanga < Ndanai < Yala < Itare < Keumbu < Kabula. The high $HNO_3$- K in Kabula soils cannot be attributed to high clay content (Table 10), but probably due to the easily extractable K in surface soils fixed from runoff water as argued in this research work. Most of the total K was not neutral $NH_4OAc$- extractable, with the latter extracting 0.4 – 1.3 % of the total K, but in the same order of magnitude of the range of 1 – 4 % given by Haby *et al.* (1990), and 0.4 % given by Sparks (1980).

Assuming, therefore, that soils with high illite: kaolinite ratio, and thus high labile K (Fig 13), will have a higher plant K availability, crops will increasingly have easier access to K in the order: Itare < Yala < Ebukanga = Kabula < Keumbu < Ndanai (Table 10, Fig 8). Differences may occur due to the K contribution by other input pathways. Ndanai soil was the least weathered (least clayey), and Itare soil the most weathered (most clayey). No efforts were made to determine how

$K^+$ ions were distributed among the fixing sites in soils. Exchangeable K increased in the order: Yala < Itare < Ebukanga < Keumbu < Ndanai < Kabula, which agrees with the sequence of likely ease of K availability to crops, discussed above.

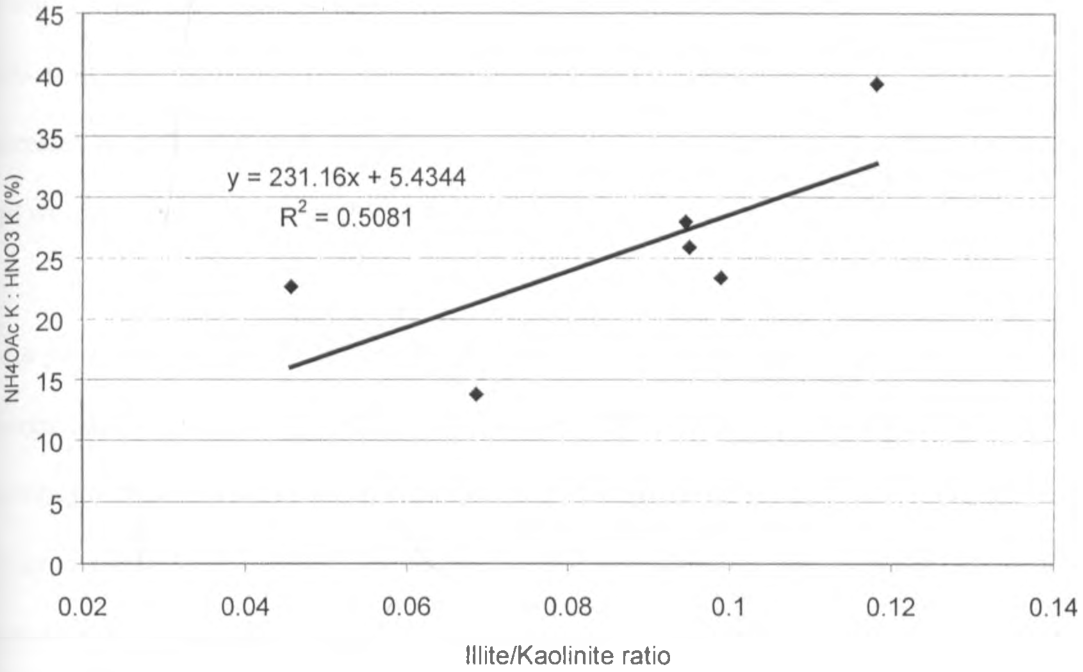

Fig 13: Exchangeable K in $HNO_3$.K (%) Vs illite/kaolinite ratio in clay of studied soils

Solution K ranged from 0.48 – 1.82 x $10^{-2}$ cmol ($p^+$) $kg^{-1}$ (Table 21), which was 2.3 – 18.2 % of the $NH_4OAc$ – K. Solution K was not significantly correlated to total K, $HNO_3$- extractable K, $NH_4OAc$ – K, or clay content. Water extracts the K that is in equilibrium with adsorbed K, and solution concentrations are dependent on the buffer power (Φ) of the particular soil (Barber, 1995). Solution K increased in the order: Keumbu < Itare < Ebukanga < Kabula < Ndanai < Yala. Heckman and Kamprath (1995), used solution- K to estimate the K potential (intensity), denoted by I, and exchangeable – K to estimate quantity, denoted by Q in soils.

Of major importance, however, is the potassium activity ratio (KAR), which takes into account the differences in K mobility that occur in soil solution as a result of repulsion, attraction or pairing by/with other cations and anions (Verloo, 1990). Potassium activity ratio ranged from 0.59 – 0.90 (Table 21) and correlated positively ($r^2 = 0.579$, $P = 0.048$) with increase in illite: kaolinite ratio of soils (Fig 14). This was probably due to reduced clay content in soils as illite: kaolinite ratio increases (Fig 8). High clay content offers great resistance to diffusion of cations (Grimme, 1979), and would probably also affect K uptake by crops.

Data for buffer power (Φ) is included in Table 21, where Φ values ranged from 5.5 – 42.7 and decreased in the order: Keumbu > Kabula >Itare > Ndanai > Ebukanga > Yala. Correlations between buffer power and soil parameters (e. g. clay, organic C, illites etc); were not significant, either in simple or in stepwise regressions. Factors that determine buffer power of soils towards K were therefore not fully described.

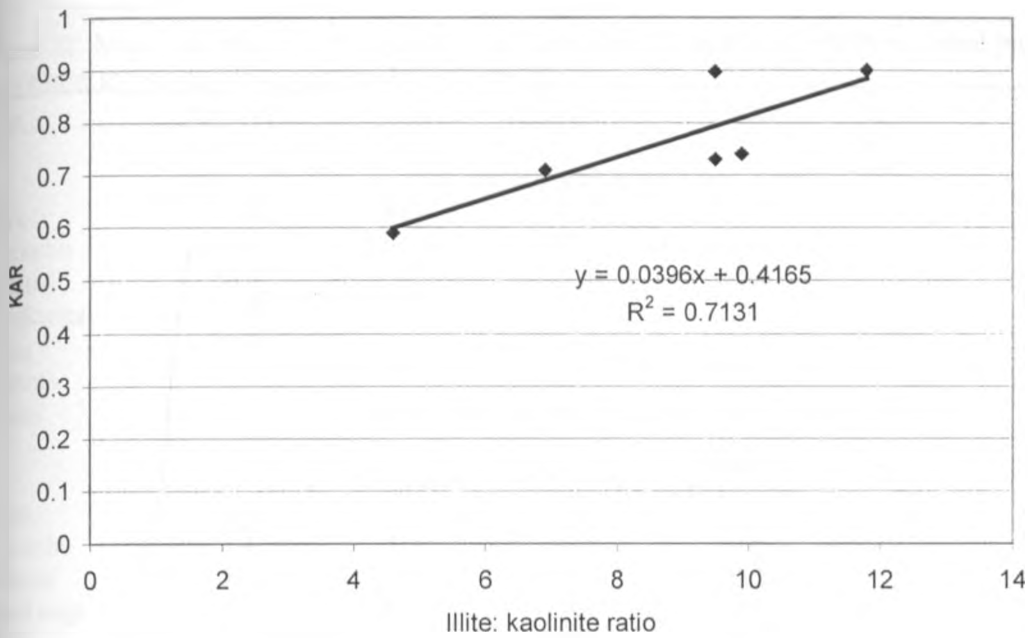

Fig 14: Variation of potassium activity ratio (KAR) with illite: kaolinite ratio of studied soils

## 4.6 Greenhouse experiments

Data for dry matter (DM) yields, K concentration and K uptake in tops of successively grown maize plants are given in Table 22.

### *4.6.1 Dry matter yields*

Variation of maize DM yields for each soil type during successive growth cycles of eight weeks is displayed in Fig 15. Yields were low in the first growth cycle in all the soils, perhaps due to nutritional imbalances caused by liming. Posse and Mendoza (1995) reported P deficiency, while other workers (Evans and Kamprath, 1970; Reeve and Sumner, 1970), reported trace element deficiencies in soils, after liming.

Table 22: Mean[1] dry matter yields (g/pot), % K content and K uptake (g/pot) from potted maize plants in successive growth cycles of eight weeks for each soil

| Site | Cycle 1 | Cycle 2 | Cycle 3 | Cycle 4 | Cycle 5 | Mean[2] |
|---|---|---|---|---|---|---|
| Dry matter yields (g/pot)[3] | | | | | | |
| Itare | 39.4 | 84.8 | 77.4 | 56.7 | 61.1 | 63.9$^{b}$ |
| Keumbu | 46.3 | 91.6 | 85.9 | 50.4 | 56.1 | 66.0$^{b}$ |
| Ndanai | 56.8 | 110.2 | 98.0 | 65.7 | 65.9 | 79.3$^{c}$ |
| Ebukanga | 39.7 | 74.6 | 65.2 | 50.4 | 46.7 | 55.3$^{a}$ |
| Yala | 48.7 | 76.4 | 68.9 | 51.2 | 52.8 | 59.6$^{ab}$ |
| Kabula | 82.9 | 100.0 | 89.1 | 73.1 | 64.6 | 81.9$^{c}$ |
| Mean | 52.3$^{a}$ | 89.6$^{d}$ | 80.7$^{c}$ | 57.9$^{b}$ | 57.9$^{b}$ | 67.7 |
| Potassium concentration in tops (%) | | | | | | |
| Itare | 1.8 | 0.7 | 0.4 | 0.3 | 0.6 | 0.7$^{b}$ |
| Keumbu | 2.4 | 0.8 | 0.5 | 0.3 | 0.4 | 0.9$^{c}$ |
| Ndanai | 3.0 | 1.2 | 0.5 | 0.3 | 0.4 | 1.1$^{d}$ |
| Ebukanga | 1.1 | 0.3 | 0.3 | 0.3 | 0.3 | 0.5$^{a}$ |
| Yala | 1.2 | 0.4 | 0.3 | 0.4 | 0.5 | 0.6$^{a}$ |
| Kabula | 1.7 | 0.6 | 0.4 | 0.4 | 0.5 | 0.7$^{b}$ |
| Mean | 1.9$^{d}$ | 0.6$^{c}$ | 0.4$^{ab}$ | 0.3$^{a}$ | 0.5$^{b}$ | 0.7 |
| Potassium uptake (g/pot) | | | | | | |
| Itare | 0.653 | 0.554 | 0.289 | 0.172 | 0.368 | 0.407$^{b}$ |
| Keumbu | 1.093 | 0.700 | 0.404 | 0.155 | 0.220 | 0.514$^{c}$ |
| Ndanai | 1.680 | 1.266 | 0.510 | 0.221 | 0.286 | 0.793$^{d}$ |
| Ebukanga | 0.436 | 0.254 | 0.211 | 0.166 | 0.151 | 0.244$^{a}$ |
| Yala | 0.594 | 0.332 | 0.232 | 0.185 | 0.278 | 0.324$^{a}$ |
| Kabula | 1.395 | 0.560 | 0.322 | 0.285 | 0.316 | 0.575$^{c}$ |
| Mean | 0.975$^{d}$ | 0.611$^{c}$ | 0.328$^{b}$ | 0.197$^{a}$ | 0.270$^{a}$ | 0.480 |

[1]Values shown are means of three replicates, [2]Superscripts: Same letter = no significant difference between means. None = P for treatment in ANOVA > 0.05. LSD of site means for Dry matter, % K and K Uptake were 4.611, 0.1148 and 0.0826 respectively. Corresponding LSD of means for cycles were 4.210, 0.1048 and 0.0754. In all cases, $P < 0.001$.[3]Each of the pots in experiment was carrying 4.5 kg of dry soil.

Liming of soils above pH 5.5 results in reduced solubility, and uptake of trace elements e.g. Fe, Zn, Cu and Mn (Sumner and Yamada, 2002). Also, liming of soils above pH 5.5 results in excessive nitrification of $NH_4^+$ - N, leading to leaching losses (Sumner and Yamada, 2002). Maize, like other non-legume plants prefer the $NO_3^-$ - to $NH_4^+$- form of N, and often exhibit an efflux of $HCO_3^-$ to achieve an electric balance in the plant tissues (Keryn *et al.,* 2003). High $HCO_3^-$ content from lime may, therefore, interfere with $NO_3^-$ uptake (common ion effect), and result in suppression of crop rowth due to N deficiency. Barber (1995) reported a decrease in boron (B) uptake with increase in

oil pH.

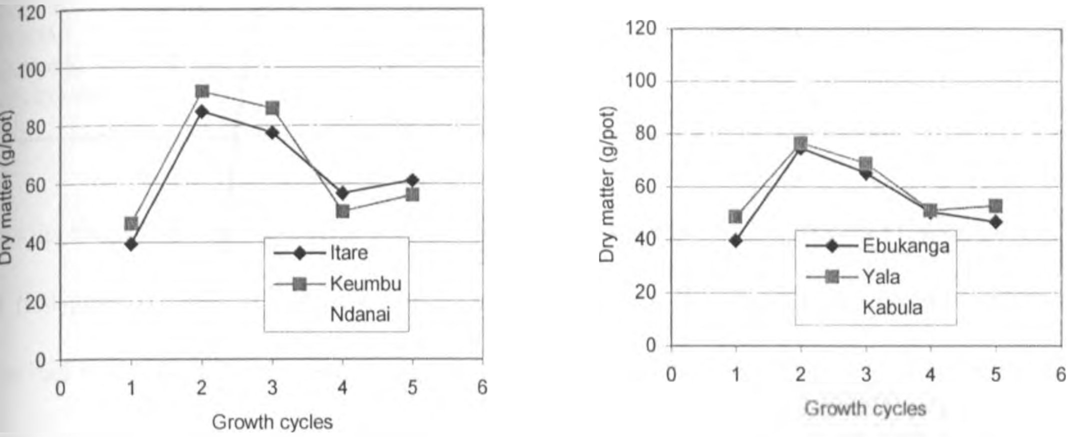

Fig 15: Variation of mean dry matter yields (g/pot) in maize tops in successive growth cycles

iming, however, improves Mo availability, because it is absorbed as molybdate ($MoO_4^{-2}$), anion rm, which is stable at high pH (Marschner, 1995). Sumner and Yamada (2002) reported reduced elds for soybean after liming soils in which Mo had been seed applied (induced deficiency of other ace elements), but yield increases were realized in the absence of Mo fertilizer, because the benefits om improved Mo availability superseded losses due to induced deficiency of other nutrients. In the cond growth cycle, however, DM yields almost doubled in all the soils (Fig 15), possibly because then, lime had reacted with the soil. There was a drop in yields in the third and subsequent cycles able 23, Fig 15), perhaps due to among other reasons, K deficiency.

oils and growth cycles had a significant ($P < 0.001$) effect on DM yields (Table 22). Simple gressions were run between DM yields in first growth cycle and forms of soil K before cropping

(Table 23).

Table 23: Correlation between DM yields in first growth cycle and K characteristics of studied soils

| Soil parameter | Regression coefficient | $r^2$ | P | SE | Significance |
|---|---|---|---|---|---|
| Total K | - | Y | 0.941 | 18.2 | ns |
| Buffer power | - 0. 500 | 0.091 | 0.288 | 15.6 | ns |
| $HNO_3$- K | 53.2 | 0.697 | 0.024 | 8.98 | * |
| NH4OAc | 157.4 | 0.625 | 0.038 | 10.00 | * |
| Solution K | 5.80 | Y | 0.441 | 7.40 | ns |
| Activity ratio | 100.1 | 0.201 | 0.207 | 15.6 | ns |
| NEK | 58.8 | 0.469 | 0.08 | 11.9 | ns |

Results show that total K, buffer power, and NEK, did not have a significant effect on the DM yields of first growth cycle, possibly because they are long term K supply characteristics (Barber, 1995), that had little effect on one season crop. If that were the case, a positive correlation between solution K (or potassium activity ratio, KAR) and DM yields for the first season was expected, because nutrient uptake increases with increase in solution concentrations (Mengel, 1985).

While both solution- K and KAR were not significantly related to DM yields of first season in a linear model, DM yields were related to KAR as shown in Fig 16. Since KAR increases with increase in illite: kaolinite ratio in soils (Fig 14), and that illite: kaolinite ratio decreased with increase in clay content (and decrease in orthoclase of sand fraction), of soils (Fig 8), it followes that less weathered soils have higher KAR, and are less likely to suffer K deficiency, particularly if cropping is not intensive. Results also imply that soils from the southern geomorphic area (SGA), formed on parent rocks that contain orthoclase as the K- containing mineral (more resistant to weathering), are less likely to have K deficiency if freshly opened (early cropping seasons) than the soils from northern geomorphic areas (NGA), where biotite is the main K- containing mineral (more weathered). The tendency to have a negative correlation between buffer power (Φ) and DM yields (Table 23); was expected because high K - buffered soils have low labile K forms, and hence uptake is curtailed (Grimme, 1979; Barber, 1995).

Correlations between DM yields and $HNO_3$- K, and $NH_4OAc$- K were positive and significant (Table 23). Dependence of DM yields on $HNO_3$- K and $NH_4OAc$- K was expected because both extractants target the slowly and readily available pools of soil K. The stronger correlation with $HNO_3$- K than $NH_4OAc$- K, confirms the findings by other workers (Rao and Subramanian, 1995; Cox *et al.,* 1999; Agarwal *et al.,* 1993); that plants, indeed, depend on more than exchangeable K in soils, for their uptake and growth.

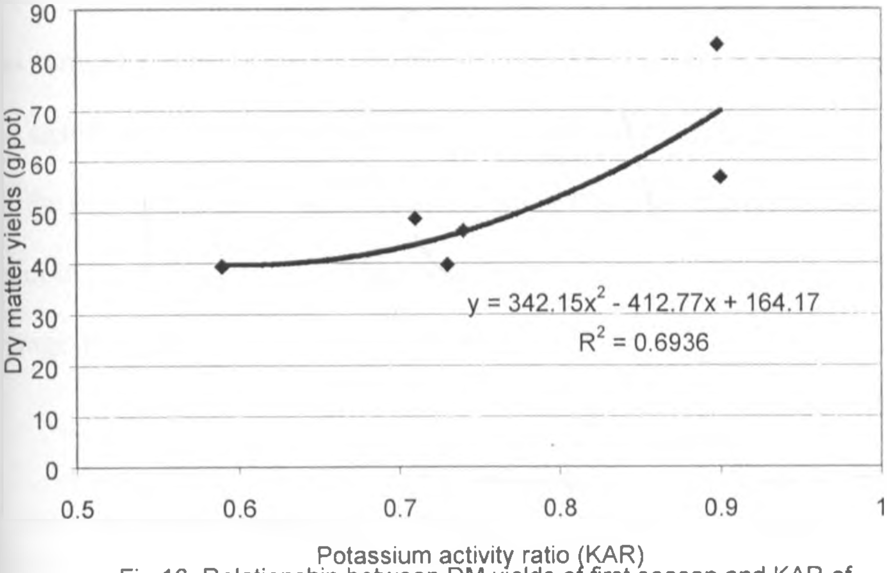

Fig 16: Relationship between DM yields of first season and KAR of studied soils

In the fifth and last growth cycle, DM yields were significantly (P = 0.031) related to the buffer power towards K (Φ), exchangeable K (EK), non-exchangeable K (NEK) and total K (TK), as shown in the derived equation below:

$$DM = 60.783 + 0.0292\ \Phi + 110.67\ EK - 22.02\ NEK - 0.4942\ TK$$

$$(R^2 = 0.998,\ P = 0.031,\ SE = 0.348)$$

This equation shows that high buffer towards K becomes an asset in exhaustively cropped soils (as in fifth growth cycle), possibly because of the ability of soils with high Φ to keep solution pool recharged with K. The negative correlation with total and non-exchangeable K is not surprising because total K (and to some extent NEK), increased with increase in orthoclase and sand content in soils (Fig 12). Sandy soils have high labile K, but which gets depleted faster than clay soils, leading to a drop in yields after prolonged cropping (Grimme, 1979, Mengel, 1985).

During the intermediate cyles, DM yields dropped progressively as K depletion in soils continued (Fig 15). The overall productivity of soils, expressed as a mean DM yield for the entire test period was correlated with the soil K determinations (Table 21) in simple regressions. There was a positive and significant correlation between DM yields and $NH_4OAc$- K ($P = 0.019$, $r^2 = 0.732$, SE = 5.54). All the other correlations were not significant at $P \leq 0.05$. The same soil parameters were tried in multiple regressions, two of which may help to explain soil characteristics that determined the average dry matter yields over the test period.

(i) Yields = 376.6 – 3.96 Clay – 11.84 Illite: kaolinite ratio ($R^2 = 0.954$, $P = 0.023$, SE = 1.95)

(ii) Yields = 32.41 – 0.4095TK –5.27 NEK + 130.18 EK + 30.38 KAR ($R^2 = 0.995$, $P = 0.046$, SE = 0.733)

Where TK= total K, NEK = non-exchangeable K, and KAR = potassium activity ratio (Table 21)

Dry matter yields declined with increase in clay content and increase in illite: kaolinite ratio (Equation i). The result appeared contradictory because illite: kaolinite ratio in soils decreased with increase in clay (Fig 8), but was attributed to the opposing individual relationships between dry matter yields and illite: kaolinite ratio on one hand, and between dry matter yields and % clay on the other hand (Fig 17). Dry matter yields may have declined with increase in clay because of the reduced K activity, and low diffusive flux in fine textured soils (Fig 14), but decreased with increase in illite: ratio because sandy soils are poorly buffered.

Yields decreased with increase in total K (TK) and increase in non-exchangeable K (NEK), but increased with increase in exchangeable K (EK) and potassium activity ratio (KAR) (Equation ii). High TK and NEK are associated with less weathered, sandy (rich in orthoclase) soils and as discussed above have a problem of having a high proportion of labile K that gets depleted quickly. Both EK and KAR are indicators of plant available K and the positive relationship with DM yields was expected.

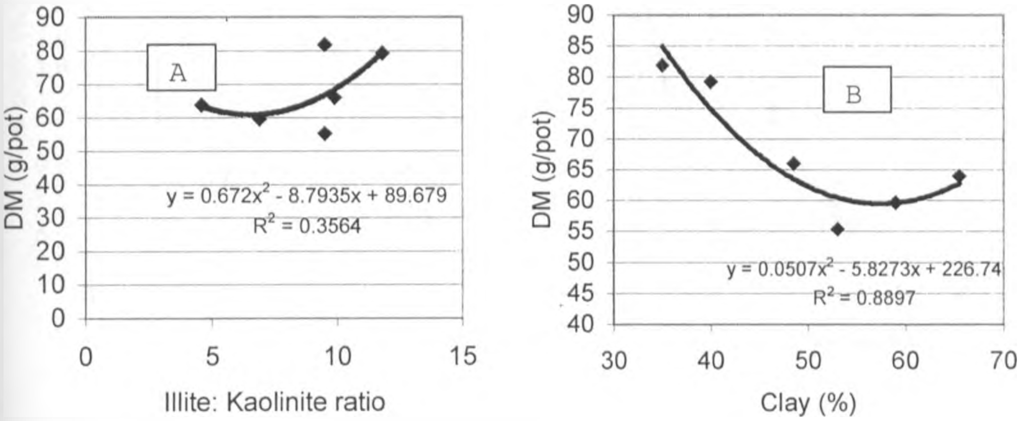

Fig 17: Average dry matter (DM) yields Vs mineralogy (A) and clay content (B) of studied soils

Lack of statistical significance between average dry matter yields and Φ was also attributed to opposing effects, where crops benefited from high labile K (low Φ), in initial years; and again benefited from higher Φ in the later growth cycles. High Φ imparts a positive effect in latter growth cycles, probably because of the contribution of non-exchangeable K. Overall, average DM yields increased in the order: Ebukanga < Yala < Itare < Keumbu < Ndanai < Kabula, which roughly divides sites into two categories: the low yielding, fine-textured soils (Ebukanga, Yala and Itare), and high yielding, coarse textured soils (Keumbu, Ndanai and Kabula).

### *4.6.2 Potassium concentration in maize tops*

Concentration of K in maize tops declined consistently and significantly ($P < 0.001$), in successive growth cycles (Table 22, Fig 18).

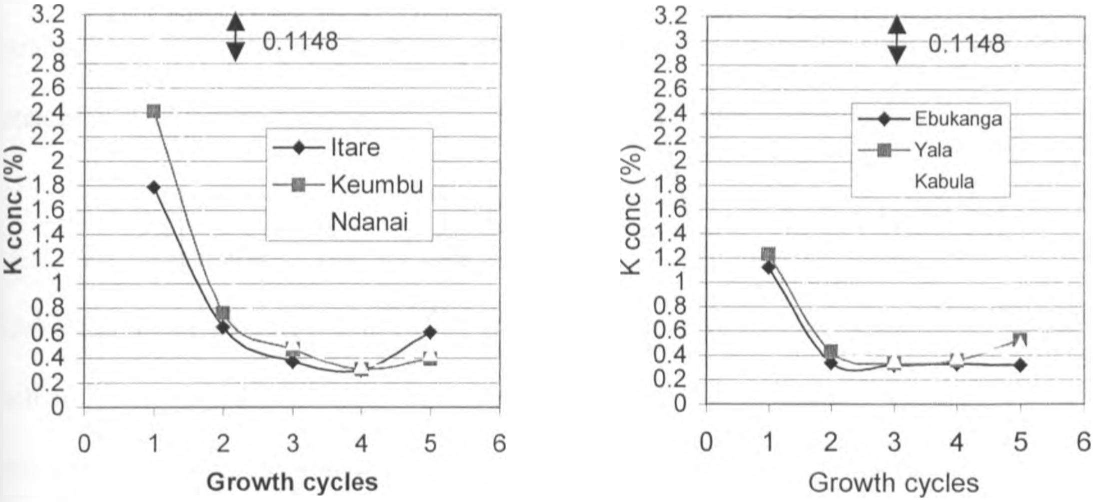

Fig 18: Variation of % K in maize tops in successive growth cycles, and different soils

Deficiency symptoms (drying up of the leaf tip and margins and weak stems); were observed from the third crop on. Potassium concentration in the tops ranged from 0.3 – 3.0 %. Differences in % K among soils were big in the beginning, probably due to luxury K consumption by plants in the soils with high labile K, but the differences were hardly detectable at the end of the third cycle (Fig 17). High levels of available K in soils result in luxury consumption, as was reported by Karachi (1984), in sweet potatoes. There appears to be a minimum attainable K concentration in tissues, tending to about 0.3 % for the given stage of growth. No efforts were made to determine the critical % K (the minimum % K in plant, required for maximum growth rate), or the highest possible % K in the plant (of little relevance to production).

The correlation between DM yields and % K across soils was not significant at $P \leq 0.05$. This is perhaps because concentrations in earlier growth cycles of some soils were higher than the critical % K (luxury consumption), and DM yields would have been as high with lower % K, as long as the critical concentrations are not surpassed. Results from studies by Grewal and Sud (1995), showed a close correlation between yields and % K concentration in the tissues of potato plants. Their results could be due to occurrence of K at concentrations < the critical levels in potato tissues, and because potatoes generally require high K levels in soils compared to maize (IFA, 1992).

### *4.6.3 Potassium uptake by maize plants*

Potassium uptake declined as cropping continued (Table 22), with overall average K uptake in each soil increasing in the order: Ebukanga = Yala < Itare < Keumbu = Kabula < Ndanai. Soils with higher clay content were found to have low K availability, perhaps due to a limited diffusive flux (Grimme, 1979; Mengel, 1995), low inherent K (lower orthoclase in sand), and limited adsorption against leaching due to the low illite: kaolinite ratio (Fig 8). Correlations with soil K extracts (Table 21), were not significant at $P \leq 0.05$, possibly because of other non-edaphic factors that equally affect uptake. In the first – third growth cycles (C1 – C3), K uptake correlated negatively and significantly to clay content in soils, but correlations for cycle four and cycle five (C4 – C5), were not significant ($P_{C1} = 0.023$, $P_{C2} = 0.030$, $P_{C3} = 0.025$, $P_{C4} = 0.124$, and $P_{C5} = Y$). Results conformed to expected benefits from high K activity ratio (Fig 14), and higher labile K content in coarse textured soils (Grimme, 1979).

A plot of cumulative K uptake against time, expressed as growth cycles (C1 – C5), is given in Fig 19. Two parameters: rate of K accumulation, and total K uptake, as defined by Heckman and Kamprath (1995), were estimated from power functions (Table 24) for each soil.

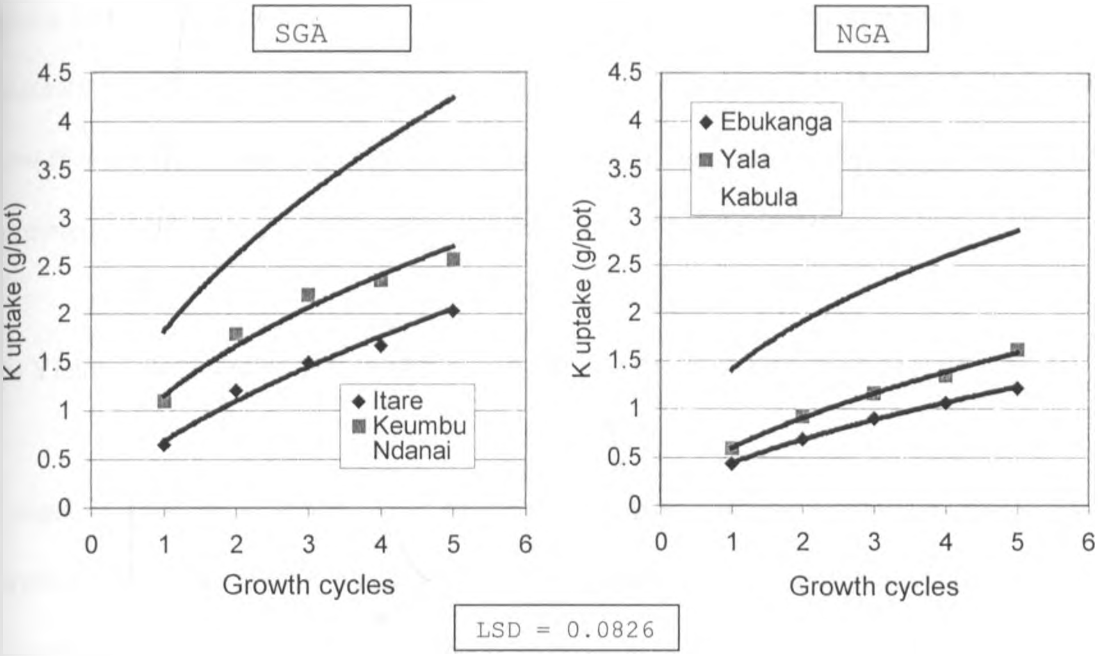

Fig 19: Cumulative potassium uptake in soils from southern (SGA) and northern (NGA) geomorphic areas

Table 24: Power functions and estimates for uptake rates and maximum potassium accumulation in maize tops

| Site | Power functions | Uptake rate (g/cycle) | Maximum K (g K/pot) | $R^2$ |
|---|---|---|---|---|
| Itare | $Y = 0.6884X^{0\ 6797}$ | 0.6884 | 2.06 | 0.9800 |
| Keumbu | $Y = 1.1568\ X^{0\ 5287}$ | 1.1568 | 2.71 | 0.9673 |
| Ndanai | $Y = 1.8233\ X^{0\ 5253}$ | 1.8233 | 4.25 | 0.9380 |
| Ebukanga | $Y = 0.4396\ X^{0\ 6073}$ | 0.4396 | 1.17 | 0.9993 |
| Yala | $Y = 0.5968\ X^{0\ 6073}$ | 0.5968 | 1.59 | 0.9970 |
| Kabula | $Y = 1.4083\ X^{0\ 4412}$ | 1.4083 | 2.86 | 0.9975 |

Rate of K accumulation, and maximum K accumulation increased in the order: Ebukanga < Yala < Itare < Keumbu < Kabula < Ndanai. The results agreed with an earlier division of soils into two groups: Ebukanga, Yala and Itare, with low rates of K accumulation in maize tops (high clay soils), and sites in Keumbu, Kabula and Ndanai, which have high uptake rates and low clay content. Potassium in high clay soils may be strongly bound through either selective adsorption or fixation. Barber (1979) and Tiwari *et al.* (1995) reported a direct relationship between K fixation and clay content, as a function of the mineralogical composition of clay. Soils of low clay content require high K intensity to meet the plant accumulation rate requirement, while K quantity (Q) is necessary to meet the total K requirements (Heckman and Kamprath, 1995). Results, therefore, show that soils that gave high DM yields had high K accumulation rates. In general, DM yields correlated positively with uptake, but negatively with % K in tissues, thus:

$$\text{DM Yields} = 58.14 - 50.8^{*}\ \%\ \text{K} + 99.3^{*}\ \text{Uptake}\ (R^2 = 0.92, \text{SE} = 3.03, P = 0.011)$$

A negative correlation with % K in maize tissue agreed with the findings by Greenwood and Karpinets (1997), who reported that the critical % K and highest possible % K decline with increase in plant mass. Under the exhaustive cropping greenhouse conditions, variation in K uptake explained 74 % of the variation in DM yields across soils and seasons (see equation below), which shows that K uptake is very important in determining crop yields.

$$\text{DM yields} = 44.\ 55 + 48.5\ \text{K Uptake}\ (r^2 = 0.744, \text{SE} = 5.41, P = 0.017)$$

During the experiment, K uptake and concentration in tissues dropped to about 20 % of the levels at the beginning (the highest attained), which compares poorly to the decline in DM yields; where lowest DM yields were still > 65 % of the highest obtained (Fig 20). Horra *et al.* (2000) when working on rhegrass in a similar experiment reported a drop to between 10 – 15% (fifth cycle) of K concentration in first cycle.

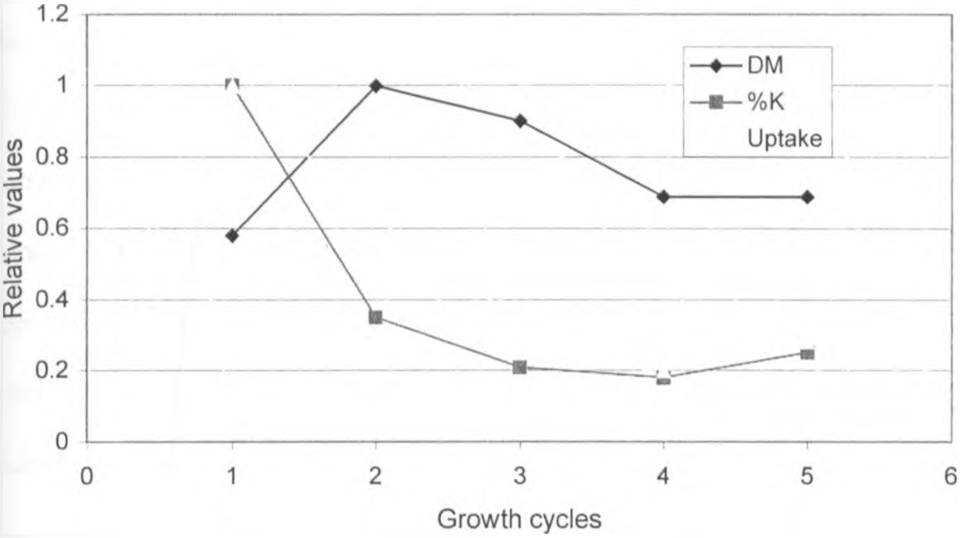

Fig 20: A plot of DM yields (g/pot), % K and uptake (g/pot) relative to the highest attained against growth cycles

This is perhaps because K concentration and uptake in earlier growth cycles were above the critical levels. Horra *et al.* (2000) when working on rhegrass in a similar esxperiment found that crops in earlier growth cycles were drawing needed K from the most labile positions in exchange complex. The result depicts a wide range of tolerance in K uptake and concentration, without necessarily affecting the DM yields. It is apparent that without K application from external sources, and with long term cropping, the plant biomass produced may not only decrease in amounts, but also get increasingly low in K content (Fig 20). Also, the result helps to explain how K levels may decline in soils without a significant decline in yields of crops, until such a time when uptake drops to below critical levels.

In mature crops, a decline in K concentration to below critical levels would be equated to a drop in harvest quality. Peter (1980) reported a drop in 1000 – grain weight for grain crops (maize, rice, wheat), crude protein content in wheat, and sugar content in banana, and sugar cane as a result of K deficiency in soils. In fact, crop response to K fertilizers may be much easily realized in experiments if quality related attributes are monitored, rather than, or in addition to the absolute yields, as is common in agronomic trials. Likimani (1973) reported increased total solids and ascorbic acid content in potatoes after application of K fertilizers. Singh and Singh (1995) when working in India reported increased number of large and medium sized tubers, and a decrease in small sized tubers after applying K fertilizers. There is, therefore, great potential in improving harvest qualities and nutritional status of marketable produce. Emerging local and international markets have set standards (e.g. Euregap of the European Union), which have to be met before farmers can be allowed to sell, and K fertilizers have potentially big roles to play.

There was a significant ($P = 0.017$), increase in % K of maize tissues between 4th and 5th growth cycles. The increase is probably associated with improved K availability after disintegration of crystal lattice of illites. Loes and Ogaard (2003) reported a decrease of illite and an increase of vermiculites and smectites minerals after prolonged cropping of soils, which he attributed to disintegration of Illite to vermiculite and smectite.

### *4.6.4 Change in soil potassium with cropping*

Exchangeable K declined in soils as cropping continued (Fig 21). The results conformed to findings from the long- term trial at NARL (1976 – to date), where some plots have been cropped continuously with optimal application of N and P fertilizers but no K fertilizer, and where soil chemical data show continuously declining exchangeable K values with time (Kanyanjua and Buresh, 1999). Horra *et al.* (2000), reported 40 –50 % decrease in exchangeable K from a greenhouse experiment, after growing ryegrass continuously in Argentinian soils optimally fertilized with N and P fertilizers.

The differences in exchangeable K among soils were big in uncropped soils, but narrowed as cropping continued (standard deviation: bef = 0.6, after 1$^{st}$ cycle = 0.2, after 2$^{nd}$ cycle = 0.1 cmol (p$^+$) kg$^{-1}$). After third cycle onwards, differences were no longer noticeable (SD = 0.0). The exchangeable levels had by then dropped to about 0.1cmol (p$^+$) kg$^{-1}$. Loes and Ogaard (2003), modelled the minimum exchangeable K attainable, after continuous depletion and extraction with ammonium acetate lactate (K-Al $_{min}$), thus:

K-Al $_{min}$ = 13.08 (units: mg kg$^{-1}$) + 0.94 * (silt % + clay %)

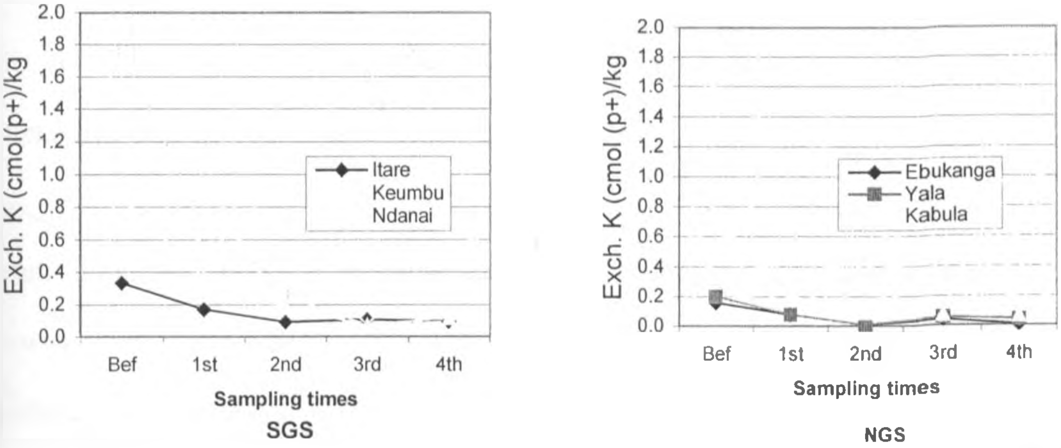

Fig 21: Change of exchangeable K in continuously cropped soils under study

Bef = before cropping, 1$^{st}$ – 4$^{th}$ = after first to fourth cropping cycles.

Since the NH$_4$OAc –L method extracts similar amounts of K as neutral NH$_4$OAc (Csatho, 2002), the calculated minimum exchangeable K values were 0.23, 0.21, 0.14, 0.18, 0.20 and 0.11 cmol (p$^+$) kg$^{-1}$; for Itare, Keumbu, Ndanai, Ebukanga, Yala and Kabula respectively. The minimum calculated is not absolute and soils can still be depleted further, but soils depleted to this level may not have a net release from the exchangeable pool (Loes and Ogaard, 2003). High clay soils (Itare, Yala and Ebukanga), attained the minimum attainable earlier, and probably started releasing plant available K from the non-exchangeable pool, before the less clayey soils (Fig 21). As cropping continued, the change in exchangeable K declined, either because the soil buffer towards K had increased, or the amount removed by crop had reduced as a result of the declining DM yields.

Before cropping and during the first three cycles, exchangeable K levels were higher in the less clayey soils, and decreased in the order: Ndanai > Keumbu > Kabula, compared to the high clay soils of Itare, Yala and Ebukanga. Exchangeable K values over the test period increased in the order: Ebukanga < Yala < Itare < Kabula < Keumbu < Ndanai; and were lower in the more clayey soils. As shown in Fig 22, exchangeable K levels at planting, explained > 90 % of the variation in K uptake by maize across soils ($P = 0.004$, $SE = 0.0749$).

Results from this study are in accordance with the findings of Sirinivasa *et al.* (2000), who likewise grew maize plants continuously in a greenhouse in India, and found a decrease in K uptake, as exchangeable K decreased. The relationship between exchangeable K in soils and DM yields is shown in Fig 23. Dry matter increased with increase in exchangeable K below 0.34- cmol (p$^+$) kg$^{-1}$, the critical value under the circumstances. Above the critical value, higher exchangeable K values, though resulting in increased uptake (Fig 22), did not improve DM yields. Using this critical soil K value and the regression equation in Fig 22, calculations show that the critical K uptake by maize plants was 0.73 g pot$^{-1}$. The critical soil - K value obtained was close to the 0.3 cmol (p$^+$) kg$^{-1}$, calculated from Fisher's formula (Fisher, 1974), (Table 16).

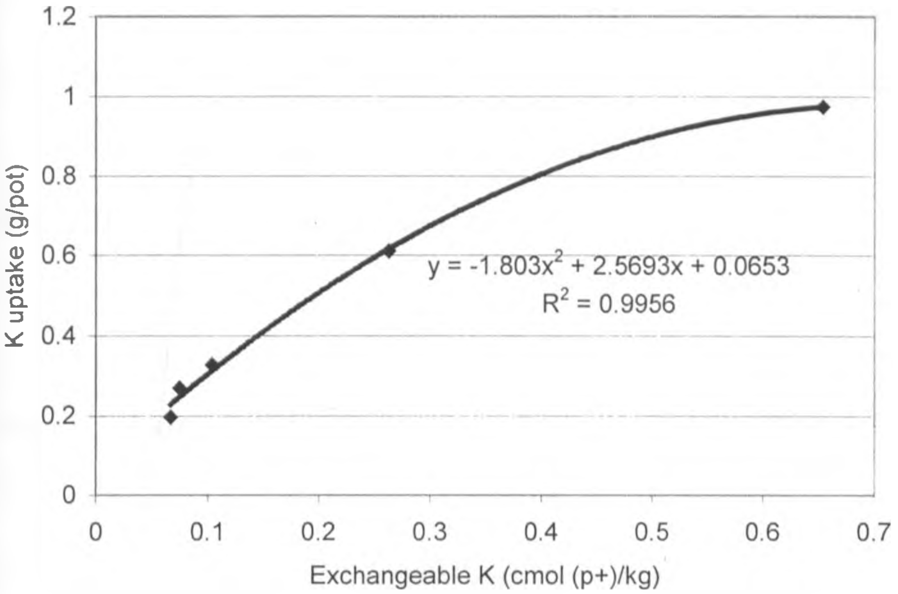

Fig 22: A plot of K uptake (g/pot) against exchangeable K in soils under study

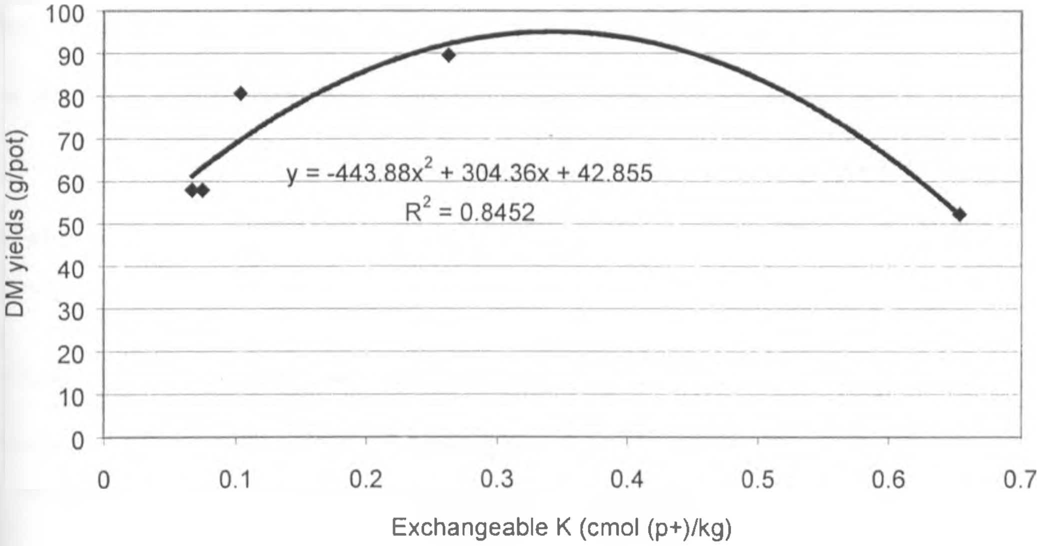

Fig 23: A plot of maize DM yields against exchangeable potassium in soils under study

Plants in the high clay soils (Itare, Ebukanga and Yala), had K contents below critical value in the first cycle, while those grown in low clay soils obtained sufficient K. Maize plants in Keumbu and Kabula soils had a deficiency in the second cycle, while Ndanai did not suffer from K deficiency until the third cycle. The situation may differ in field conditions because maize roots are allowed to explore a larger volume of soil and take much longer in the field. Also, plant adaptive mechanisms have greater opportunity to operate in the field than in pots.

As exchangeable K levels dropped in soils, crops may have utilized K fractions that were not initially $NH_4OAc$- extractable. According to Horra *et al.* (2000), NEK is released from interlayers of nonexpendable 2: 1 clay minerals (illites, micas), as well as from lattice in feldspars. The estimated contribution of non-exchangeable pool to crop uptake is given in Table 25.

Non-exchangeable K contributed between 0 - 68 % of the K uptake in the first cropping cycle with non-exchangeable K (NEK) contribution increasing in the order: Ndanai < Keumbu < Kabula < Itare < Yala < Ebukanga (Table 25). There was greater contribution of NEK in the high clay than low clay soils. Uptake from NEK pool continued during the experiment period, and all the K from high- clay soils of Ebukanga, Yala and Itare was sourced from NEK pool during the third cycle and afterwards (Table 26).

Results were in conformity with the findings by Loganathan *et al.* (1995), who after exhaustively growing maize in a greenhouse concluded that contribution of non-exchangeable pool to total K uptake was dependent on the type of geological deposits from which the soils had developed. The results confirm an underestimate of K supply potential of soils that are highly buffered (high clay), (Cox *et al.*, 1999), when exchangeable K is used as the test for K requirements. Underestimation of crop available- K is compounded by the quasi-exchangeable nature of $K^+$ in micaceous soils

(Thomas, 1982). Haby *et al.* (1990) attributed the lack of initial crop response to applied K in low exchangeable- K soils, to rapid release of NEK from micaceous sub- soils.

Table 25: Estimates of amounts of K uptake (%) from NEK[¶] pool of soils under investigation, by maize, in successive growth cycles

| | Cropping cycles[*] | | | |
|---|---|---|---|---|
| Site | C1 | C2 | C3 | C4 |
| Itare | 59 | 75 | 100 | 100 |
| Keumbu | 21 | 54 | 73 | 71 |
| Ndanai | 0 | 40 | 74 | 90 |
| Ebukanga | 68 | 55 | 100 | 100 |
| Yala | 64 | 65 | 100 | 100 |
| Kabula | 38 | 66 | 94 | 100 |

[¶] NEK = non-exchangeable potassium, [*] C1 – C4 = successive cropping cycles

Shen and Stucki (1994), reported uncontrolled and unrecognised transformations between the various soil K pools, between time of soil testing and time of crop uptake, which sometimes results in poor crop response predictions to K fertilizers. A soil may test low in exchangeable K at the time of, or before planting, but by the time the plant is making an attempt to absorb nutrients, sufficient K will have been released from NEK pool to exchangeable K. Conversely, a soil may test high in exchangeable K at planting, only to have K fixation to NEK pool at the time of uptake, leading to K deficiency.

Application of K fertilizers should, therefore, take into considerations the likely transformations of soil K during growth, and unique crop characteristics, before a fertilizer program is drawn (Greenwood and Karpinets, 1997). Release of NEK is triggered by depletion of the readily available K (Cox *et al.*, 1999). The high- buffered soils have an inherent inability to supply plant K in the readily available form, which affects both the rate of accumulation and the maximum that can accumulate in the plant (Table 25). Plants have lower uptake rates and accumulate less K in soils whose large part of the plant available K is sourced from NEK pool (Table 25). Knowledge of NEK concentration and NEK contribution to crop nutrition is of importance in determining the soil K reserves (Horra *et al.*, 2000)

When cropping continued without addition of K fertilizers, Rao and Subramanian (1995) and Loganathan *et al.* (1995), found that the crop was continuously depending on non-exchangeable K (NEK) pool. Rao and Subramanian (1995), however caution that continued dependence on the NEK increases the K fixing capacity and future fertilizer K applications will have poor efficiency of K recovery due to fixation. Yakimenko (1995), predicted poor response to K fertilization in such soils, as applied K replaces the NEK first before sufficient amounts are available in soil solution.

The capacity to exploit NEK is also a function of the plant species. According to Grimme (1979), plants will differ in their ability to exploit K reserves in the soil, due to their rooting patterns. Maize, like other crops in the grass family with a fibrous root system, has higher ability to mobilize K from the soil than tap- rooted crops. It follows, therefore, that beans may increasingly lack sufficient K where maize is grown continuously as the K remaining after continuous depletion is strongly held in the soil.

Results from greenhouse studies isolated the high clay soils from Itare, Ebukanga and Yala, as the soils likely to have an emerging K deficiency in intensively cropped agro-ecological zones of Kenya. Clay soils have low labile K contents, which lowers the rate of K accumulation and the maximum K accumulated in crops. Current research results and those obtained from other countries (Rao and Subramanian, 1995; Loganathan *et al.,* 1995; Yakimenko, 1995), show the likely environmental impact of continuously cropping the soils, without application of K fertilizers. In such situations, crops would exploit NEK pools, increase the fixing capacity of soils, and increase the costs of any future attempts to fertilize the soils with K fertilizers. Results from greenhouse studies give an idea of how the crop may behave in field conditions, but Wapakala (1973), got different results under the two conditions when he studied copper requirements of wheat in some soils of Kenya. There is, therefore, a need to validate the results obtained in the greenhouse by conducting experiments on-farm.

## 4.7 Maize response to N-P-K fertilizers

### *4.7.1 Overview*

Maize yield data for successive seasons in five clusters are given in Annex II. There were large differences in yields between clusters, and between seasons among clusters. The effect of seasons on grain yields was not discussed, because climatic data was not collected at on-farm level. Control yields were obtained in the first season of each cluster only, because farmers refused to maintain the check treatment in subsequent seasons. In analysing the effects of K fertilizers, therefore, the plot fertilized with optimal levels of N and P, but no K fertilizer (NPK0 treatment), (Table 3), was the check treatment.

### *4.7.2 Control yields*

Control yields ranged from 1.09 – 3.68 Mg $ha^{-1}$, and decreased in the order: Kabula = Itare > Yala = Keumbu > Ebukanga. After running simple regressions of control yields against soil parameters, e. g. organic C, exchangeable Ca, Mg and K, and extractable P, none of these were significant at $P \leq 0.05$. Stepwise regressions did not give a significant equation either. The correlation between field and average greenhouse performance was not significant at $P \leq 0.05$. After inspecting the relationship between greenhouse and field performance of maize (Fig 24), it was observed that yields obtained in the field were better in the two clayey soils from Itare and Yala, than the relative performance in greenhouse. This is probably because exploitation of non- exchangeable pools of nutrients is favored by the long period of growth, while benefits from easily available pools in less clayey soils are subdued in the field. Another possibility is that crops need not exploit the strongly bound (non-exchangeable) pools for their K uptake because of the increased soil volume under field conditions. Wapakala (1973); reported dissimilar findings from field and greenhouse studies when studying copper requirements for wheat in the Rift Valley province of Kenya.

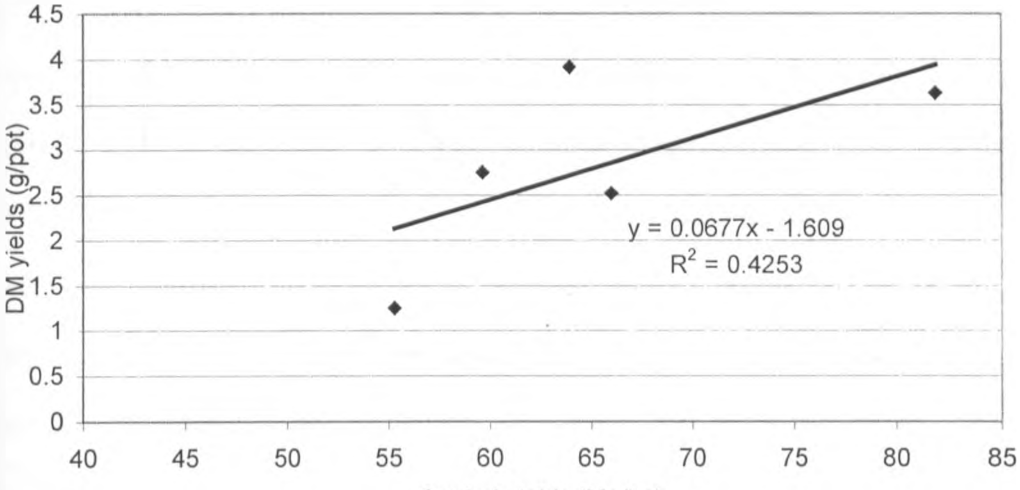

Fig 24: Relationship between Control yields in field and average DM yields in greenhouse

According to Recke *et al.* (1997), control yields can be used to estimate the yield potential of a given soil, and represent the average yields without fertilizers. In the field study, therefore, fine textured soils appeared to produce better than coarse textured soils without fertilizers. Unlike in the greenhouse, where high clay soils had low dry matter yields, maize yielded better in such fine-textured soils under field conditions. This is perhaps because the high buffer towards K, and probably other nutrients, works in favor of such soils. The other clayey soil from Ebukanga (Table 10), would, perhaps, have behaved similarly, were it not for the high infestation of the witch weed, *Striga harmonthica*. The control yields obtained in this study were high, but seldom obtained in farmers' fields, because experimental plots had high standards of husbandry practices, such as ideal plant population density, good certified seed, early planting and timely weeding.

### *4.7.3 Effect of nitrogen and phosphate fertilizers on maize yields*

Nitrogen and P fertilizers, applied at 75 and 33 kg of N and P ha$^{-1}$, respectively, increased maize yields by 59, 85, 114, 37 and 46 %, in Itare, Keumbu, Ebukanga, Yala and Kabula clusters, respectively. There were big differences among sites on how N and P fertilizers increased yields (average: 68.2 ± 28.0 %). Also, there was a negative relationship between the proportion by which NP fertilizers increased yields, and control yields obtained (Fig 25). Where control yields were low, N and P fertilizers had a big impact on maize yields, showing that, indeed, the two nutrients were limiting in those soils. In sites where control yields were high, there were perhaps other limitations to production that required to be corrected before a reasonable response to N and P fertilizers could be realized.

In Keumbu and Ebukanga where control yields were lowest, and N and P fertilizers increased yields by highest percentages (85 and 114 % respectively), 89 and 83 % of the soil samples analysed, respectively, were deficient in P (see Annex I). Yala, Itare and Kabula soils, though equally deficient in P, may have had other more serious fertility problems. The 37 – 114 % increase in maize yields after N and P fertilizers were applied, to some extent supports the status quo, where Kenyan agriculture has remained dependent on N and P fertilizers for decades (Kanyanjua and Buresh, 1999; Mwaura and Woomer, 1999), and agrees with Anderson (1973), that P and N are the most limiting nutrients in the tropics.

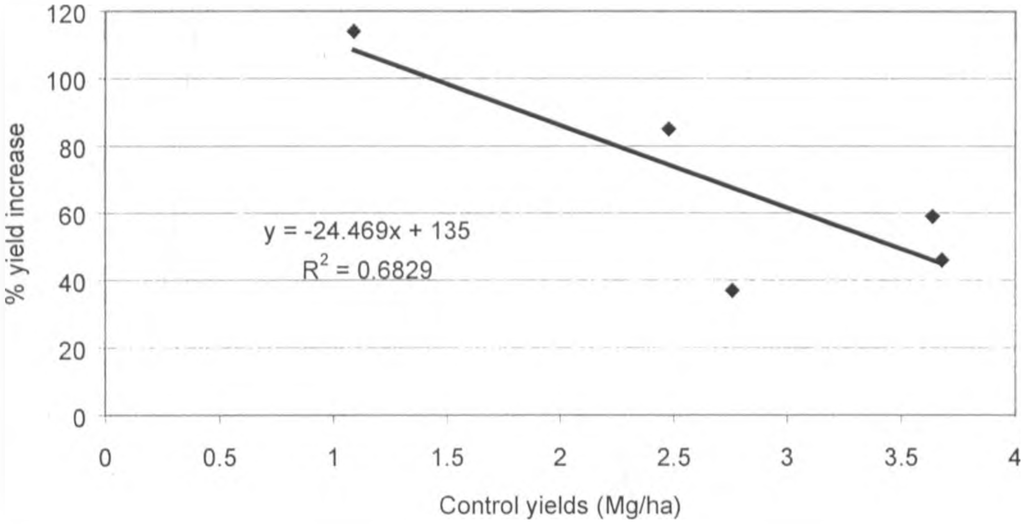

Fig 25: Relationship between maize response to NP treatment and control yields in western Kenya

### *4.7.4 Effect of potassium fertilizers on maize yields*

Analysis of variance (ANOVA) results for the effect of applying K fertilizers on maize yields is given in Table 26. Apart from Keumbu cluster, where K fertilizers increased yields significantly when applied at 25 kg K $ha^{-1}$, during the LR 2000 season (Table 26), response to K fertilizers was not significant in other clusters and seasons. These results were disappointing, considering that exchangeable $K^+$ levels were low in many farms within the clusters. It was even more confusing, that response was obtained in Keumbu cluster where exchangeable $K^+$ levels were in the high range (Table 4).

Table 26: Maize grain yields (Mg $ha^{-1}$) obtained from clusters under investigation, and treatment effects

| Season | Treatments | | | | Mean | P | $LSD_{P=0.05}$ |
|---|---|---|---|---|---|---|---|
| | NPK0 | NPK25 | NPK50 | NPK75 | | | |
| Itare cluster | | | | | | | |
| LR 2000 | 5.78 | 5.11 | 5.70 | 5.24 | 5.46 | 0.400 | 0.965 |
| LR 2001 | 3.88 | 4.28 | 3.94 | 4.15 | 4.06 | 0.117 | 0.365 |
| SR 2001 | 5.53 | 5.78 | 5.62 | 6.18 | 5.78 | 0.084 | 0.530 |
| LR 2002 | 4.45 | 4.76 | 5.13 | 5.33 | 4.92 | 0.072 | 0.707 |
| Keumbu cluster | | | | | | | |
| LR 2000 | 4.58 | 5.83 | 5.29 | 5.62 | 5.33 | 0.028 | 0.847 |
| LR 2001 | 5.78 | 6.07 | 5.61 | 5.82 | 5.82 | 0.609 | 0.698 |
| LR 2002 | 3.84 | 4.36 | 3.94 | 3.59 | 3.93 | 0.348 | 0.882 |
| Ebukanga cluster | | | | | | | |
| LR 2001 | 2.33 | 1.95 | 2.53 | 2.54 | 2.33 | 0.426 | 0.819 |
| LR 2002 | 2.72 | 2.81 | 2.85 | 2.94 | 2.83 | 0.911 | 0.616 |
| Yala cluster | | | | | | | |
| LR 2001 | 3.78 | 3.90 | 3.87 | 4.16 | 3.93 | 0.552 | 0.5618 |
| LR 2002 | 3.05 | 3.18 | 2.50 | 2.58 | 2.83 | 0.098 | 0.644 |
| Kabula cluster | | | | | | | |
| LR 2000 | 5.38 | 5.62 | 6.38 | 5.98 | 5.84 | 0.085 | 0.808 |
| LR 2001 | 3.92 | 4.29 | 4.18 | 4.39 | 4.20 | 0.172 | 0.4391 |
| LR 2002 | 4.62 | 4.31 | 4.06 | 4.12 | 4.28 | 0.206 | 0.579 |

‡ Seasons: LR = long (March – May) rains, SR = short (Oct- Nov) rains of respective years. LSD: Itare, treatments = 0.4287 ($P < 0.001$), seasons = 0.3834 ($P < 0.001$), Keumbu, treatments = 0.5863 ($P < 0.001$), and seasons = 0.4542 ($P < 0.001$), Ebukanga, treatments = 0.4756 ($P < 0.001$), seasons = 0.3008 ($P = 0.01$), Yala, treatments = 0.4549 ($P = 0.008$), seasons = 0.2877 ($P < 0.001$), Kabula.treatments = 0.4620 ($P < 0.001$), seasons = 0.3578 ($P < 0.001$)

Results of the study, therefore, cast doubts on the utility of exchangeable K soil test values in predicting yields or results of fertilizer experiments, and supports similar findings by Kemmler and Hobt (1986). Stucki and Huo (1997), caution that poor correlations between soil tests and crop response to K fertilizers leads to unreliable and inefficient fertilizer recommendations.

According to Stucki and Huo (1997), it is difficult to differenciate available from unavailable forms of K, because of unrecognized re- distribution of soil K among the various forms. Potassium movement between soil pools occurs in an uncontrolled and unpredictable manner, and may occur between the time of soil testing and time the plant "sees" the soil, leading to eroneous results.

Lack of significant response to K fertilizers in maize agreed with the findings of earlier workers (Wapakala *et al.,* 1969; MOA, 1964, 1975; Rutto *et al.,* 1982; Ouma and Wapakala, 1986; Olang, 1980; Hinga and Foum, 1972), who found no response, low, or sometimes negative response, of various crops to K fertilizers. While non-response to K fertilizers was attributed to high K content in soils during those days, a number of hypotheses are given here, which may help to explain the poor response of maize to K fertilizers. These hypotheses may be tested in future.

In Ebukanga and Yala, there was widespread infestation of the parasitic striga weed (*Striga harmonthica*), a weed that is most problematic in areas of Africa where mineral nutrient and organic matter content of soils are low (Ransom, 2000). Prevalence of this weed may interfere with K- fertilizer response in maize. Soils from the northern geomorphic area (NGA), (Fig 3, Table 2), were low in pH, low in exchangeable $Ca^{2+}$, and medium in exchangeable $Mg^{2+}$ (Table 4). Anderson (1973), predicted poor response to K fertilizers in soils deficient in Ca, Mg and S. Silva *et al.* (1995), reported improved significance in K response to cotton after liming. Messing (1974), reported reduced response to K fertilizers in bananas, when Ca and Mg levels decreased due to excessive mining, in soils from West- Indies. Recke *et al.* (1997) did not find response to N and P in potatoes until the soils were amended with lime and potash in central Kenya. In this study, no efforts were made to study the interaction between K fertilizers and lime, and maize response to K fertilizers, in field soils from the region.

Soils from the southern geomorphic area (SGA), (Fig 3, Table 2), were rich in exchangeable K and other bases (Table 4). According to some workers (Panique *et al.,* 1997, Zschernitz, 1974), many crops may not respond to K fertilizers in such soils. According to earlier workers (Hinga and Kuria, 1976; Kemmler and Malicornet, 1976; Kemmler and Hobt, 1986), the test period of three seasons of optimal N and P fertilizer application may not have been long enough to deplete readily available K. The time taken before responses can be achieved is a function of buffer capacity of soils. Practical effects of K exhaustion from well- buffered soils may be delayed indefinitely under field conditions. Indeed, results from greenhouse studies identified the extent of K depletion from soils as a major determinant of the total K uptake by maize plants.

Grimme (1979), emphasized the high efficiency of fibrous roots of the grass family in K uptake, while maize roots are known to grow deep enough to reach leached K. Response may, therefore, be more sensitively reflected by other crops, with less efficient rooting system, than maize. Qureshi (1979), Grimme (1979), and Mamo and Hague (1988), attributed low response of crops to K fertilizers to K- fixation, and Qureshi (1979), observed upto 50 % fixation of applied K in Kisii soils. Potassium fixation in soils was not investigated in the current study, but the presence of illitic minerals in studied soils (Table 14), is a pointer to such possibilities (Tiwari *et al.,* 1995).

### *4.7.5 Use of the agronomic optimum and relative yields*

#### *4.7.5.1 Agronomic optimum*

Considering that maize gave no important, and certainly no significant response to K fertilization within a three- season period, other methods of analyses were used, to at least identify the sites where response to K fertilizers may occur in future. This approach would allow, not only to detect soils with a K deficiency, but also the soils that may require fertilizer input, rather than wait until K deficiencies become limiting to maize growth in future. The agronomic optimum, in accordance to the definition by Recke *et al.* (1997), was the highest, K fertilized yield obtained by each farmer in each season, during the experimental period and annotated NPK*max* in Tables 42 – 57 (Annex II).

Table 27: Mean grain yields (Mg $ha^{-1}$) of maize, and comparison of NPK0 and NPKmax treatments from trials in western Kenya

| Season‡ | NPK0 | NPKmax | n† | PHo⊥ |
|---|---|---|---|---|
| | | Itare cluster | | |
| 1st | 5.8 | 6.1 | 8 | $0.745^{ns}$ |
| 2nd | 3.9 | 4.6 | 17 | $0.120^{ns}$ |
| 3rd | 5.5 | 6.3 | 10 | $0.432^{ns}$ |
| 4th | 4.5 | 5.8 | 12 | $0.005^{**}$ |
| | | Keumbu cluster | | |
| 1st | 4.6 | 6.3 | 9 | $0.175^{ns}$ |
| 2nd | 5.8 | 6.8 | 16 | $0.103^{ns}$ |
| 3rd | 3.8 | 4.7 | 8 | $0.064^{ns}$ |
| | | Ebukanga cluster | | |
| 1st | 2.3 | 3.1 | 8 | $0.157^{ns}$ |
| 2nd | 2.7 | 3.4 | 8 | $0.142^{ns}$ |
| | | Yala cluster | | |
| 1st | 3.8 | 4.6 | 16 | $0.088^{ns}$ |
| 2nd | 3.1 | 3.5 | 14 | $0.343^{ns}$ |
| | | Kabula cluster | | |
| 1st | 5.4 | 6.7 | 6 | $0.176^{ns}$ |
| 2nd | 3.9 | 4.7 | 14 | 0.026 ~~ns~~ |
| 3rd | 4.6 | 4.7 | 12 | $0.847^{ns}$ |

‡ Seasons: successive seasons, irrespective of the years †n = number of participating farmers ⊥pHo= probability of the null hypothesis that the two means from a T-test are equal.

The fertilizer rate associated with the NPK*max* is referred to as the K rate and included in Annex II. Each season of a cluster was analysed separately, to determine whether the probability that there is no response to K fertilizers (null hypothesis) after a T-test, was changing in successive seasons. In every cluster and season, the NPK*max* had higher yields than NPK0 treatment, implying increased maize yields from K fertilization in all seasons (Table 27).

The NPK*max* yields were obtained after applying K fertilizer at rates ranging from 37.5 - 58 kg K ha$^{-1}$ (average 45.8 kg K ha$^{-}$), depending on the season. The results (Table 27) identified three sites (Itare, Keumbu and Ebukanga), where the probability of not obtaining a response was declining with seasons (short rains season for Itare was ignored), i.e. the $P_{Ho}$ was tending to 0.05 as cropping continued. Kemmler and Malicornet (1976), and Hinga and Kuria (1976), reported similar observations where crops failed to respond to K fertilizers in the beginning, but responses appeared soon after, when readily available K in the soil was thought to have been exhausted.

### *4.7.5.2 Relative yields*

The data in Table 27 was used to calculate relative yields (Walmsley, 1971), using the formula

*Relative yields (K) = Yield from NPK0 treatment/Yield from NPKmax treatment*

Results from these calculations are included in Annex II. Relative yields range was arbitrarily divided in three sub-ranges thus: strongly responding (0 – 0.75), moderate responding (0.75 – 0.8) and slightly - to - non-responding (> 0.8). The proportions of participating farmers in each sub-range for each season were calculated and summarized in Table 28.

The fertilizer- to- maize, input/ output price ratio (50: 11), was largely in favor of grain, relative to fertilizer K, in the local market. Farmers were involved in setting the limit below which the incentive to invest in K fertilizer was to disappear. Suppose a farmer realizes 4000 kg ha$^{-1}$ of maize after adding NPK fertilizer that incorporates 60 kg K ha$^{-1}$. Yields without K fertilizer at a relative yield of 0.8 are 3200 kg ha$^{-1}$, where the farmer foregoes a grain yield of 800 kg ha$^{-1}$. At the existing input/output price ratio, the farmer saves KES 3,000 worth of fertilizer, but loses KES 8,800 of grain value. The value/cost ratio (VCR) is 2.93, and economical to use K fertilizer in production.

Table 28: Distribution of farmers in the various relative yield[¶] ranges (%) in study sites

| Season | Relative yield ranges | | |
|---|---|---|---|
| | < 0.75 | 0.75 –0.80 | > 0.80 |
| | | Itare | |
| LR 2000 | 25 | 0 | 75 |
| LR 2001 | 35 | 24 | 41 |
| SR 2001 | 20 | 20 | 60 |
| LR 2002 | 46 | 0 | 54 |
| Mean | 32 | 10 | 58 |
| | | Keumbu | |
| LR 2000 | 40 | 30 | 30 |
| LR 2001 | 28 | 33 | 39 |
| LR 2002 | 50 | 0 | 50 |
| Mean | 39 | 21 | 40 |
| | | Ebukanga | |
| LR 2001 | 38 | 0 | 62 |
| LR 2002 | 50 | 0 | 50 |
| Mean | 44 | 0 | 56 |
| | | Yala | |
| LR 2001 | 40 | 0 | 60 |
| LR 2002 | 50 | 0 | 50 |
| Mean | 45 | 0 | 55 |
| | | Kabula | |
| LR 2000 | 50 | 17 | 33 |
| LR 2001 | 43 | 7 | 50 |
| LR 2002 | 8 | 0 | 92 |
| Mean | 34 | 8 | 58 |

[¶]Relative yields (K) = Yield from NPK0 plot/Yield from NPKmax plot

This calculation shows that the farmer would still be in profitable business if by adding 60 kg K ha$^{-1}$ would make him increase the yields by 550 kg ha$^{-1}$ (i.e. from 3450 – 4000 kg ha$^{-1}$), when the VCR would be about 2.0, and a relative yield of 0.86. Both strongly and moderately responding sites were, therefore, considered worth receiving a K fertilizer recomendation. All the farms with relative yields < 0.8 were therefore put in the category that has a real or emerging K deficiency. From these results, 42, 60, 44, 45 and 42 % of the farms in Itare, Keumbu, Ebukanga, Yala and Kabula clusters, respectively, require maintenance K fertilization, in addition to N and P fertilizers.

### *4.7.6 Economic analysis*

A summary of the economic analysis results is given in Tables 29 and 30 for sites in SGA and NGA, respectively. In Itare, it was not economical to apply K fertilizer in maize during the first season. The situation changed in followup seasons and application of K fertilizer was profitable when applied at 25, 75 and 75 kg K $ha^{-1}$. There was, therefore, increased benefit from the application of K fertilizer with continuous cropping. Non- response to K fertilizer in first season was ascribed to high exchangeable K levels (Table 4), which were higher than the 0.3 cmol (p+) $kg^{-1}$, critical value, in all samples (Table 38, Annex 1). This work associated the high amounts of labile K with mineralization of organic matter, and location of labile K in weakly adsorbing sites, as a result of high Ca and Mg containing soils. The inherent sources must be limited because basalts have low mineral K contents (Sparks, 1987; Hunt, 1972).

Table 29: Economic analysis of fertilizer use in successive maize seasons in soils from SGA[1]

| Economic variables[2] | Treatments | | | | |
|---|---|---|---|---|---|
| | CONT | NPK0 | NPK25 | NPK50 | NPK75 |
| | | Itare – LR 2000[3] | | | |
| Mean yields[4] | 3.8 | 5.8 | 5.1 | 5.7 | 5.2 |
| TR | 41800 | 63800 | 56100 | 62700 | 57200 |
| TC | 0 | 10500 | 12000 | 13500 | 15000 |
| NR | 41800 | **53300**[5] | 44100 | 49200 | 42200 |
| | | Itare- LR 2001 | | | |
| Mean yields | ND | 3.9 | 4.3 | 3.9 | 4.1 |
| TR | | 42900 | 47300 | 42900 | 45100 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | 32400 | **35300** | 29400 | 30100 |
| | | Itare- SR2001 | | | |
| Mean yields | ND | 5.5 | 5.8 | 5.6 | 6.2 |
| TR | | 60500 | 63800 | 61600 | 68200 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | 50000 | 51800 | 48100 | **53200** |
| | | Itare – LR2002 | | | |
| Mean yields | ND | 4.5 | 4.8 | 5.1 | 5.3 |
| TR | | 49500 | 52800 | 56100 | 58300 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | 39000 | 40800 | 42600 | **43300** |
| | | Keumbu- LR 2000 | | | |
| Mean yields | 2.5 | 4.6 | 5.8 | 5.3 | 5.9 |
| TR | 27500 | 50600 | 63800 | 58300 | 64900 |
| TC | 0 | 10500 | 12000 | 13500 | 15000 |
| NR | 27500 | 40100 | **51800** | 44800 | 49900 |
| | | Keumbu- LR 2001 | | | |
| Mean yields | ND | 5.8 | 6.1 | 5.6 | 5.8 |
| TR | | 63800 | 67100 | 61600 | 63800 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | 53300 | **55100** | 48100 | 48800 |
| | | Keumbu- LR 2002 | | | |
| Mean yields | ND | 3.8 | 4.4 | 3.9 | 3.6 |
| TR | | 41800 | 48400 | 42900 | 39600 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | 31300 | **36400** | 29400 | 24600 |

[1]SGA = Southern geomorphic area, [2]Mean yields in Mg ha$^{-1}$, TR = Total returns (KES ha$^{-1}$), TC = Total costs (KES ha $^{-1}$), NR = Net return (KES ha$^{-1}$). [3]LR = long rains, SR = short rains of the corresponding year, [4]Calculations based on seasonal means given in Table 27, [5]Economically- optimal rate of fertilizer (bolded), ND = not determined.

Table 30: Economic analysis of fertilizer use in successive maize seasons in the NGA[1]

| Economic variables[2] | Treatments | | | | |
|---|---|---|---|---|---|
| | CONT | NPK0 | NPK25 | NPK50 | NPK75 |
| Ebukanga- LR 2001[3] | | | | | |
| Mean yields[4] | 1.3 | 2.3 | 2.0 | 2.5 | 2.5 |
| TR | 14300 | 25300 | 22000 | 27500 | 27500 |
| TC | 0 | 10500 | 12000 | 13500 | 15000 |
| NR | 14300 | **14800**[5] | 10000 | 14000 | 12500 |
| Ebukanga- LR 2002 | | | | | |
| Mean yields | ND | 2.7 | 2.8 | 2.9 | 2.9 |
| TR | | 29700 | 30800 | 31900 | 31900 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | **19200** | 18800 | 18400 | 16900 |
| Ebukanga- SR 2002 | | | | | |
| Mean yields | ND | 2.3 | 2.0 | 2.3 | 2.3 |
| TR | | 25300 | 22000 | 25300 | 25300 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | **14800** | 10000 | 11800 | 10300 |
| Yala- LR 2001 | | | | | |
| Mean yields | 2.8 | 3.8 | 3.9 | 3.9 | 4.2 |
| TR | 30800 | 41800 | 42900 | 42900 | 46200 |
| TC | 0 | 10500 | 12000 | 13500 | 15000 |
| NR | 30800 | **31300** | 30900 | 29400 | 31200 |
| Yala- LR 2002 | | | | | |
| Mean yields | ND | 3.1 | 3.2 | 2.5 | 2.6 |
| TR | | 34100 | 35200 | 27500 | 28600 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | **23600** | 23200 | 14000 | 13600 |
| Yala- SR 2002 | | | | | |
| Mean yields | ND | 1.5 | 1.7 | 1.7 | 1.3 |
| TR | | 16500 | 18700 | 18700 | 14300 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | 6000 | **6700** | 5200 | -700 |
| Kabula- LR 2000 | | | | | |
| Mean yields | 3.8 | 5.4 | 5.6 | 6.4 | 6.0 |
| TR | 41800 | 59400 | 61600 | 70400 | 66000 |
| TC | 0 | 10500 | 12000 | 13500 | 15000 |
| NR | 41800 | 48900 | 49600 | **56900** | 51000 |
| Kabula- LR 2001 | | | | | |
| Mean yields | ND | 3.9 | 4.3 | 4.2 | 4.4 |
| TR | | 42900 | 47300 | 46200 | 48400 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | 32400 | **35300** | 32700 | 33400 |
| Kabula- LR 2002 | | | | | |
| Mean yields | ND | 4.6 | 4.3 | 4.1 | 4.1 |
| TR | | 50600 | 47300 | 45100 | 45100 |
| TC | | 10500 | 12000 | 13500 | 15000 |
| NR | | **40100** | 35300 | 31600 | 30100 |

[1] NGA=Northern geomorphic area, [2]Mean yields in Mg ha$^{-1}$, TR = Total returns (KES ha$^{-1}$), TC = Total costs (KES ha$^{-1}$), NR = Net return (KES ha$^{-1}$). [3]LR = long rains, SR = short rains of the corresponding year, [4]Calculations based on seasonal means given in Table 27, [5]Economically- optimal rate of fertilizer (bolded), ND = not determined.

Potassium fertilizer was recommended in the site, as a means of sustaining high yields, particularly in this area, where N and P fertilizers are often applied in food crops. The net returns were calculated and ranged from 43, 300 – 53,300 KES ha$^{-1}$ (Table 31). Both the K use efficiency (KUE) and value/cost (VCR) values dropped with the seasons, probably because other nutrient limitations were emerging. In Keumbu, application of K fertilizer remained a profitable option throughout the three- season test period.

In all the seasons, the most profitable K rate was 25 kg K ha$^{-1}$, which gave net returns ranging from 36,400 – 55,100 KES ha$^{-1}$. The variation of KUE and VCR with season was not consistent. The VCR in all the seasons was above 2.0, indicating the continuously low risk of using K fertilizer in Keumbu soils.

Table 31: Optimal NPK fertilizer recommendations for maize in western Kenya, and economic indices

| Site | Season¶ | Economic Optimum fertilizer rate | Net returns (KES ha$^{-1}$) | ‡KUE | †VCR |
|---|---|---|---|---|---|
| Itare | LR2000 | NPK0 | 53,300 | 0 | 0 |
| | LR2001 | NPK25 | 41,800 | 13.3 | 2.93 |
| | SR2001 | NPK75 | 53,200 | 7.78 | 1.71 |
| | LR2002 | NPK75 | 43,300 | 5.56 | 1.22 |
| Keumbu | LR2000 | NPK25 | 51,800 | 40.00 | 8.80 |
| | LR2001 | NPK25 | 55,100 | 10.00 | 2.20 |
| | LR2002 | NPK25 | 36,400 | 18.00 | 4.40 |
| Ebukanga | LR2001 | NPK0 | 14,800 | 0 | 0 |
| | LR2002 | NPK0 | 19,200 | 0 | 0 |
| | SR2002 | NPK0 | 14,800 | 0 | 0 |
| Yala | LR2000 | NPK0 | 31,300 | 0 | 0 |
| | LR2001 | NPK0 | 30,800 | 0 | 0 |
| | SR2002 | NPK25 | 7,700 | 6.67 | 1.47 |
| Kabula | LR2000 | NPK50 | 56,900 | 16.7 | 3.67 |
| | LR2001 | NPK25 | 41800 | 13.3 | 2.93 |
| | LR2001 | NPK0 | 41800 | 0 | 0 |

¶ Seasons: LR = Long rains, SR = short rains, in corresponding years, ‡KUE = potassium fertilizer use efficiency (kg yield/ kg fertilizer), †VCR = value/cost ratio.

In the two sites at Ebukanga and Yala in NGA, it was not economical to apply K fertilizer in maize crop. Low profitability in fertilizing maize in Ebukanga and Yala was attributed to high infestation by *Striga harmonthica*, whose growth is accelerated by K fertilizer application (Farina *et al.,* 1985). In Kabula, there was good response in the first two seasons, where net returns ranged from 41,800 – 56,900 KES $ha^{-1}$, and economic indices declining with seasons. A drop in KUE and VCR was perhaps due to the decline in $Mg^{2+}$ and $Ca^{2+}$ availability, as a result of the enhanced yields and continuous cropping. The inconsistent trend in soils from Kabula was also attributed to the confounding effects of intermittent runoff from higher grounds to the area, and the likely fixation of K by surface soils.

These results conformed to the findings and recommendations arrived at after a three-year NPK trial on maize in western Kenya (MOA, 1964). The workers too did not get significant responses to K in the first two years, but profitable returns were recorded in the final year. Similar findings were reported by Hinga and Kuria (1976), who failed to realize significant response to K fertilizers but went ahead to recommend it on the basis of the low mineral reserves of studied soils. Kemmler and Malicornet (1976), and Kemmler and Hobt (1986), when working in Germany, did not get significant response to K fertilizers until the second, third, and sometimes fourth year, when, according to them the readily available K was exhausted. The period it takes for response to occur depends on the level of N and P fertilizer application, the intensity of cropping (yields obtained), and buffer power of soils towards K (Kemmler and Hobt, 1986).

Field experiments re-affirmed the complications involved in developing recommendations for K fertilizers on the basis of soil analytical results. Greenhouse experiments, too, did not provide useful leads in predicting maize response to K fertilizers. From the results obtained, however, K fertilizer was recommended in Itare and Keumbu at 25 kg K $ha^{-1}$. Liming was recommended in Itare, Keumbu and Kabula, where VCR was dropping with seasons, and control of *Striga harmonthica* in Ebukanga and Yala before yields can increase due to the application of K fertilizers. With increased demand for food in future, intensification of production through increased use of N and P fertilizers is bound to increase, and the need for K fertilizers can only grow from the recommended level of 25 kg K $ha^{-1}$.

# CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

1 A map of Kenya, showing areas that are likely to have an emerging K deficiency was made in Geographical Information Systems (GIS), using moisture availability index data in the Almanach Characterization Tool (ACT). The mapped area, covering about 7.5 million hectares (13 % of the total land area in Kenya), is of considerable significance as any future work on K in Kenya may be concentrated in the region.

2 Soils from the mapped region located in the NGA were consistently deficient in exchangeable K. Since laboratory analysis of soil samples is a widely used method in assessing K status, the outcome of this research validates the K status map developed, at least in the NGA.

3 Clay content of soils is not solely dependent on the type and extent of weathering of parent materials as commonly believed. The result gives credence to the many factors that are involved in determining soil properties (the universal soil forming equation), and need to consider such processes as sedimentation and plinthitization and their role in determining soil texture.

4 The illite – to – kaolinite mineral ratio in soils decreased with increase in mafic (ferromagnesian) – to – felsic (quartz, feldspar rich) mineral ratio in rocks. It is of significance that, from this study, acid rocks (rich in felsic minerals), weather to soils that are better in holding K selectively against leaching, and may also fix K from applied fertilizerss, due to the proportionately higher 2:1 clay minerals than soils from basic rocks (rich in mafic minerals).

5 Plant available K and Ca in soils do not entirely depend on their total content in parent rocks. The need to consider all processes, e.g. mineralization of organic matter, alluvial deposits, and

form of the cation – bearing mineral in parent rocks and their susceptibility to weathering, before making a decision on the overall availability of cations was brought to light after this research work.

6 As the clay content increased in studied soils: the illite – to – kaolinite mineral ratio decreased, total K decreased, exchangeable K decreased, solution K decreased, and maize K uptake decreased. Going with the general knowledge that the finer the texture, the greater the extent of weathering of a soil, the result from this study attributes K deficiency to extreme weathering; a factor widely acknowledged in tropical soils.

7 Maize response to K fertilizers was increasing in subsequent seasons (the probability of null hypothesis decreased and tended to 0.05 as cropping continued). Since the country has a history of not using K fertilizers in food crops due to none, low, or negative response to K fertilizers, this research elucidated the reasons behind such results. Of significance, however, is that such poor responses may be short term and K fertilizers are to be needed sooner rather than later, as cropping continues, and in particular if application of N and P fertilizers is included in management strategies that aim at increasing yields.

8 Economic returns from application of K fertilizers in maize were positive in virtually all the seasons in the two sites from SGA (Itare and Keumbu). The result supports a case for the need of adoption of N-P-K fertilizers in place of the hitherto used N-P fertilizers in SGA, and a similar treat of soils from NGA, as long as the incidence of *Striga hermonthica* is controlled and proper strategies for liming soils (to correct Ca and Mg deficiency); are developed.

## SUMMARY OF RECOMMENDATIONS

1. Any efforts to address potassium problems in Kenyan soils should be concentrated in the areas mapped out of this research work, subject to further review of the map in future. Measures should be put in place to slow down the rate of K loss from soils by intensifying soil conservation measures, encouraging the recycling of crop residues, and applying K fertilizers.

2. Soils developed from parent rocks with higher mafic: felsic mineral ratios (e.g. basalts), which also happen to have a higher content of clay, low total K, and low solution and exchangeable K, have limited capacity to fix or hold K selectively against leaching, and should therefore be fertilized with caution, to avoid unprecedented losses and low efficiency of utilization of K fertilizers. Rather than apply the recommended dose at once, a split application program would be preferred to avoid leaching losses. Soils formed from acid rocks (e.g. granite), have on the other hand great reserves for K, but have a bigger fraction of the total K in labile form. High soil tests for K in coarse textured soils should be taken with caution because they get depleted quickly and crops may have deficiencies after only a few croppings.

3. Clayey soils are more likely to have K deficiency than coarse textured soils. According to results from this research work, clayey soils have limited reserve capacity (total and non-exchangeable K), and lower capacity to fix and hold K selectively against leaching. Where K deficiencies may appear, therefore, fine textured soils would require more attention than coarse textured soils.

4. The capacity of soil laboratories in Kenya to determine clay mineralogy of soils is very limited

and should be strengthened. Information on type of parent rock, clay content and type of clay minerals forms important baseline information for predicting the amount of soil K, plant available K, and needs of K fertilizer application.

5. It is evident from this work that response of crops to K fertilizers may not occur in the initial years or seasons, but occur in subsequent years or seasons when readily available K is depleted. It has also been proven that though the effects of fertilizer application may not be agronomically significant, yield increments obtained were profitable because of the low market price of K fertilizer in Kenya, and probably the whole word. After considering all these factors and practical experiences on the ground, K fertilizers were not recommended in soils from the NGA (Ebukanga, Yala and Kabula)- due to low economic returns as a result of high striga infestation and low Ca and Mg status; but were recommended in soils from the SGA (Itare, Keumbu and Ndanai), at a modest rate of 25 kg K $ha^{-1}$.

# SUGGESTIONS FOR FURTHER RESEARCH

1 The map developed from this research study should be revised because not all the soils in mapped region were deficient in K. More data should be collected from a study incorporating the interaction between moisture availability index, (r/Eo), parent materials and cropping systems, and fed to a model to produce a better map.

2 There is need to carry out a complete potassium balance study in soils from western Kenya. The amounts of K released through weathering, mineralization of organic residues, and surface contamination by colluvial clay deposits should be quantified and variation of each input over time determined. At the same time, losses through uptake, surface runoff, soil erosion and leaching should be quantified. The various indices should be combined in a model for predicting changes in plant available K over time.

3 An investigation should be carried out to determine how *in situ* weathering of rocks, gain/loss of clay to/out of surface soils, and plinthitization, influence the clay content, and K dynamics of soils from western Kenya. An attempt should be made to obtain fresh rock cores from great depths so that better correlations than witnessed in this study may be achieved.

4 Field investigations on K requirements for various crops should be pursued further: (i) under longer periods of cropping, (ii) under limed and other nutrients optimisation, and (iii) under conditions where striga weed has been controlled. Potassium fertilizer response experiments should be done on crops with different K uptake capacities rather than that of maize. In addition, further investigations should be conducted to determine the effects of K fertilizer on harvest quality, alongside the effects on yields.

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# ANNEX 1

Table 32: Textural characteristics of soils from Itare cluster

| Farmer | Sand (%) | Silt ( %) | Clay (%) | Textural Class |
|---|---|---|---|---|
| Augostino Ouko | 26 | 32 | 42 | C |
| Christopher Bosire | 16 | 26 | 58 | C |
| Fluorence Onsongo | 20 | 30 | 50 | C |
| Grace Matisi | 20 | 24 | 56 | C |
| Itare primary | ND | ND | ND | ND |
| John Ndege | 18 | 28 | 54 | C |
| Obadia Nyameri | 16 | 36 | 48 | C |
| Omboga Ongaga | 22 | 32 | 46 | C |
| Ondora Ondoro | 16 | 34 | 50 | C |
| Rhoda Nyatangi | 22 | 36 | 42 | C |
| Stephen Nyangau | 20 | 30 | 50 | C |
| Tabitha Nyachana | 24 | 28 | 38 | CL |
| Winfred Ongega | 16 | 36 | 48 | C |
| Zacharia Siro | 24 | 34 | 42 | C |
| Mean | 20 | 31 | 48 | C |
| STD | 3 | 4 | 6 | |

ND = not determined

Table 33: Textural characteristics of soils from Keumbu cluster

| Farmer | Sand % | Silt % | Clay % | Textural class |
|---|---|---|---|---|
| Bathiseba Onchiri | 28 | 34 | 38 | CL |
| Benedicto Orunde | 22 | 26 | 52 | C |
| Benson M Nyasani | 26 | 28 | 46 | C |
| Callen Iteba | 24 | 36 | 40 | CL |
| Chirochiro WG | 26 | 38 | 36 | CL |
| Fluorence Atemba | 28 | 22 | 50 | C |
| Francis Ochichi | ND | ND | ND | ND |
| Grace Angima | 24 | 26 | 50 | C |
| James Bigingi | ND | ND | ND | ND |
| Jane Ogeto | 24 | 24 | 52 | C |
| Jeria Nyakaga | 28 | 32 | 40 | CL |
| Jogoo Amwata | 22 | 22 | 56 | C |
| Kefa Nyambiche | 26 | 24 | 50 | C |
| Margaret Kerobo | 28 | 34 | 38 | CL |
| Naomi Gekonge | 28 | 32 | 40 | CL |
| Obino Makwero | 26 | 26 | 48 | C |
| Robert Onsario | 32 | 36 | 32 | CL |
| Robina Mog | ND | ND | ND | ND |
| Samwel Makori | 26 | 30 | 44 | C |
| Mean | 26 | 29 | 45 | C |
| SDEV | 3 | 5 | 7 | |

ND = not determined

Table 34: Textural characteristics of soils from Ebukanga cluster

| Farmer | Sand | Silt | Clay | Tex. |
|---|---|---|---|---|
| Abedinego Abuyeka | 40 | 20 | 40 | Sandy Clay |
| Asman Chapia | 40 | 15 | 45 | Clay |
| Dishon Ameyo | 30 | 20 | 50 | Clay |
| Dora Dan Ndola | 30 | 30 | 40 | Clay Loam |
| Festo Atianga | 50 | 15 | 35 | Sandy Clay Loam |
| Frank Atieli | 40 | 5 | 55 | Clay |
| Ibrahim Sikombe | ND | ND | ND | ND |
| Jacob Okwomi | 35 | 5 | 60 | Clay |
| James Consolata | 35 | 25 | 40 | Clay Loam |
| Jane Okotse | 45 | 25 | 30 | Sandy Clay Loam |
| John Butiko | 55 | 15 | 30 | Sandy Clay Loam |
| Margaret Amasiebe | 30 | 20 | 50 | Clay |
| Moses Isiye | 40 | 10 | 50 | Clay |
| Phanise Esikimo | 45 | 20 | 35 | Clay Loam |
| Silas Msafiri | 30 | 35 | 35 | Clay Loam |
| Zedekiah Sakhunya | 40 | 10 | 50 | Clay |
| Mean | 39 | 18 | 43 | |
| SDEV | 8 | 9 | 9 | |

**ND= not determined**

Table 35: Textural characteristics of soils from Yala cluster

| Farmer | Sand | Silt | Clay | Tex |
|---|---|---|---|---|
| Aggrey Ochido | 45 | 10 | 45 | Clay |
| Ben Otiende | 45 | 15 | 40 | Sandy Clay |
| Dominick Adiedo | 25 | 10 | 65 | Clay |
| Dorca Kidha | 35 | 15 | 50 | Clay |
| Dorcas Muhado | 33 | 17 | 50 | Clay |
| Hellen Oder0 | 45 | 10 | 45 | Clay |
| Herbert Maganga | 25 | 25 | 50 | Clay |
| Isaac Walle | 30 | 25 | 45 | Clay |
| Jenipher Arwa | 25 | 25 | 50 | Clay |
| Joab Achieng | 25 | 35 | 40 | Clay |
| Joyce Omoro | 25 | 25 | 50 | Clay |
| Mike Oloo | 75 | 15 | 10 | Sandy Loam |
| Monica Abwonyi | 25 | 25 | 50 | Clay |
| Nicodemus Agutu | 35 | 0 | 65 | Clay |
| Nifa Okoth | 25 | 5 | 70 | Clay |
| Ochieng Mwosi | 25 | 15 | 60 | Clay |
| Samwel Odipo | 30 | 20 | 50 | Clay |
| Silverous Odhiambo | 20 | 20 | 60 | Clay |
| Simon O. Bolo | 30 | 20 | 50 | Clay |
| Mean | 33 | 17 | 50 | |
| SDEV | 13 | 8 | 13 | |

Table 36: Textural characteristics of soils from Kabula cluster

| Farmer | Sand | Silt | Clay | Tex |
|---|---|---|---|---|
| David Waswa | 65 | 0 | 35 | Sandy Clay Loam |
| Everlyne Mchele | ND | | | |
| Floriano Sifuna | 75 | 0 | 25 | Sandy Clay Loam |
| Francis Adagala | 80 | 5 | 15 | Sandy Clay |
| Fred Simiyu | 80 | 0 | 20 | |
| Gabriel Sifuna | 70 | 0 | 30 | Sandy Clay Loam |
| Gladys Ochieng | 80 | 0 | 20 | Sandy Clay Loam |
| Ignatius Chemku | 70 | 5 | 25 | Sandy Clay Loam |
| Kizito Simiyu | 55 | 0 | 45 | Sandy Clay |
| Mariana Wasike | 70 | 5 | 25 | Sandy Clay Loam |
| Melitus Makhanu | 70 | 5 | 25 | Sandy Clay |
| Methus Barase | ND | | | |
| Patrick Wanjala | 55 | 5 | 40 | Sandy Clay |
| Paul Wafula | 70 | 0 | 30 | Sandy Clay |
| Peter Masinde | 75 | 5 | 20 | Sandy Clay Loam |
| Philip Kuloba | 75 | 5 | 20 | Sandy Clay Loam |
| Silvester Masike | 55 | 10 | 35 | Sandy Clay Loam |
| Vincent Baraza | ND | ND | ND | ND |
| Mean | 70 | 3 | 27 | |
| STD | 9 | 3 | 8 | |

ND = not determined

Table 37: Physiochemical properties[¶] of soils from Itare cluster

| Farmer | $pH_{H2O}$ 1: 2.5 | OC | Ca | Mg | K | Na | CEC | Ca/K | Mg/K | P |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (g/kg) | ← | | cmol kg$^{-1}$ | | → | | | |
| Augostino Ouko | 5.5 | 19 | 4.4 | 1.5 | 0.8 | 0.05 | 31.7 | 6.0 | 1.8 | 8 |
| Christopher Bosire | 6.0 | 15 | 7.5 | 2.2 | 1.3 | 0.08 | 30.5 | 5.7 | 1.7 | 33 |
| Fluorence Onsongo | 6.1 | 15 | 10.0 | 2.5 | 2.1 | 0.04 | 33.3 | 4.8 | 1.2 | 8 |
| Grace Matisi | 5.7 | 20 | 7.5 | 2.2 | 1.6 | 0.04 | 32.0 | 4.7 | 1.4 | 8 |
| Itare primary | 6.0 | 18 | 9.2 | 2.5 | 1.4 | 0.02 | 32.0 | 6.6 | 1.8 | 25 |
| John Ndege | 5.5 | 16 | 4.3 | 1.7 | 0.6 | 0.04 | 32.7 | 7.5 | 3.0 | 8 |
| Obadia Nyameri | 5.5 | 19 | 6.2 | 2.1 | 0.7 | 0.06 | 36.5 | 9.3 | 3.1 | 10 |
| Omboga Ongaga | 6.2 | 21 | 12.7 | 3.4 | 1.5 | 0.04 | 34.5 | 8.7 | 2.3 | 22 |
| Ondora Ondoro | 6.0 | 21 | 9.9 | 2.7 | 1.3 | 0.06 | 31.4 | 7.5 | 2.0 | 28 |
| Rhoda Nyatangi | 5.9 | 22 | 10.6 | 2.9 | 2.3 | 0.04 | 35.0 | 4.6 | 1.3 | 10 |
| Stephen Nyangau | 6.0 | 21 | 8.8 | 2.1 | 1.7 | 0.01 | 32.2 | 5.2 | 1.2 | 22 |
| Tabitha Nyachana | 5.8 | 23 | 9.3 | 2.3 | 1.7 | 0.04 | 36.7 | 5.6 | 1.4 | 20 |
| Winfred Ongega | 6.2 | 19 | 10.7 | 3.1 | 2.3 | 0.03 | 32.8 | 4.6 | 1.3 | 8 |
| Zacharia Siro | 5.9 | 24 | 11.6 | 3.3 | 2.3 | 0.08 | 39.3 | 5.0 | 1.4 | 17 |
| Mean | | 20 | 8.8 | 2.5 | 1.5 | 0.05 | 40.1 | 6.1 | 1.8 | 16.2 |
| STD | | 05 | 2.5 | 0.6 | 0.6 | 0.02 | 5.3 | 1.6 | 0.6 | 8.7 |

[¶] OC = organic carbon, CEC = cation exchange capacity, P in mg P kg$^{-1}$ soil (Meh)

Table 38: Physio-chemical properties[¶] of soils from Keumbu cluster

| Farmer | $pH_{H2O}$ 1:2.5 | OC (g/kg) | Ca | Mg | K | Na | CEC[**] | Ca/K | Mg/K | P |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | ← | | cmol $kg^{-1}$ | | → | | | |
| Bathiseba Onchiri | 5.8 | 17 | 7.1 | 2.4 | 1.0 | 0.06 | 23.2 | 7.1 | 2.4 | 2 |
| Bene Orunde | 5.4 | 13 | 3.6 | 1.5 | 0.6 | 0.05 | 22.7 | 6.0 | 2.5 | 8 |
| Benson M Nyasani | 5.4 | 14 | 3.7 | 1.2 | 0.8 | 0.04 | 26.1 | 4.6 | 1.5 | 10 |
| Callen Iteba | 5.7 | 12 | 7.1 | 1.6 | 1.6 | 0.05 | 23.8 | 4.4 | 1.0 | 5 |
| Chirochiro WG | 5.7 | 23 | 8.7 | 2.0 | 1.3 | 0.06 | 22.6 | 6.7 | 1.5 | 10 |
| Fluorence Atemba | 5.1 | 15 | 1.1 | 0.4 | 0.5 | 0.03 | 26.0 | 2.2 | 0.8 | 10 |
| Francis Ochichi | 6.2 | 19 | 2.8 | 1.5 | 0.9 | 0.04 | 26.8 | 3.1 | 1.7 | 10 |
| Grace Angima | 5.6 | 20 | 4.6 | 1.8 | 1.1 | 0.07 | 21.7 | 4.2 | 1.6 | 14 |
| James Bigingi | 5.5 | 15 | 3.9 | 1.3 | 0.8 | 0.03 | 26.2 | 4.9 | 1.6 | 14 |
| Jane Ogeto | 5.6 | 19 | 5.0 | 1.6 | 0.8 | 0.05 | 21.8 | 6.3 | 2.0 | 5 |
| Jeria Nyakaga | 6.1 | 17 | 11.3 | 2.9 | 1.5 | 0.04 | 26.2 | 7.5 | 1.9 | 25 |
| Jogoo Amwata | 5.2 | 16 | 1.8 | 0.8 | 0.5 | 0.04 | 26.3 | 3.6 | 1.6 | 10 |
| Kefa Nyambiche | 5.7 | 18 | 3.1 | 1.4 | 1.4 | 0.07 | 23.8 | 2.2 | 1.0 | 25 |
| Margaret Kerobo | 5.6 | 21 | 9.8 | 2.8 | 1.6 | 0.05 | 26.5 | 6.1 | 1.8 | 8 |
| Naomi Gekonge | 5.8 | 20 | 9.0 | 2.3 | 0.8 | 0.03 | 26.5 | 11.3 | 2.9 | 5 |
| Obino Makwero | 5.5 | 20 | 5.6 | 1.9 | 0.5 | 0.03 | 32.4 | 11.2 | 3.8 | 5 |
| Robert Onsario | 6.2 | 17 | 11.8 | 4.0 | 2.6 | 0.07 | 34.5 | 4.5 | 1.5 | 14 |
| Robina Mog | 5.7 | 19 | 6.8 | 1.7 | 1.6 | 0.05 | 21.9 | 4.3 | 1.1 | 10 |
| Samwel Makori | 5.7 | 23 | 4.8 | 1.5 | 1.1 | 0.03 | 29.1 | 4.4 | 1.4 | 5 |
| Mean | | 18 | 5.9 | 1.8 | 1.1 | 0.05 | 24.5 | 5.5 | 1.8 | 10 |
| SDEV | | 3.1 | 3.1 | 0.8 | 0.5 | 0.0 | 2.0 | 2.5 | 0.7 | 6.2 |

[¶] CEC = Cation exchange capacity by NaOAc pH 7, OC = organic carbon

Table 39: Physio-chemical characteristics[¶] of soils from Ebukanga cluster

| Farmer | $pH_{H2O}$ 1:2.5 | OC (g/kg) | Ca | Mg | K | Na | Ca/K | Mg/K | P |
|---|---|---|---|---|---|---|---|---|---|
| | | | ← | | cmol $kg^{-1}$ | → | | | |
| Abedinego Abuyeka | 5.4 | 14 | 5.2 | 1.1 | 0.2 | 0.04 | 26.0 | 5.5 | 2.0 |
| Asman Chapia | 5.5 | 12 | 6.7 | 1.3 | 0.3 | 0.06 | 22.3 | 4.3 | 8.0 |
| Dishon Ameyo | 4.9 | 08 | 3.9 | 1.1 | 0.1 | 0.02 | 39.0 | 11.0 | 14.0 |
| Dora Dan Ndola | 5.0 | 10 | 4.9 | 1.0 | 0.1 | 0.05 | 49.0 | 10.0 | 2.0 |
| Festo Atianga | 4.6 | 14 | 5.6 | 1.1 | 0.1 | 0.01 | 56.0 | 11.0 | 20.0 |
| Frank Atieli | 4.6 | 07 | 4.8 | 1.4 | 0.1 | 0.01 | 48.0 | 14.0 | |
| Ibrahim Sikombe | 4.6 | 15 | 5.1 | 0.9 | 0.2 | 0.04 | 25.5 | 4.5 | 20.0 |
| Jacob Okwomi | 5.4 | 13 | 5.5 | 2.0 | 0.3 | 0.05 | 18.3 | 6.7 | 12.0 |
| James Consolata | 5.5 | 14 | 5.6 | 1.3 | 0.3 | 0.05 | 18.7 | 4.3 | |
| Jane Okotse | 4.2 | 11 | 3.7 | 1.0 | 0.1 | 0.02 | 37.0 | 10.0 | 14.0 |
| John Butiko | 4.2 | 04 | 2.1 | 0.7 | 0.1 | 0.03 | 21.0 | 7.0 | 3.5 |
| Moses Isiye | 4.4 | 05 | 2.5 | 0.9 | 0.1 | 0.01 | 25.0 | 9.0 | 2.0 |
| Phanise Esikimo | 5.0 | 08 | 3.6 | 1.0 | 0.2 | 0.04 | 18.0 | 5.0 | 2.0 |
| Silas Msafiri | 4.4 | 17 | 4.3 | 1.1 | 0.2 | 0.04 | 21.5 | 5.5 | 30.0 |
| Zedekiah Sakhunya | 4.9 | 10 | 5.0 | 1.5 | 0.2 | 0.04 | 25.0 | 7.5 | 5.0 |
| mean | | 11 | 4.6 | 1.2 | 0.2 | 0.03 | 30.0 | 7.7 | 10.4 |
| SDEV | | 4 | 1.2 | 0.3 | 0.1 | 0.02 | 12.5 | 3.0 | 9.0 |

[¶] OC = organic carbon, P in mg P $kg^{-1}$ soil (Meh)

Table 40: Physio-chemical characteristics¶ of soils from Yala cluster

| Farmer | $pH_{H2O}$ | OC | Ca | Mg | K | Na | Ca/K | Mg/K | P |
|---|---|---|---|---|---|---|---|---|---|
| | 1:2.5 | g kg$^{-1}$ | ← | cmol kg$^{-1}$ | | → | | | |
| Aggrey Ochido | 4.4 | 07 | 4.2 | 1.1 | 0.2 | 0.02 | 21.0 | 5.5 | 06.0 |
| Ben Otiende | 4.9 | 16 | 5.7 | 0.9 | 0.1 | 0.04 | 57.0 | 9.0 | 10.0 |
| Dominick Adiedo | 4.2 | 08 | 3.7 | 1.0 | 0.1 | 0.01 | 37.0 | 10.0 | 12.0 |
| Dorca Kidha | 4.0 | 04 | 2.3 | 1.0 | 0.2 | 0.02 | 11.5 | 5.0 | 06.0 |
| Dorcas Muhado | 5.0 | 2.8 | 4.1 | 1.1 | 0.1 | 0.04 | 41.0 | 11.0 | 02.0 |
| Hellen Odero | 5.5 | 6.2 | 5.5 | 1.4 | 0.4 | 0.06 | 13.8 | 3.5 | 14.0 |
| Herbert Maganga | 4.5 | 17 | 5.7 | 2.4 | 0.1 | 0.02 | 57.0 | 24.0 | 25.0 |
| Isaac Walle | 4.7 | 17 | 6.7 | 2.3 | 1.1 | 0.18 | 6.1 | 2.1 | 35.0 |
| Jenipher Arwa | 4.0 | 12 | 3.9 | 1.7 | 0.2 | 0.01 | 19.5 | 8.5 | 05.0 |
| Joab Achieng | 4.6 | 05 | 6.1 | 1.9 | 0.5 | 0.10 | 12.2 | 3.8 | 07.2 |
| Joyce Omoro | 5.2 | 08 | 6.4 | 1.6 | 0.9 | 0.13 | 7.1 | 1.8 | 07.0 |
| Margaret Amasiel | 4.2 | 11 | 4.0 | 1.4 | 0.2 | 0.02 | 20.0 | 7.0 | 25.0 |
| Mike Oloo | ND | ND | 3.9 | 1.2 | 0.9 | 0.19 | 4.3 | 1.3 | ND |
| Monica Abwonyi | 4.7 | 17 | 6.6 | 1.8 | 0.8 | 0.13 | 8.3 | 2.3 | 17.0 |
| Nicodemus Agutu | 4.0 | 02 | 4.3 | 1.8 | 0.8 | 0.11 | 5.4 | 2.3 | 16.0 |
| Nifa Okoth | 4.1 | 02 | 4.3 | 1.2 | 0.2 | 0.05 | 21.5 | 6.0 | 18.0 |
| Ochieng Mwosi | 3.8 | 12 | 2.2 | 0.9 | 0.2 | 0.01 | 11.0 | 4.5 | 17.0 |
| Samwel Odipo | 4.3 | 07 | 3.2 | 1.0 | 0.3 | 0.06 | 10.7 | 3.3 | 05.0 |
| Silverous Odhiambo | 5.0 | 09 | 4.9 | 2.1 | 0.7 | 0.12 | 7.0 | 3.0 | 12.0 |
| Simon O. Bolo | 4.3 | 07 | 2.4 | 0.9 | 0.2 | 0.02 | 12.0 | 4.5 | 07.0 |
| Mean | | 09 | 4.5 | 1.4 | 0.4 | 0.07 | 19.2 | 5.9 | 13.0 |
| SDEV | | 05 | 1.4 | 0.5 | 0.3 | 0.06 | 16.2 | 5.1 | 8.5 |

¶OC = organic carbon, P in mg P kg$^{-1}$ soil (Meh), ND = not determined

Table 41: Physio-chemical characteristics[¶] of soils from Kabula cluster

| Farmer | PH$_{H20}$ | Org C | Ca | Mg | K | Na | Ca/K | Mg/K | P |
|---|---|---|---|---|---|---|---|---|---|
| | 1:2.5 | g kg$^{-1}$ | ← | cmol$_c$ kg$^{-1}$ | | → | | | |
| David Waswa | 3.9 | 09 | 2.0 | 0.6 | 0.4 | 0.06 | 5.0 | 1.5 | 8.0 |
| Everlyne Mchele | 5.0 | 06 | 1.6 | 0.5 | 0.2 | 0.01 | 8.0 | 2.5 | 10.0 |
| Floriano Sifuna | 5.4 | 12 | 2.8 | 0.7 | 0.3 | 0.06 | 9.3 | 2.3 | 8.0 |
| Francis Adagala | 5.2 | 12 | 1.4 | 0.3 | 0.1 | 0.01 | 14.0 | 3.0 | 20.0 |
| Fred Simiyu | 4.7 | 07 | 2.1 | 0.7 | 0.5 | 0.05 | 4.2 | 1.4 | 5.0 |
| Gabriel Sifuna | 5.1 | 04 | 2.1 | 0.4 | 0.1 | 0.02 | 21.0 | 4.0 | 10.0 |
| George Wekesa | 4.8 | 07 | 3.9 | 1.4 | 0.6 | 0.10 | 6.5 | 2.3 | 2.0 |
| Gladys Ochieng | 5.5 | 05 | 2.4 | 0.6 | 0.2 | 0.01 | 12.0 | 3.0 | 5.0 |
| Ignatius Chemku | 5.5 | 06 | 4.1 | 1.0 | 0.2 | 0.02 | 20.5 | 5.0 | 10.0 |
| Kizito Simiyu | 5.2 | 09 | 3.4 | 1.2 | 0.3 | 0.05 | 11.3 | 4.0 | 5.0 |
| Mariana Wasike | 5.1 | 15 | 3.1 | 0.7 | 0.2 | 0.02 | 15.5 | 3.5 | 10.0 |
| Melitus Makhanu | 4.1 | 06 | 1.5 | 0.3 | 0.1 | 0.01 | 15.0 | 3.0 | 2.0 |
| Methus Barase | 5.1 | 08 | 1.5 | 0.4 | 0.1 | 0.01 | 15.0 | 4.0 | 8.0 |
| Patrick Wanjala | 4.8 | 16 | 2.9 | 0.8 | 0.3 | 0.04 | 9.7 | 2.7 | 8.0 |
| Paul Wafula | 4.7 | 06 | 2.2 | 0.8 | 0.3 | 0.04 | 7.3 | 2.7 | 2.0 |
| Peter Masinde | 4.7 | 0.8 | 2.7 | 0.7 | 0.2 | 0.04 | 13.5 | 3.5 | 5.0 |
| Philip Kuloba | 4.5 | 09 | 1.3 | 0.4 | 0.1 | 0.01 | 13.0 | 4.0 | 2.0 |
| Phostin Wanjala | 4.0 | 11 | 1.2 | 0.6 | 0.3 | 0.04 | 4.0 | 2.0 | 2.0 |
| Silina Kavesa | 4.8 | 13 | 3.3 | 1.1 | 0.2 | 0.02 | 16.5 | 5.5 | 2.0 |
| Silvester Masike | 5.1 | 14 | 2.9 | 0.9 | 0.4 | 0.04 | 7.3 | 2.3 | 10.0 |
| Vincent Baraza | 5.2 | 12 | 1.8 | 0.6 | 0.3 | 0.02 | 6.0 | 2.0 | 5.0 |
| Mean | | 09 | 2.4 | 0.7 | 0.3 | 0.03 | 11.2 | 3.1 | 6.6 |
| STDEV | | 04 | 0.9 | 0.3 | 0.1 | 0.02 | 5.0 | 1.1 | 4.4 |

[¶] OC = organic carbon, P in mg P kg$^{-1}$ soil (Meh), ND = not determined

# ANNEX II

Table 42: Variation of maize yields (t/ha) in Itare cluster during the long rains 2000 (LR 2000)

| Farmer | Control | NPK0¶ | NPK25 | NPK50 | NPK75 | NPKmax | RY(K)* | Krate** |
|---|---|---|---|---|---|---|---|---|
| Augostino Ouko | 2.6 | 3.6 | 4.0 | 4.1 | 4.8 | 4.8 | 0.75 | 90 |
| Christopher Bosire | 2.9 | 5.7 | 5.9 | 6.2 | 5.6 | 6.2 | 0.92 | 60 |
| Grace Matisi | 2.6 | 3.1 | 3.1 | 4.3 | 2.4 | 4.3 | 0.72 | 60 |
| Omboga Ongaga | 6.2 | 8.2 | 8.4 | 9.4 | 6.9 | 9.4 | 0.87 | 60 |
| Ondora Ondoro | 5.8 | 7.4 | 6.0 | 9.0 | 7.1 | 9.0 | 0.82 | 60 |
| Rhoda Nyatangi | 3.2 | 6.1 | 5.1 | 4.2 | 4.8 | 5.1 | 1.20 | 0 |
| Tabitha Nyachana | 2.9 | 4.5 | 3.5 | 4.1 | 4.9 | 4.9 | 0.91 | 90 |
| Winfred Ongega | 4.2 | 7.8 | 4.9 | 4.3 | 5.3 | 5.3 | 1.46 | 0 |
| Mean | 3.8 | 5.8 | 5.1 | 5.7 | 5.2 | 6.1 | 0.96 | 53 |
| STDev | 1.5 | 1.9 | 1.7 | 2.3 | 1.4 | 2.0 | 0.25 | 35 |
| CV% | 38 | 33 | 33 | 40 | 28 | 32 | 26 | 67 |

¶ N and P at 75 and 33 kg ha$^{-1}$ *RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 43: Variation of maize yields (t/ha) in Itare during the long rains 2001 (LR 2001)

| Farmer | NPK0¶ | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|
| Augostino Ouko | 2.4 | 2.1 | 3.7 | 3.3 | 3.7 | 0.66 | 60 |
| Christopher Bosire | 2.4 | 2.4 | 2.7 | 3.0 | 3.0 | 0.81 | 90 |
| Fluorence Onsongo | 3.4 | 4.3 | 4.0 | 4.6 | 4.6 | 0.73 | 90 |
| Grace Matisi | 3.7 | 3.7 | 3.1 | 3.7 | 3.7 | 1.00 | 0 |
| Ibrahim Kombo | 4.0 | 4.0 | 3.4 | 4.6 | 4.6 | 0.87 | 90 |
| Jepta Atandi | 5.6 | 5.9 | 5.6 | 6.0 | 6.0 | 0.93 | 90 |
| Joel Mitioko | 3.9 | 4.2 | 3.6 | 5.1 | 5.1 | 0.77 | 90 |
| John Ndege | 2.7 | 3.6 | 2.4 | 3.3 | 3.6 | 0.75 | 30 |
| John Nyangau | 3.3 | 3.7 | 3.1 | 3.1 | 3.7 | 0.90 | 30 |
| Joseph Kemosi | 3.1 | 3.7 | 4.0 | 4.0 | 4.0 | 0.77 | 60 |
| Omboga Ongaga | 6.4 | 5.4 | 4.8 | 6.0 | 6.0 | 1.06 | 0 |
| Rhoda Nyatangi | 3.6 | 4.8 | 4.2 | 3.0 | 4.8 | 0.75 | 30 |
| Roel Nyaora | 1.8 | 2.8 | 2.8 | 2.4 | 2.8 | 0.66 | 30 |
| Stephen Nyangau | 4.6 | 4.6 | 4.2 | 3.7 | 4.6 | 0.99 | 0 |
| Tabitha Nyachana | 3.7 | 4.7 | 5.2 | 3.7 | 5.2 | 0.71 | 60 |
| Wilfred Ndege | 4.0 | 5.2 | 4.3 | 4.3 | 5.2 | 0.76 | 30 |
| Zacharia Siro | 7.3 | 7.8 | 6.2 | 6.7 | 7.8 | 0.94 | 30 |
| Mean | 3.9 | 4.3 | 3.9 | 4.1 | 4.6 | 0.83 | 48 |
| STDev | 1.4 | 1.4 | 1.0 | 1.2 | 1.2 | 0.12 | 34 |
| CV% | 37 | 32 | 26 | 29 | 27 | 15 | 71 |

¶ N and P at 75 and 33 kg ha$^{-1}$ *RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 44: Variation of maize yields (t/ha) in Itare during the Short rains 2001 (SR 2001)

| Farmer | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|
| Abednego Samwel | 5.7 | 5.8 | 6.5 | 6.7 | 6.7 | 0.86 | 90 |
| Christopher Bosire | 3.6 | 3.3 | 4.2 | 4.4 | 4.2 | 0.85 | 60 |
| Fluorence Onsongo | 7.9 | 7.9 | 6.9 | 7.8 | 7.9 | 1.00 | 0 |
| John Ndege | 3.4 | 4.3 | 4.6 | 4.3 | 4.6 | 0.75 | 60 |
| Omboga Ongaga | 7.6 | 7.6 | 6.9 | 7.9 | 7.9 | 0.96 | 90 |
| Rhoda Nyatangi | 4.4 | 5.8 | 4.5 | 5.2 | 5.8 | 0.75 | 30 |
| Stephen Nyangau | 7.6 | 5.9 | 5.7 | 6.5 | 6.5 | 1.17 | 0 |
| Wilfred Ndege | 7.6 | 8.8 | 8.3 | 9.7 | 9.7 | 0.78 | 90 |
| Winfred Ongega | 2.4 | 2.4 | 2.2 | 2.2 | 2.4 | 0.98 | 0 |
| Zacharia Siro | 5.2 | 6.1 | 6.4 | 7.2 | 7.2 | 0.72 | 90 |
| mean | 5.5 | 5.8 | 5.6 | 6.2 | 6.3 | 0.9 | 51 |
| STDev | 2.1 | 2.0 | 1.8 | 2.2 | 2.1 | 0.14 | 40 |
| CV% | 37 | 35 | 32 | 35 | 34 | 16 | 79 |

[¶] N and P at 75 and 33 kg ha$^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 45: Variation of maize yields (t/ha) in Itare during the long rains 2002 (LR 2002)

| Farmer | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|
| Augostino Ouko | 6.0 | 5.9 | 7.2 | 6.5 | 7.2 | 0.83 | 60 |
| Christopher Bosire | 2.7 | 2.6 | 2.7 | 4.1 | 4.1 | 0.66 | 90 |
| Fluorence Onsongo | 4.0 | 4.3 | 5.3 | 5.4 | 5.4 | 0.74 | 90 |
| Jepta Atandi | 4.7 | 6.4 | 7.5 | 3.9 | 7.5 | 0.63 | 60 |
| Joel Mitioko | 5.2 | 4.5 | 5.9 | 5.6 | 5.9 | 0.88 | 60 |
| John Ndege | 3.3 | 6.5 | 5.1 | 6.9 | 6.9 | 0.48 | 90 |
| Joseph Michote | 4.1 | 4.4 | 4.2 | 4.1 | 4.4 | 0.93 | 30 |
| Rhoda Nyatangi | 5.2 | 3.9 | 5.2 | 4.2 | 5.2 | 1.00 | 0 |
| Roel Nyaora | 3.7 | 2.9 | 3.6 | 4.5 | 4.5 | 0.82 | 90 |
| Stephen Nyangau | 5.9 | 5.4 | 5.7 | 6.6 | 6.6 | 0.89 | 90 |
| Tabitha Nyachana | 3.9 | 5.8 | 4.7 | 6.4 | 6.4 | 0.61 | 90 |
| Zacharia Siro | 4.7 | 4.5 | 4.5 | 5.8 | 5.8 | 0.81 | 90 |
| Mean | 4.5 | 4.8 | 5.1 | 5.3 | 5.8 | 0.77 | 70 |
| STDev | 1.0 | 1.3 | 1.4 | 1.1 | 1.1 | 0.15 | 30 |
| CV% | 23 | 27 | 27 | 21 | 19 | 20 | 42 |

[¶] N and P at 75 and 33 kg ha$^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 46: Variation of maize yields (t/ha) in Keumbu during the long rains 2000 (LR 2000)

| Farmer | Control | NPK0[1] | NPK25 | NPK50 | NPK75 | NPKmax | RY(K) | Krate |
|---|---|---|---|---|---|---|---|---|
| Benedicto Orunde | 2.9 | 8.0 | 10.7 | 8.0 | 8.0 | 10.7 | 0.75 | 30 |
| Benson M Nyasani | 0.5 | 1.7 | 1.8 | 2.2 | 2.0 | 2.2 | 0.75 | 60 |
| Chirochiro WG | 3.5 | 6.9 | 6.8 | 7.5 | 6.8 | 7.5 | 0.92 | 60 |
| Fluorence Atemba | 0.0 | 1.9 | 3.7 | 4.4 | 4.4 | 4.4 | 0.43 | 60 |
| Grace Angima | 6.2 | 6.5 | 8.3 | 6.1 | 6.5 | 8.3 | 0.79 | 30 |
| James Bigingi | 3.7 | 6.4 | 6.6 | 6.7 | 7.7 | 7.7 | 0.83 | 90 |
| Jeria Nyakaga | 3.5 | 4.1 | 7.1 | 6.8 | 7.4 | 7.4 | 0.55 | 90 |
| Jogoo Amwata | 1.6 | 3.1 | 3.7 | 1.7 | NA | 3.7 | 0.83 | 30 |
| Mokutu Mojibane | 0.8 | 2.7 | 3.9 | 4.4 | 4.7 | 4.7 | 0.57 | 90 |
| Mean | 2.5 | 4.6 | 5.8 | 5.3 | 5.9 | 6.3 | 0.71 | 60 |
| STD Dev | 2.0 | 2.4 | 2.8 | 2.3 | 2.1 | 2.7 | 0.16 | 26.0 |
| CV% | 78 | 53 | 48 | 43 | 35 | 43 | 23 | 29 |

[1] N and P at 75 and 33 kg ha$^{-1}$ *RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 47: Variation of maize yields (t/ha) in Keumbu during the long rains 2001 (LR 2001)

| Farmer | NPK0[1] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|
| Bathiseba Onchiri | 6.1 | 7.2 | 4.6 | 4.6 | 7.2 | 0.84 | 30 |
| Benedicto Orunde | 5.8 | 7.2 | 4.6 | 4.6 | 7.2 | 0.80 | 30 |
| Benson M Nyasani | 4.0 | 5.3 | 4.0 | 4.0 | 5.3 | 0.75 | 30 |
| Callen Iteba | 9.3 | 7.8 | 7.9 | 7.5 | 7.9 | 1.18 | 60 |
| Chirochiro WG | 7.9 | 7.9 | 7.3 | 8.2 | 8.2 | 0.96 | 90 |
| Fluorence Atemba | 1.7 | 2.7 | 5.2 | 5.5 | 5.5 | 0.30 | 90 |
| Grace Angima | 7.3 | 7.7 | 6.0 | 6.6 | 7.7 | 0.95 | 30 |
| Jane Ogeto | 5.3 | 6.1 | 4.9 | 4.6 | 6.1 | 0.86 | 30 |
| Jeria Nyakaga | 4.8 | 4.8 | 4.8 | 6.3 | 6.3 | 0.76 | 90 |
| Jogoo Amwata | 4.2 | 4.0 | 5.1 | 4.0 | 5.1 | 0.83 | 60 |
| Kefa Nyambiche | 8.1 | 9.1 | 7.5 | 7.9 | 9.1 | 0.89 | 30 |
| Margaret Kerobo | 7.8 | 5.7 | 6.9 | 4.4 | 6.9 | 1.13 | 60 |
| Naomi Gekonge | 4.7 | 6.0 | 5.1 | 5.7 | 6.0 | 0.79 | 30 |
| Obino Makwero | 4.1 | 4.7 | 4.2 | 5.8 | 5.8 | 0.70 | 90 |
| Robert Onsario | 5.1 | 5.4 | 5.7 | 5.3 | 5.7 | 0.89 | 60 |
| Samwel Makori | 6.6 | 5.4 | 6.0 | 8.3 | 8.3 | 0.79 | 90 |
| Mean | 5.8 | 6.1 | 5.6 | 5.8 | 6.8 | 0.84 | 56 |
| SDEV | 2.0 | 1.7 | 1.2 | 1.5 | 1.2 | 0.19 | 27 |
| CV% | 34 | 27 | 22 | 26 | 18 | 23 | 47 |

[1] N and P at 75 and 33 kg ha$^{-1}$ *RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 48: Variation of maize yields (t/ha) in Keumbu during the long rains 2002 (LR 2002)

| Farmer | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|
| Benedicto Orunde | 3.2 | 5.5 | 4.4 | 2.5 | 5.5 | 0.58 | 30 |
| Benson M Nyasani | 3.0 | 4.2 | 4.3 | 3.2 | 4.3 | 0.70 | 60 |
| Callen Iteba | 5.0 | 3.8 | 2.6 | 2.9 | 3.8 | 1.32 | 30 |
| Grace Angima | 3.7 | 4.2 | 4.3 | 3.2 | 4.3 | 0.86 | 60 |
| Jeria Nyakaga | 4.4 | 5.3 | 4.8 | 4.0 | 5.3 | 0.83 | 30 |
| Kefa Nyambiche | 5.3 | 5.7 | 4.1 | 4.8 | 5.7 | 0.93 | 30 |
| Samwel Makori | 3.5 | 2.5 | 3.8 | 5.2 | 5.2 | 0.67 | 90 |
| Teresa Basweti | 2.6 | 3.7 | 3.2 | 2.9 | 3.7 | 0.70 | 30 |
| Mean | 3.8 | 4.4 | 3.9 | 3.6 | 4.7 | 0.82 | 45 |
| STDev | 1.0 | 1.1 | 0.7 | 1.0 | 0.8 | 0.23 | 23 |
| CV% | 25 | 25 | 18 | 27 | 17 | 28 | 50 |

[¶] N and P at 75 and 33 kg ha$^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 49: Variation of maize yields (t/ha) in Ebukanga during the long rains 2001 (LR 2001)

| Farmer | Control | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|---|
| Dishon Ameyo | 0 | 1.4 | 0.1 | 0.3 | 0.7 | 0.7 | 2.00 | 0 |
| Festo Atianga | 0.6 | 1.5 | 1.9 | 3.1 | 2.6 | 3.1 | 0.48 | 60 |
| Ibrahim Sikombe | 0.5 | 2.5 | 2.0 | 2.2 | 2.4 | 2.4 | 1.04 | 0 |
| Jacob Okwomi | 1.2 | 2.6 | 1.7 | 2.8 | 2.3 | 2.8 | 0.93 | 60 |
| Jane Okotse | 2.1 | 3.3 | 2.5 | 2.4 | 3.1 | 3.1 | 1.06 | 0 |
| John Butiko | 1.1 | 1.8 | 2.0 | 4.7 | 1.4 | 4.7 | 0.38 | 60 |
| Livingstone Asmani | 2.3 | 2.2 | 2.5 | 2.9 | 4.1 | 4.1 | 0.54 | 0 |
| Silas Msafiri | 2.2 | 3.3 | 2.9 | 1.8 | 3.7 | 3.7 | 0.89 | 90 |
| Mean | 1.3 | 2.3 | 2.0 | 2.5 | 2.5 | 3.1 | 0.92 | 34 |
| SDEV | 0.9 | 0.7 | 0.8 | 1.2 | 1.1 | 1.2 | 0.51 | 37 |

[¶] N and P at 75 and 33 kg ha$^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 50: Variation of maize yields (t/ha) in Ebukanga during the long rains 2002 (LR 2002)

| Farmer | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|
| Jane Okotse | 1.2 | 0.9 | 1.6 | 0.8 | 1.6 | 0.75 | 60 |
| Silas Msafiri | 2.6 | 2.8 | 1.6 | 3.5 | 3.5 | 0.74 | 90 |
| Margaret Onguru | 3.4 | 1.7 | 2.3 | 2.9 | 2.9 | 1.17 | 90 |
| Selpha Buchichi | 3.6 | 3.8 | 4.3 | 3.9 | 4.3 | 0.84 | 60 |
| Janet Makutwa | 2.8 | 3.1 | 2.2 | 3.0 | 3.1 | 0.90 | 30 |
| Frida Andayi | 2.8 | 3.7 | 3.8 | 3.3 | 3.8 | 0.74 | 60 |
| Ernest Asima | 2.9 | 3.3 | 2.7 | 2.3 | 3.3 | 0.88 | 30 |
| Obet Otenyo | 2.5 | 3.2 | 4.3 | 3.8 | 4.3 | 0.58 | 60 |
| Mean | 2.7 | 2.8 | 2.9 | 2.9 | 3.4 | 0.83 | 60 |
| SDEV | 0.7 | 1.0 | 1.1 | 1.0 | 0.9 | 0.17 | 23 |

[¶] N and P at 75 and 33 kg ha$^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 51: Variation of maize yields (t/ha) in Ebukanga during the short rains 2002 (SR 2002)

| Farmer | Control | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|---|
| Ernest Asima | 0.6 | 1.8 | 1.9 | 2.3 | 2.3 | 2.3 | 0.78 | 60 |
| Frida Andayi | 0.8 | 3.3 | 3.1 | 2.8 | 2.1 | 3.1 | 1.06 | 30 |
| Jane Okotse | 0.9 | 2.4 | 1.4 | 2.0 | 2.6 | 2.6 | 0.92 | 90 |
| Selpha Buchichi | 0.8 | 1.6 | 1.7 | 2.1 | 2.0 | 2.1 | 0.76 | 60 |
| Mean | 0.8 | 2.3 | 2.0 | 2.3 | 2.3 | 2.5 | 0.88 | 60 |
| SDEV | 0.1 | 0.8 | 0.7 | 0.4 | 0.3 | 0.4 | 0.14 | 24 |

[¶] N and P at 75 and 33 kg ha$^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 52: Variation of maize yields (t/ha) in Yala during the long rains 2001 (LR 2001)

| Farmer | Control | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|---|
| Dominick Adiedo | 3.2 | 4.3 | 5.0 | 5.2 | 5.7 | 5.7 | 0.75 | 90 |
| Dorca Kidha | 3.0 | 4.4 | 3.6 | 3.7 | 4.3 | 4.3 | 1.02 | 0 |
| Isaac Walle | 3.3 | 3.6 | 4.3 | 3.4 | 3.4 | 4.3 | 0.84 | 30 |
| Jenipher Arwa | 2.1 | 2.4 | 2.0 | 1.8 | 1.2 | 2.0 | 1.20 | 0 |
| Joab Achieng | 2.9 | 3.9 | 4.3 | 4.4 | 4.0 | 4.4 | 0.89 | 60 |
| Jorim Otieno | 2.6 | 3.6 | 3.8 | 5.3 | 3.8 | 5.3 | 0.68 | 60 |
| Mariko Rading | 3.0 | 5.2 | 4.4 | 4.3 | 7.0 | 7.0 | 0.74 | 90 |
| Monica Obwonyi | 2.4 | 2.8 | 5.1 | 5.4 | 3.7 | 5.4 | 0.52 | 60 |
| Monica Oketch | 2.7 | 3.6 | 4.2 | 3.6 | 3.3 | 4.2 | 0.86 | 30 |
| Nicodemus Agutu | 5.4 | 4.5 | 3.7 | 4.7 | 6.9 | 6.9 | 0.65 | 90 |
| Nifa Okoth | 3.3 | 4.9 | 3.3 | 3.7 | 4.4 | 4.4 | 1.11 | 0 |
| Ochieng Mwosi | 1.7 | 4.1 | 4.4 | 4.7 | 5.0 | 5.0 | 0.82 | 90 |
| Owino Daraja | 0.2 | 1.1 | 1.2 | 1.7 | 1.5 | 1.7 | 0.65 | 60 |
| Samwel Odipo | 2.6 | 4.9 | 4.6 | 1.7 | 4.1 | 4.6 | 1.07 | 0 |
| Silverous Odhiambo | 0.4 | 2.1 | 2.9 | 3.0 | 2.7 | 2.9 | 0.72 | 30 |
| Simon Bolo | 5.3 | 5.0 | 5.6 | 5.3 | 5.6 | 5.6 | 0.89 | 30 |
| Mean | 2.8 | 3.8 | 3.9 | 3.9 | 4.2 | 4.6 | 0.84 | 45 |
| SDEV | 1.4 | 1.2 | 1.1 | 1.3 | 1.6 | 1.5 | 0.19 | 35 |

[¶] N and P at 75 and 33 kg ha$^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 53: Variation of maize yields (t/ha) in Yala during the long rains 2002 (LR 2002)

| Farmer | NPK0¶ | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|
| Dominick Adiedo | 3.4 | 3.4 | 1.7 | 1.1 | 3.4 | 1.00 | 0 |
| Joab Achieng | 4.2 | 5.6 | 4.6 | 3.2 | 5.6 | 0.75 | 30 |
| Mariko Rading | 4.2 | 4.1 | 2.2 | 3.1 | 4.1 | 1.02 | 0 |
| Monica Obwonyi | 2.4 | 3.8 | 3.3 | 2.7 | 3.8 | 0.63 | 30 |
| Monica Oketch | 1.7 | 2.0 | 2.3 | 1.9 | 2.3 | 0.74 | 60 |
| Nicodemus Agutu | 2.8 | 3.2 | 1.2 | 3.1 | 3.2 | 0.88 | 30 |
| Nifa Okoth | 4.3 | 4.0 | 3.4 | 3.9 | 4.0 | 1.08 | 0 |
| Ochieng Mwosi | 2.4 | 2.9 | 3.7 | 3.1 | 3.7 | 0.65 | 60 |
| Samwel Odipo | 5.7 | 3.2 | 1.0 | 3.9 | 3.9 | 1.46 | 0 |
| Simon O. Bolo | 4.1 | 4.2 | 2.9 | 2.2 | 4.2 | 0.98 | 30 |
| Harrison Mwosi | 2.8 | 2.1 | 3.3 | 2.1 | 3.3 | 0.85 | 60 |
| Evans Owino | 2.4 | 2.9 | 2.3 | 1.6 | 2.9 | 0.83 | 30 |
| James Omullo | 1.0 | 1.8 | 1.9 | 1.9 | 1.9 | 0.53 | 60 |
| Fransisca Okoth | 1.3 | 1.3 | 1.2 | 2.3 | 2.3 | 0.57 | 90 |
| Mean | 3.1 | 3.2 | 2.5 | 2.6 | 3.5 | 0.85 | 34 |
| SDEV | 1.3 | 1.1 | 1.1 | 0.8 | 0.9 | 0.25 | 28 |

¶ N and P at 75 and 33 kg $ha^{-1}$ *RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 54: Variation of maize yields (t/ha) in Yala during the short rains 2002 (SR 2002)

| Farmer | Control | NPK0¶ | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|---|
| Dominick Adiedo | 0.7 | 0.7 | 1.5 | 0.8 | 0.6 | 1.5 | 0.47 | 30 |
| Fransisca Okoth | 0.4 | 0.8 | 0.5 | 0.4 | 0.5 | 0.5 | 1.60 | 0 |
| Harrison Mwosi | 0.4 | 1.4 | 1.5 | 2.3 | 1.5 | 2.3 | 0.61 | 60 |
| Jorim Otieno | 1.4 | 4.2 | 3.7 | 4.2 | 3.0 | 4.2 | 1.00 | 0 |
| Monica Obwonyi | 0.7 | 1.8 | 1.6 | 1.6 | 0.8 | 1.6 | 1.13 | 0 |
| Monica Oketch | 0.3 | 0.5 | 0.9 | 0.5 | 0.4 | 0.9 | 0.56 | 30 |
| Nicodemus Agutu | 1.4 | 1.6 | 1.6 | 1.6 | 1.8 | 1.6 | 1.00 | 0 |
| Ochieng Mwosi | 0.5 | 1.3 | 2.2 | 1.9 | 1.6 | 2.2 | 0.59 | 30 |
| Samwel Odipo | 0.9 | 1.9 | 2.5 | 2.2 | 1.8 | 2.5 | 0.76 | 30 |
| Simon O. Bolo | 0.5 | 1.2 | 1.0 | 1.3 | 1.0 | 1.3 | 0.92 | 60 |
| Mean | 0.7 | 1.5 | 1.7 | 1.7 | 1.3 | 1.9 | 0.86 | 24 |
| SDEV | 0.4 | 1.0 | 0.9 | 1.1 | 0.8 | 1.0 | 0.34 | 24 |

¶ N and P at 75 and 33 kg $ha^{-1}$ *RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 55: Variation of maize yields (t/ha) in Kabula during the long rains 2000 (LR 2000)

| Farmer | Control | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|---|
| Everlyne Mchele | 2.1 | 4.3 | 4.4 | 5.8 | 4.4 | 5.8 | 0.74 | 60 |
| Floriano Simwenyi | 6.1 | 7.1 | 7.7 | 7.3 | 8.5 | 8.5 | 0.84 | 90 |
| Gladys Ochieng | 1.9 | 3.0 | 3.3 | 4.0 | 4.1 | 4.1 | 0.73 | 90 |
| Mariana Wasike | 3.4 | 6.1 | 5.0 | 6.5 | 5.0 | 6.5 | 0.93 | 60 |
| Silvester Tsuma | 4.4 | 6.2 | 6.2 | 6.2 | 6.9 | 6.9 | 0.90 | 90 |
| Simiyu Wasari | 4.9 | 5.6 | 7.1 | 8.5 | 7.0 | 8.5 | 0.66 | 60 |
| Mean | 3.8 | 5.4 | 5.6 | 6.4 | 6.0 | 6.7 | 0.80 | 75 |
| SDEV | 1.6 | 1.5 | 1.7 | 1.5 | 1.7 | 1.7 | 0.11 | 16 |

[¶] N and P at 75 and 33 kg $ha^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 56: Variation of maize yields (t/ha) in Kabula during the long rains 2001 (LR 2001)

| Farmer | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY(K) | Krate |
|---|---|---|---|---|---|---|---|
| David Waswa | 3.2 | 3.1 | 3.8 | 4.5 | 4.5 | 0.71 | 90 |
| Everlyne Mchele | 4.2 | 5.3 | 5.4 | 5.8 | 5.8 | 0.72 | 90 |
| Floriano Simwenyi | 4.9 | 5.2 | 4.7 | 4.8 | 5.2 | 0.95 | 30 |
| Fred Simiyu | 3.0 | 3.6 | 4.0 | 4.6 | 4.6 | 0.65 | 90 |
| Gabriel Sifuna | 3.0 | 4.0 | 3.5 | 5.0 | 5.0 | 0.61 | 90 |
| Gladys Ochieng | 4.5 | 3.8 | 4.4 | 4.3 | 4.4 | 1.01 | 0 |
| Ignatius Chemku | 4.9 | 3.9 | 3.9 | 3.7 | 3.9 | 1.26 | 0 |
| Kizito Simwenyi | 4.9 | 5.6 | 5.1 | 5.7 | 5.7 | 0.85 | 90 |
| Mariana Wasike | 4.2 | 5.9 | 4.1 | 5.7 | 5.9 | 0.70 | 30 |
| Meldas Baraza | 2.3 | 3.1 | 2.5 | 2.1 | 3.1 | 0.75 | 30 |
| Patrick Wanjala | 4.4 | 5.1 | 4.9 | 5.3 | 5.3 | 0.83 | 90 |
| Philip Kuloba | 3.2 | 4.0 | 3.9 | 3.6 | 4.0 | 0.80 | 30 |
| Silvester Tsuma | 4.9 | 4.3 | 4.6 | 2.9 | 4.6 | 1.07 | 0 |
| Vincent Baraza | 3.3 | 3.2 | 3.7 | 3.5 | 3.7 | 0.90 | 60 |
| Mean | 3.9 | 4.3 | 4.2 | 4.4 | 4.7 | 0.84 | 51 |
| SDEV | 0.9 | 0.9 | 0.7 | 1.1 | 0.8 | 0.18 | 38 |

[¶] N and P at 75 and 33 kg $ha^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

Table 57: Variation of maize yields (t/ha) in Kabula during the long rains 2002 (LR 2002)

| Farmer | NPK0[¶] | NPK25 | NPK50 | NPK75 | NPKmax | RY (K) | Krate |
|---|---|---|---|---|---|---|---|
| Ester Simiyu | 5.7 | 3.9 | 4.4 | 4.6 | 4.6 | 1.24 | 0 |
| Everlyne Mchele | 3.5 | 2.9 | 3.6 | 2.5 | 3.6 | 0.97 | 60 |
| Floriano Simwenyi | 5.7 | 6.1 | 5.3 | 5.1 | 6.1 | 0.93 | 30 |
| Gabriel Sifuna | 5.5 | 4.2 | 4.1 | 4.5 | 4.5 | 1.22 | 0 |
| Gladys Ochieng | 3.6 | 3.5 | 3.6 | 2.9 | 3.6 | 1.00 | 0 |
| Ignatius Chemku | 6.1 | 6.1 | 4.6 | 5.1 | 6.1 | 1.00 | 0 |
| Kizito Simwenyi | 4.2 | 4.3 | 3.8 | 4.3 | 4.3 | 0.98 | 30 |
| Mariana Wasike | 3.3 | 3.7 | 1.5 | 3.7 | 3.7 | 0.89 | 30 |
| Paulicap Wafula | 4.9 | 3.8 | 4.5 | 3.9 | 4.5 | 1.09 | 0 |
| Peter Masinde | 5.1 | 5.2 | 3.5 | 3.2 | 5.2 | 0.98 | 30 |
| Phostine Wanjala | 4.4 | 4.5 | 6.2 | 6.7 | 6.7 | 0.66 | 90 |
| Protus Waraba | 3.5 | 3.5 | 3.6 | 2.9 | 3.6 | 0.97 | 60 |
| Mean | 4.6 | 4.3 | 4.1 | 4.1 | 4.7 | 0.99 | 28 |
| SDEV | 1.0 | 1.0 | 1.1 | 1.2 | 1.1 | 0.15 | 30 |

[¶] N and P at 75 and 33 kg ha$^{-1}$ [*]RY(K) = Relative yields: NPKyield/NPKmax yield, Krate= K fert rate giving NPKmax yield

# PLATES

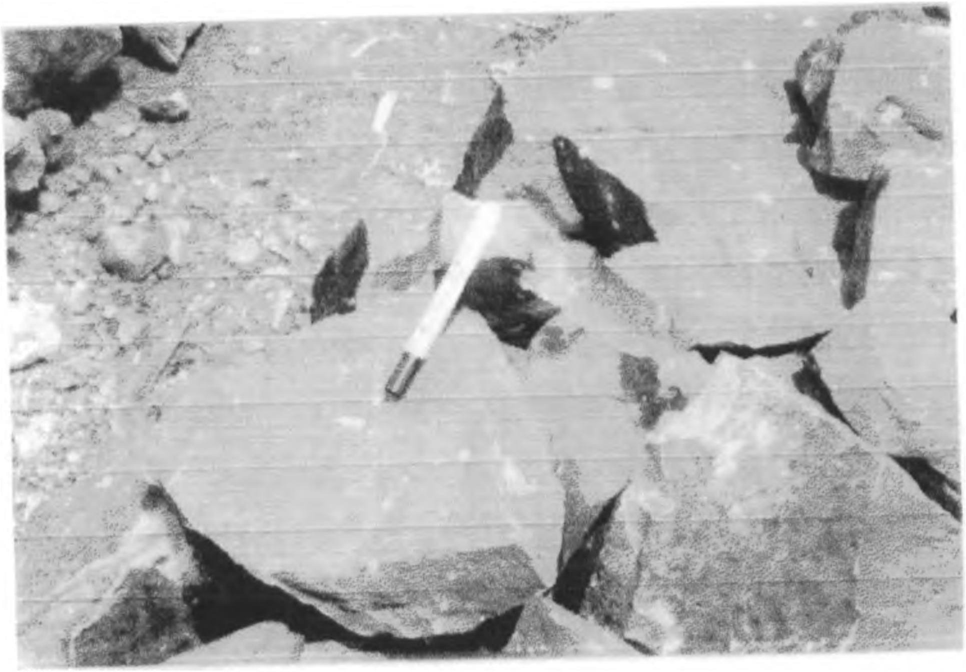

Plate 1A: A fresh sample of trachyte from Keumbu

Plate 1B: A weathered sample of trachyte from Keumbu

Plate 2A: Colluvial deposits on soils from Ndanai

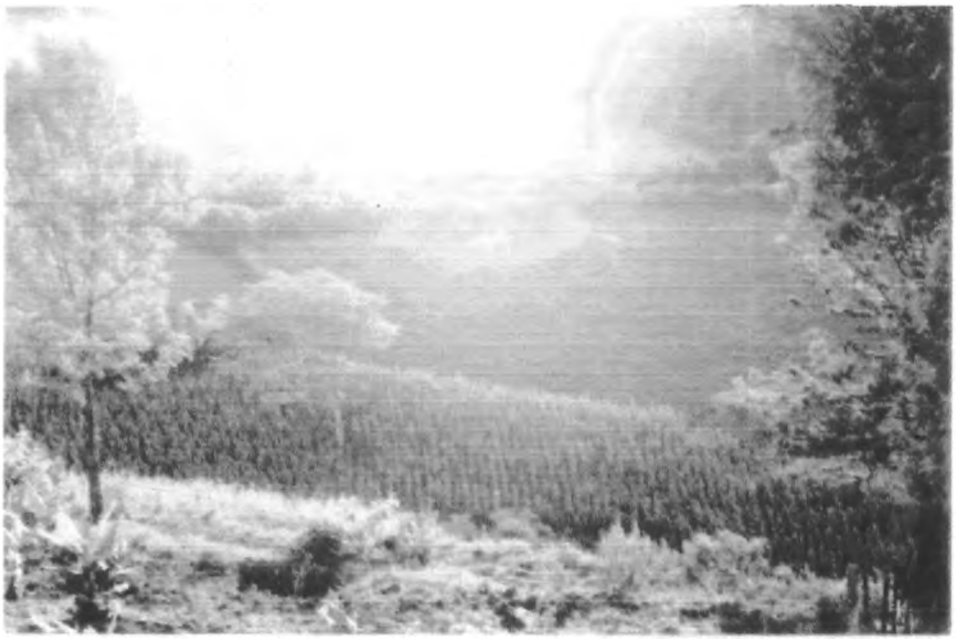

Plate 2B: Healthy crop on alluvial soils from Ndanai