

/LIME REQUIREMENTS OF KENYA
ACID SOILS

BY

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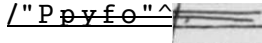
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A Thesis submitted in partial fulfilment
for the Degree of Master of Science in
the University of Nairobi
Department of Soil Science

DEDICATED TO MY DEAR PARENTS

DECLARATION

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

Signed: 
•TOE ~~KAN~~ENGERE-NUWAMANYA

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

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A B S T R A C T

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Four buffer methods were evaluated using Ca(OH)_2 -titration to pH 6.5 and CaCO_3 -incubation to pH 6.0 and 5.5 as reference methods and using 26 soils representing major agricultural acid soils in Kenya. The buffer methods selected were Shoemaker - McLean - Pratt single buffer method (SMP-SB), Shoemaker - McLean - Pratt double buffer (SMP-DB), Mehlich I (for crops with high lime requirements) and Mehlich II (for crops with low lime requirements). Exchange acidity (Ace), residual acidity (Acr) and total acidity (Act) were also correlated with lime requirements measured by the four buffer methods to pH 6.5, 6.0 and 5.5. The effect of lime on nodulation of beans and growth of maize and beans were also studied in the greenhouse using three selected soils.

The lime requirement values measured by the reference methods to pH 6.5, 6.0 and 5.5 were well correlated with the values measured by the four buffer methods. The lime requirement values measured by the four buffer methods were also well correlated with amounts of exchangeable aluminium, exchange acidity, residual acidity, total acidity and organic carbon. The SMP-DB method gave the highest correlation coefficient values with the reference methods, the least variations from the ideal lines, and was

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particularly impressive at lower pH target (5.5). The sensitivity of the SMP-DB and SMP-SB methods was, however, comparable for soils of high and low lime requirements, while the sensitivity of Mehlich methods was only adequate for soils of low and intermediate lime requirements. All the soil acidity components were well correlated with lime requirements measured by the buffer and reference methods to pH 6.5, 6.0 and 5.5. None of the buffer methods gave a significantly higher correlation coefficient for any of the acidity components than the other methods. There was an improvement in correlation coefficients when a multiple regression using exchange acidity and residual acidity was used over simple regression using exchange acidity, residual acidity or total acidity alone. In the greenhouse experiment the highest dry matter yield was obtained at pH 5.9, 5.7 and 5.8 in National Agricultural Laboratory (NAL), Mariene and Gituarriba soils respectively, while the highest nodulation of beans was obtained at pH 5.9, 5.7 and 5.5 in NAL, Mariene and Gituamba soils, respectively. There was a decline in dry matter yield of maize and beans and nodule production of beans at pH levels beyond these. At these pH levels, exchangeable aluminium and manganese were essentially zero.

It was concluded that liming of these soils to achieve pH 5.5 to 6.0 would be ideal. Overliming of the soils to high pH levels is likely to cause

a nutrient imbalance resulting in a decline in yields. Response of maize and beans to lime on NAL soil with virtually no exchangeable aluminium indicates that exchangeable aluminium would not be a good criterion for liming these soils. Since it might not be necessary to lime these soils to pH levels higher than 6.0, the performance of SMP-DB method at lower pH targets would make it the best choice. Besides its sensitivity over the entire lime requirement range, the SMP-DB method has the added advantage over the SMP-SB method of not requiring established tables. Thus any pll target can be selected.

I N T R O D U C T I O N

CHAPTER I

INTRODUCTION

In Kenya there is a wide range of soils due to differences in their parent materials, climate and topography. Altitude in Kenya varies from sea level to 5200 m (Mt. Kenya). The mean annual rainfall also varies from 255 to 2030 mm (Climatological statistics for E. Africa, 1975). Thus there are marked differences in organic matter content of soils, the rate of development and rate of leaching of nutrients from one location to another. Because of the nature of the parent material and the intensity of leaching, some soils in Kenya are either very strongly, strongly or medium acid.

For a long time it has been realized that many crops do not grow well on acid soils. The poor growth of plants on acid soils has been attributed to some harmful effects, including the toxicity of excess aluminium and/or manganese, deficiency of phosphorus, magnesium, calcium and various trace elements such as boron and molybdenum, coupled with decreased activity and population of soil microorganisms.

In temperate agriculture it is an accepted practice to lime soils to near neutrality for optimum growth and yield of most crops (Truog and

Meacham, 1919; Volk et al., 1973; Coleman and Thomas, 1967). In the tropics, however, response of some crops, particularly legumes, to liming of acid soils has been erratic indicating that it might be necessary in some acid soils and not in others.

Recent studies have indicated that exchangeable aluminium is generally the predominant cation in the leached soils of tropical regions where the soil pH is 5.0 or below (Coleman et al., 1958; Kamprath, 1970). It is believed that high concentrations of exchangeable aluminium may cause root injury and phosphorus starvation, coupled with a reduction in calcium uptake by plants (Wright, 1937). All these constitute aluminium toxicity, a factor which has been identified to be responsible for poor growth of most plants in many acid soils (Vlaminis, 1953; Coleman et al., 1958 and Kamprath, 1970).

Manganese toxicity also has been regarded as a primary cause for poor growth of plants in many acid soils. Depending on the parent material, quantities of exchangeable manganese may be large for soils with low pH.

When an acid soil is limed, many facets of the soil environment are changed. Responses of crops to lime have been attributed to changes in soil environment (Albrecht et al., 1953; Adams et al.;

1967; Coleman et al., 1958; Kamprath, 1970 and McLean, 1971) with regard to:

- (a) Reduced solubilities of toxic substances, like aluminium and manganese.
- (b) Increased availabilities of calcium, magnesium and phosphorus.
- (c) Availability of trace elements.
- (d) Increased activity and population of soil microorganisms.

Many laboratory methods for determination of lime requirements of acid soils have been developed and evaluated in many parts of the world. The moist CaCO^{\wedge} -incubation method is the oldest and probably the most accurate method for determination of lime requirements of soils. However, this method has not been good enough for routine soil analysis because of its long equilibration period. For example, some workers have used equilibration times of between 5 and 20 months (McLean et al., 1960, 1966 and 1978). This would mean long waiting for farmers who want results in time to lime their fields before the next growing season begins. As a result several buffer mixtures as quick methods for determination of lime requirements of soils have been developed. Peech (1965a) and Schofield (1933) buffer methods

require equilibrations overnight, followed by titration; Woodruff (1947) buffer method requires equilibration for 2 hours, followed by pH measurement; Shoemaker et al. (1961) buffer method requires only continuous shaking for 10 minutes or intermittent stirring for 20 minutes, followed by pH measurement, while Mehlich triethanolamine buffer method (Mehlich, 1948) involves a titration technique. The results obtained from these buffer methods are in some cases highly correlated with CaCO^{\wedge} - incubation measured values.

While buffer methods might be suitable for routine soil analysis because of their speed, their degree of accuracy with which they measure lime requirements largely depends on the soil characteristics. A good method should indicate the correct lime requirement values at both the low and high levels. Mclean et al. (1958) observed that Woodruff (1947) buffer method had the tendency to indicate too much lime at low lime requirement levels and too little at high lime requirement levels. The Mehlich (1948) triethanolamine buffer method at pH 8.1 was found (McLean et al., 1958) to indicate approximately the correct amount of lime for soils of high lime requirements but too much for those of low lime requirements. The Shoemaker et al. (1961) buffer method is well adapted to soils of high lime requirements (ie more than 4.0 me/100 g soil, having

pH less than 5.8, containing less than 10% organic matter, and having appreciable quantities of soluble aluminium) but with relatively large errors for soils low in cation exchange capacity.

More recently, however, the Shoemaker - McLean - Pratt single buffer (SMP-SB) has been improved by incorporating its features with the double buffer (Yuan, 1976) features (McLean et al., 1978). This adaptation has been found to improve the accuracy, especially for soils of low cation exchange capacity, where SMP-SB has been known to lack desired accuracy. Since large number of soils in Kenya have low cation exchange capacity values, newly developed SMP-DB method might be a suitable one. Mehlich (1976) developed a new buffer mixture based on the exchange acidity of soils. The method was found to be accurate, especially, for soils which fell within ultisol and oxisol soil orders. Many soils in Kenya fall within these soil orders and this Mehlich buffer might be suitable for these soils. In addition the Mehlich buffer can estimate lime requirement depending on whether the crop in question has a low or high lime requirement.

The objectives of this study, therefore were:

To evaluate the suitability of four quick-buffer methods for determining lime requirements (LR) of Kenya acid soils using the CaCO_3 -incubation method as the standard.

The following buffer methods were evaluated:

- (i) Shoemaker - McLean - Pratt single buffer (SMP - SB)
- (ii) Shoemaker - McLean - Pratt double buffer (SMP - DB).
- (iii) Mehlich's new buffer method for crops with high lime requirements (Mehlich I).
- (iv) Mehlich's new buffer method for crops with low lime requirements (Mehlich II).

To identify major components of soil acidity in Kenya acid soils and show how these are related to lime requirements of the soils as measured by the selected buffer methods above and the CaCO_3 -incubation method.

To evaluate the effects of soil properties such as organic matter content, exchangeable aluminium, exchangeable manganese, exchange acidity, residual acidity and soil pH on lime requirements of the soils measured above.

To relate crop response, mainly beans and maize, in the greenhouse to lime requirement values indicated by the buffer methods and acidity components.

L I T E R A T U R E R E V I E W

CHAPTER II

LITERATURE REVIEW

2.1. Possible causes of poor growth of plants on acid soils

Many investigators have attempted to establish the causes of poor growth of plants on acid soils. Perhaps the most controversial aspect of crop response to lime has been that of toxicity of aluminium and manganese versus availability of calcium and magnesium. Two schools of thought have been in existence. One maintains that it is due to detrimental effects of low pH, aluminium and/or manganese toxicity (Vlamis, 1953; Gilbert and Pember, 1935; Hardy, 1926; Ligon and Pierre, 1932; and Magistad, 1925). The other considers acid soil infertility primarily as a calcium deficiency (Arnon et al., 1942; Albrecht and Smith, 1953). Radio-calcium studies have indicated that poor growth of plants on acid soils may not be due to calcium deficiency in the soil or within the plant (Schmel et al., 1950; 1952). This and other findings (Gilbert and Pember, 1935; Hardy, 1926; Kittrick and Jackson, 1956; MacLeod and Bradfield, 1961; Pierre and Stuart, 1933; Schmel et al., 1952; Coleman et al., 1958; Kamprath and Foy, 1971; Kamprath, 1970; Reeve and Sumner, 1970; Hoyt and Nyborg, 1971 and White, 1970) support the view that poor establishment may be an effect of aluminium and/or manganese toxicity.

2.1.1. Aluminium and manganese toxicity

Aluminium toxicity would be the primary cause of poor growth of plants only where pH values are lower than 5.0 (Hsu, 1964; Kamprath, 1970). Hsu (1964) showed that above pH 5.0 aluminium and iron exist mainly as hydroxides and oxides, respectively. Coleman et al. (1958) have found that if the soil contains more than 1 me/100g soil of exchangeable aluminium, root growth is largely inhibited. Growth is arrested during the early seedling stage when the source of nutrient supply shifts from seed reserves to active uptake from the external medium (MacLeod et al., 1961). MacLeod and Bradfield (1961) have showed that legumes with small seed reserves were most affected by acid conditions. A typical lack of root elongation and appearance of bumps on the stunted roots was evident.

Many investigators (Cole et al., 1950; Coleman, et al. 1958; Coleman et al., 1960; Harward and Coleman, 1954; Shoop et al., 1961) showed that the majority of mineral acid soils are predominantly aluminium saturated. Moschler et al. (1960) reported a close inverse relation between aluminium in the soil and increased alfalfa yield and longevity. It is believed that aluminium interferes with the uptake and translocation of phosphate and that this is the primary cause for aluminium toxicity (Pearson and Adams, 1967; McCormick

and Borden, 1972; Magistad, 1925). It was also observed that nutrient solution aluminium (10 or 100 ppm) interfered badly with calcium accumulation, another possible mechanism for aluminium toxicity (Schmel et al., 1952).

Manganese toxicity also has been regarded as a primary cause for the poor growth of plants in many acid soils. In acid soils, manganese concentration in the soil solution increases as the pH decreases. Experiments on plants in nutrient solutions show that even low concentrations of manganese may depress the plant growth. As little as 1 ppm to 4 ppm of manganese/ml of solution may depress the yields of lespedeza, soya beans and barley (Morris and Pierre, 1949; Olsen, 1936). Manganese is taken up more readily by most plants and may accumulate in high concentrations in the above-ground parts of most plants. Although plants grown in soils usually do not contain more than 100 ppm Mn/g of dry matter, the concentration may be much higher under conditions of manganese toxicity. Hale and Heintze (1946) reported an extreme case in which leaves of field grown potato plants contained 11300 ppm Mn/g of dry matter. In this connection, Vlamis (1953) observed some brown spotting of leaves indicative of manganese toxicity in plants grown in the acidified, manganese-treated solution of 16 ppm/ml of solution.

2.1.2. Plant tolerance to aluminium and manganese

Plant species differ in their tolerance to both aluminium and manganese. This accounts, to some extent, for the different responses of different species to soil reactions. McLean and Gilbert (1928) found beets, carrots and alfalfa to be particularly sensitive to aluminium toxicity, while growth of rye, oats, cabbage and maize was not markedly reduced by as much as 3.6 ppm aluminium.

Black (1957) reported work which showed 1 to 4 ppm of manganese to reduce the yields of soya beans, lespedeza and barley, while maize -tolerated at least 15 ppm. Lohnis and Marie (1951) concluded that the tolerance of certain plants to high levels of substrate manganese was related to inefficient adsorption. Oats and mangolds, two tolerant species were found to accumulate considerably less manganese from a given substrate than did susceptible species. On the other hand, some plants such as tobacco can accumulate large amounts of manganese without apparent injury.

The "critical values" of exchangeable aluminium for legumes have been established by many workers, as reported by Adams and Pearson (1967) to be 0.2 me/100 g soil; Jones and Thomas (1960) to be 0.1 me/100 g soil; Shoop et al. (1961) to be 2 me/100 g soil. Variation in the critical values, however, is to be expected for different types of

soil, different methods of aluminium extraction, and different degrees of aluminium tolerance by different crops.

From a consideration of the quantities of exchangeable and soluble aluminium and manganese in many acid soils, it is evident that inhibiting effects on the growth of plants and particularly of roots do occur frequently.

2.2. Effects of lime on acid soils and plant growth

Lime additions to acid soils modify the solubilities of a number of trace elements, leading to the reduction of toxicities in some instances, and inducing deficiencies in others. Lime serves both as a fertilizer in supplying calcium and magnesium (dolomitic limestone) and as a soil amendment by adjusting pH and base saturation (Nicholas et al. 1960). Liming thus affects nutrient availability (Albrecht et al., 1952; Macleod et al., 1961; Olsen, 1957); microbial breakdown of organic matter, various transformations of compounds and nitrogen fixation (Alexander, 1961).

Anderson (1956) has summarized much of the work done in Australia on lime - molybdenum relationships in legume production. He concluded that lime has profound effects on the response of plants to molybdenum. Lime raises the availability of soil

molybdenum, and increases yield and nitrogen fixation of legumes.

Just as higher plants respond to soil factors which interact with lime, so do the microorganisms which inhabit the soil and carry out a multitude of processes which may be favourable or unfavourable to the growth and development of crops. Bacteria which carry out nitrification are not very active in soils with pH less than about 5.5 (Russel, 1950). Thus one result of liming acid soils is to increase the rate of oxidation of ammonia to nitrate.

Liming can affect both non-symbiotic and symbiotic nitrogen fixation. Azotobacter will not fix nitrogen below pH 6.0 (Black, 1957). Nitrogen fixation by legumes also is markedly influenced by soil reaction. For example, Mehlich and Colwell (1943) found the nitrogen contents of soybeans to increase regularly with calcium saturation in the case of two mineral soils, but to change little between 40 and 80% saturation (C.E.C. 8.2) for an organic soil.

Rice et al[^]. (1977) investigated the effects of soil acidity on nitrogen fixation by alfalfa and red clover in the field and greenhouse experiments, and found that Rhizobium meliloti numbers, nodulation scores and relative yields of alfalfa decreased sharply as the pH of the soil decreased below 6.0.

Rhizobium trifolii were reduced when the pH of the soil was less than 4.9.

In another study by Rice (1975) on the effects of lime on nodulation and growth of alfalfa in Alberta acid soils, he found that when calcium carbonate was applied to soil (4 mg CaCO³/g soil) to reduce substrate aluminium to subtoxic levels, the relative yield (yield without N/yield with N) of alfalfa increased from 0.7 with no inoculation to 1.0 with 3×10^7 rhizobia per seed. Increasing the inoculum level from no inoculation to 3×10^7 rhizobia per seed decreased the amount of ineffective nodule tissue from 0.65 to 0.27 mg/pot without calcium carbonate added, and from 0.60 to 0.06 mg/pot with addition of 4.0 mg CaCO₃/g soil.

These results demonstrate that liming acid soils may increase the production of legumes by improving survival and growth of rhizobia, coupled with enhancing nodule formation. Legume crop yields can be reduced (below pH 6.0) due to inefficient nitrogen-fixation resulting from poor survival of rhizobium and inadequate nodulation (Rice, 1975), and yield of most agricultural crops can be reduced by aluminium toxicity below pH 5.5 which approximate the minimum value for full base saturation of the permanent charge exchange capacity of soils (Turner and Clark, 1967).

2.2.1. Liming studies in East Africa

In East Africa studies have indicated that liming may benefit crop growth.

In a study on Nachingwea acid soils in Tanzania, Evans and Wilson (1965) indicated that maize yields could only be increased by liming soils which had given no response to P and N treatments.

Mills (1956) could not get a maize crop from plots which had not received lime (pH 3.8 - 4.0) in Uganda's reclaimed swamps of Kigezi.

Similar work on the Yala reclaimed swamp of Western Kenya indicated that sensitive crops such as vegetables and legumes could not do well unless lime was applied to increase pH and neutralize toxic substances (Nyandat, 1973).

Work on the effect of lime and molybdenum on legumes in the highlands of Kenya (Birch, 1960) indicated that legumes such as alfalfa benefited from lime. Alfalfa showed heavy nodulation on all plots which had received lime dressings.

Liming studies have also been carried out on the Andosols (commonly known as the "Bracken zone" soils) of Kenya. These soils are characteristically light and porous, and contain large amounts of allophane and free alumina. In experiments carried out in Nyeri (pH 4.48 - 4.94), Muranga (pH 4.60-4.70) and Meru (pH 4.48 - 4.98) districts,

it was found out that field crops such as maize, bulrush millet, potatoes and oats grew very poorly in the plots which did not get lime dressings. Maize in Meru failed to germinate because of the high level of toxic aluminium. At Gituamba Agricultural Research Station increase in mean yield of maize on the limed plots was 165%. It was concluded that the "bracken zone" soils require liming to saturate the permanent charge and thereby minimise fixation of P by exchangeable aluminium, and supply of calcium and magnesium in balanced amounts before they can respond to phosphate and nitrogen fertilizers (Mehlich and Theisen, 1966; Boswinkle, 1956, 1957, 1958). Owing to the very large reactive surface and buffering capacity of allophane and amorphous alumina, the lime requirement runs into several tonnes/hactare.

Foster (1970) obtained significant positive response to lime only 2 out of 15 experiments in Uganda and one significant negative response at a site which had previously shown similar response to MgO. The soil was high in bases and low in exchange acidity ($Al + H = 0.08$ me/100g soil).

Some trials at the major research stations in Uganda indicated that responses to lime could be expected (Forster, 1969). At Kawanda (Stephens, 1967), Namulonge (LeMare, 1963; Ogborn, 1966), and Serere (Wadsworth, 1965) Research Stations

significant responses of cotton to lime had been recorded. Similarly, significant responses to lime were recorded using beans at Kawanda, and sorghum at Serere. Groundnuts grown a year or more after lime application gave significant yield increases in all six trials where exchangeable calcium level was below 6 me/100g soil (Forster, 1969).

2.3. Determination of lime requirements of soils

Soil test methods involving measurement of pH and soluble aluminium and manganese have been developed to identify problem soils (Hoyt and Nyborg, 1972; Hoyt and Webber, 1974). However, at present there has not been a general agreement on the method for determination of lime requirement of highly weathered soils (Amedee and Peech, 1976a), as soil pH value alone in the highly weathered soils of humid tropics could not be a good criterion for liming recommendations because of its variations in the exchange capacity of soils.

As a result many methods have been developed for measuring lime requirements of soils. In some instances buffers have been suggested, and in others lime rates have been determined on the basis of neutralization of toxic aluminium and/or manganese levels.

Among the buffers more widely used are barium chloride-triethanolamine (Mehlich, 1947); p-nitrophenol-calcium acetate (Woodruff, 1948); p-nitrophenol-boric acid-potassium chloride (Adams and Evans, 1962) and p-nitrophenol-potassium chloride-calcium acetate-calcium chloride (Shoemaker et al., 1961). All these buffers have been used as a basis to estimate the lime requirements of soils.

Extensive research in temperate agriculture has been done with the buffer methods in the determination of lime requirements of acid soils. For example, in an experiment to determine lime requirements of Canadian acid soils, (Webber et al., 1977) it was established that Peech (1965a) and Schofield (1933) buffer methods required equilibrations overnight, followed by titration; Woodruff (1948) buffer method, on the otherhand, required equilibration for 2 hours, followed by pH measurement, while Shoemaker et al. (1961) buffer method required only continuous shaking for 10 minutes or intermittent stirring for 20 minutes, followed by pH measurement. Owing to its rapidity and simplicity, Shoemaker et al. (1961) buffer method was recommended for routine soil testing for the Canadian acid soils .

However, the accuracy with which the buffer methods measure lime requirement of soils depends on the soil characteristics. For example, McLean et al. (1958) observed that Woodruff (1948) buffer method for determination of lime requirements of acid soils did not give accurate indication of the actual lime need to bring certain Ohio soils to a favourable reaction for plant growth. Investigations and observations suggested that the soils which gave the greatest discrepancy between the actual lime needs and test indicated needs were those with the most extractable aluminium in them. Slopes and intercepts of regression line revealed the marked tendency for the Woodruff (1948) buffer method to indicate too much at low lime requirement levels and too little at high lime requirement levels. Mehlich (1947) buffer method at pH 8.1 indicated approximately the correct amount of lime for soils of high lime requirements but too much for those at low levels (McLean, 1958). The Shoemaker et al. (1961) buffer method was found to be relatively rapid, accurate and especially well adapted for soils high in lime requirements. It was, however, found to have relatively large errors for soils of low lime requirements (Shoemaker et al., 1961).

More recently, McLean et al. (1978) have applied the double - buffer (DB) features of the recently - published Yuan method (Yuan, 1976) to the Shoemaker et al. (1961) single buffer (SB) method at several buffer pH levels, shaking times and soil/solution ratios. The results based on the regression analysis of buffer-indicated values versus Ca(OH)_2 - titrated acids showed that the widely used Shoemaker - McLean - Pratt single buffer (SMP-SB) method could be improved considerably by incorporation of double buffer quick-test and mathematical adjustment features with the SMP-SB features. This adaptation has been found to increase the accuracy of estimate of lime requirements especially for soils of low lime requirements where SMP-SB method has been known to lack desired accuracy.

Mehlich (1976) also proposed a new buffer method based on exchangeable acidity in a group of soils, primarily ultisols of North Carolina. He found that correlation coefficients between buffer pH acidity and exchange acidity were 0.966 and 0.956 for mineral soils and histosols, respectively. He also noted that percentage maximum yield was obtained when rates of CaCO^{\wedge} were above buffer pH acidity or exchange acidity for plants with high lime requirements.

M A T E R I A L S A N D M E T H O D S

CHAPTER III

MATERIALS AND METHODS

3.X. Selected soil samples

Bulk samples of soil (from the plough layer, 0 - 15 cm) were collected from seven provinces of Kenya, namely, Western, Nyanza, Rift Valley, Central, Nairobi, Eastern, and Coast provinces. Out of what was collected, 26 soils were chosen for this study. The criterion used to select the 26 soils was based on their varying properties, like quantities of exchangeable aluminium and manganese, organic matter content, cation exchange capacity, pK values and soil order. Soils with a wide range of these properties were selected. All soil samples were collected from the agricultural research station where surveys by the Soil Survey Department of Kenya had previously been carried out.

3.2. Soil analysis

The soils (except those for pot studies) were air-dried and sieved to pass a 2 mm sieve, and analysed for soil pH, % carbon, cation exchange capacity, exchangeable aluminium and manganese, exchange acidity, residual acidity and texture.

3.2.1. Soil pH

Soil pH was measured using a pH meter (E350B) with a glass electrode at soil/water ratio of 1:1 (W/V).

3.2.2. Soil % carbon

Soil organic carbon was determined according to Walkley and Black (1947) method.

3.2.3. Exchangeable aluminium

Soil was leached with 1N KCl after shaking for 1 hour, followed by centrifugation and filtration. The leachate was then titrated with 0.1N NaOH to get
+ 3+
total exchange acidity due to H^+ and Al^{3+} ions, and then back-titrating with 0.1N HCl to get exchangeable aluminium alone as described by Lin and Coleman (1960).

3.2.4. Exchangeable manganese

Soil was leached with 1N KCl after shaking for 1 hour, followed by centrifugation and filtration. Manganese in the leachate was then measured by atomic absorption spectrophotometer as described by Webber (1974).

3.2.5. Cation exchange capacity

Cation exchange capacity was determined by extracting the soil with 1N ammonium acetate at pH 7.0 as described by Pratt (1957) and Peech et al. (1962).

3.2.6. Exchange acidity

Exchange acidity was determined according to Mehlich (1976) by leaching the soil with 0.6N BaCl₂ and then titrating the leachate with 0.05N NaOH to pH 7.0.

3.2.7. Residual acidity

Residual acidity was determined according to Mehlich (1976) by leaching the soil (already leached with 0.6N BaCl[^] for exchange acidity above) with BaCl[^] - triethanolamine buffered at pH 8.25, and then back-titrating the leachate to pH 4.8 with 0.1N NCl.

3.2.8. Texture

Soil texture was determined using the Bouyoucus (1927) Hydrometer method.

3.3. Moist CaCO₃-incubation studies

Out of the 26 soils chosen for the study 15 soils with pH below 5.5 were selected for incubation studies.

Ten - 1 kg samples of each soil were weighed and CaCO₃ powder added at the rate of 0.0, 2.0, 4.0, 6.0, 8.0, 12.0, 16.0 and 20.0 me/100 g soil. After thorough mixing, the soils were moistened to field capacity and placed in open polythene bags. Additional

water was added frequently to replace that which evaporated. After months of incubation the soils were allowed to air-dry; clods were crushed and water was again added to bring the soils to field capacity. The soils were allowed to incubate for a total period of months after which they were air-dried, crushed, sieved to pass a 2 mm mesh and stored in closed containers.

The pH of each soil was then measured and the resulting pH was plotted against the amount of CaCO_3 added to a given soil. The amount of CaCO_3 in me/100 g soil required to bring a soil to pH 6.5, 6.0 and 5.5 was then determined from the curve. Exchangeable aluminium and manganese, exchange acidity and residual acidity were also determined.

3.4. Ca(OH)_2 - titration method

Lime requirements to achieve pH 6.5 in all the 26 soils was determined by Ca(OH)_2 - titration. The Ca(OH)_2 - titrated values were used as a basis for evaluation of the four buffer methods for estimation of lime requirements of acid soils.

Previous studies of 14 Ohio soils showed that Ca(OH)_2 - titration to pH 7.2 after 72 hours of intermittent shaking gave average values of 5% lower than those for CaCO_3 - incubation to pH 6.8 after 17 months (13.2 vs. 13.8) and were highly correlated ($r = 0.99$) (McLean et al., 1960). Shoemaker et al. (1961)

indicated that the 3 day Ca(OH)_2 - titration to pH 7.2 was approximately the same as CaCO_3 - incubation to pH 6.5 after 20 months. For this reason, lime requirement values obtained by Ca(OH)_2 titration method to pH 7.2 were taken as an index of lime requirement's to pH 6.5 in this study, and lime requirement values obtained by buffer methods were also computed on the pH 6.5 basis to allow comparison of methods.

Ten - 1 g samples of the soils were suspended in 20 ml of distilled water and then titrated to pH 7.2 with 0.025N Ca(OH)_2 . After 24 hours, more Ca(OH)_2 was added to again bring the pH of soil suspension to pH 7.2. This was repeated over a period of 2 to 3 days until each soil remained at pH 7.2 for 24 hours. All the soil/solution ratios were also adjusted to 1:5 with water (50 ml of total solution) after the final addition of base to soil suspension was made. Then the total volume of base used for each sample to maintain pH 7.2 for 24 hours was used to compute the amount of lime in me/100 g soil. This amount of lime was then taken as the lime requirement of the soil to pH 6.5.

3.5. Buffer methods

The following buffer methods were evaluated:

3.5.1. Shoemaker - McLean - Pratt r.ingle buffer
(SMP-SB) method

The buffer mixture was prepared according to Shoemaker et al. (1961). Five - g samples of soil were weighed into plastic cups and 5 ml of distilled water added. The soil water suspension was stirred and pH determined. The 10 ml of the SMP-SB mixture was added to the soil-water suspension of pH below 6.3, and the soil buffer suspension stirred. The soil-buffer suspensions were then shaken continuously for 15 minutes on a mechanical shaker at 175 oscillations per minute (O.P.M.). The pH of the soil-buffer suspension was then determined. From the pH readings of the soil-buffer suspension, the amount of lime required to bring a given soil to pH 6.5 was determined from the Shoemaker et al. (1961) established tables which give recommended amount of lime in tons/acre. The amount of lime in tons/acre determined was then converted in me/100g soil to allow comparison with other methods.

3.5.2. Shoemaker - McLean - Pratt double buffer
(SMP-DB) method

The buffer mixture was prepared according to Shoemaker et al. (1961) and portions of the buffer mixture were adjusted to two pll levels of

7.5 and 6.0 according to Yuan (1976) and McLean et al. (1978).

Two - 5 g samples of soil were weighed into plastic cups and 5 ml of distilled water added. The soil-water suspension were stirred and pH determined. Then 10 ml of the buffer mixtures (adjusted to pH 7.5 and 6.0) were added to soil-water suspensions separately. The soil-buffer suspensions were then shaken continuously for 15 minutes on a mechanical shaker at 175 oscillations per minute. Then the pH of the soil-buffer suspensions were measured after 30 minutes standing time. The double-buffer formula and mathematical function used in the double buffer method (Yaan, 1974 and 1976) and in the improved SMP buffer method (McLean et al., 1978) as indicated below were used to convert the soil-buffer pH readings to lime requirement values at pH 6.5, 6.0 and 5.5.

Double-buffer formula:

$$d = \Delta pH_2 \times \frac{\Delta d_2^0}{\Delta pH_2^0} + \left[\left(\Delta pH_1 \times \frac{\Delta d_1^0}{\Delta pH_1^0} - \Delta pH_2 \right) \times \frac{\Delta d_2^0}{\Delta pH_2^0} \right] \times \left(\frac{pH_1 - pH_2}{pH_1 - pH_2} \right)$$

Where:

pH_1 = Soil-buffer pH in pH 7.5 buffer

pH_2 = Soil-buffer pH in pH 6.0 buffer

a_{pH_x} = $7.5 - pH_1$

a_{pH_2} = $6.0 - pH_2$

$\Delta d^\circ / \Delta pH^\circ$ = change in acidity/unit change
in pH of 10 ml of pH 7.5 buffer
by titration — 0.14 me/unit pH,

$\Delta d^\circ / \Delta pH^2$ = change in acidity/unit change
in pH of 10 ml of pH 6.0 buffer
by titration — 0.13 me/unit
pH,

d = the acidity in me/5g of soil measured
by the double buffer procedure, and

x = any chosen pH to which soil is to be
limed. In this study x was 6.5,
6.0 and 5.5.

Mathematical function:

$$LR \text{ in me/100g soil} = 1.69y - 0.86$$

where $y = 20d$.

The mathematical function was used to correct
for less than complete reaction with the soil acidity
in 15 minutes shaking time and 30 minutes standing
time.

3.5.3. Mehlich new buffer method.

The new buffer mixture was prepared according to Mehlich (1976). Soil samples (10 g) were weighed into plastic cups, and 10ml of the buffer reagent were added to the soil-water suspensions. Then the pH of the soil-buffer suspensions (BpH) was measured after 60 minutes of standing. The soil-buffer pH readings were then converted into buffer pH acidity (Ac) from the relationship:

$$Ac \text{ (in me CaCO}_3\text{/100 g soil)} = (6.6 - BpH)/$$

0.25. The lime requirement was then calculated from the equation below according to Mehlich (1976):-

$$LR \text{ (in me CaCO}_3\text{/100g soil)} = 0.1 (AC)^2 + AC$$

The lime requirement values calculated from the above equation were for crops with low lime requirements (MEHLICH II). The value from the above equation was multiplied by 1.5 to get values (MEHLICH I) for crops with high lime requirements (Mehlich, 1976).

.6. Greenhouse studies

Three soils were used in the greenhouse study. The soils used were:

1. Gituanba II soil - a Humic Andosol (Oxic Dystrandept) which was under tea at Gituamba Agricultural Research Station with 4.56% C, 32.00 me C.E.C./100 g, 4.20 me Al/100g, 0.31 me Mn/100g and 41% clay.
2. Meru soil - a Humic Nitosol (Typic Palehumult) which was under coffee at Mariene Coffee Research Station with 1.74% C, 25.00 me C.E.C./100g, 4.40 me Al/100g, 0.89 me Mn/100g and 59% clay.
3. National Agricultural Laboratories (N.[^]L.) soil - a Humic Nitosol (Oxic Paleusi-ult) v/hich was under grass at the National Agricultural Laboratories with 1.74% C, 21.00 me C.E.C./100g, 0.30 me Al/100g, 0.16 me Mn/100g and 70% clay.

The pH of the soil was adjusted by adding CaCO[^] powder, followed by moist-incubation for six pH levels of each soil selected. The amount of CaCO[^] required in each soil to achieve any of these pH levels having been determined in earlier incubation studies in the laboratory.

Beans and maize were used as test crops. At

all levels of pH, beans were inoculated with rhizobium bacteria in a peat-base medium. A treatment of inoculated seed pelleted with CaCO_3 powder at the lowest lime level (no CaCO^{\wedge} added) was also included in the bean experiment, and a completely randomized design for all soils together was used.

Basal fertilizer application were 50 kg P/ha to all the soils as triple superphosphate; 350 kg Mg/ha to only Gituamba soil as MgCl_2 ; 60 kg S/ha to all the soils as $\text{I}^{\wedge}\text{SO}^{\wedge}$, and 1 me/100g soil Ca to only control pots (pots with no CaCO^{\wedge} added) as CaSO^{\wedge} . Nitrogen was applied only to maize pots at the rate of 100 kg N/ha as urea. The fertilizers were mixed with 1 kg of soil used in each pot.

All treatments received Mn, B, Cu, Zn and Mo at rates of 7.0, 3.5, 2.5, 7.0 and 0.8 kg/ha, respectively. These micronutrients were applied in solution after planting.

In the bean experiment six bean seeds were planted per pot, and in the maize experiment six grains of maize were also planted per pot. All the bean and maize plants were later thinned to four plants per pot. All the four plants in each pot were harvested after 43 days of growth (when 50% of bean plants had flowered). The plants harvested were oven-dried (70°C) and weighed. Two of the bean plants harvested for dry matter were

carefully uprooted, washed and nodules removed. The nodules were then oven-dried at 60°C, and weighed.

R E S U L T S A N D D I S C U S S I O

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Soil properties

The analysis of the soils used in this study indicates that they have a wide range of properties (Table 1), with soil pH ranging from 4.50 to 6.20; exchangeable aluminium from 0.00 to 4.40 me/100g soil; exchangeable manganese from 0.01 to 0.95 me/100 g soil; exchange acidity from 0.00 to 7.95 me/100g soil; residual acidity from 0.00 to 20.48 me/100g soil; and cation exchange capacity from 3.50 to 40.00 me/100g soil. Organic carbon and clay contents ranged from 0.39 to 4.56 and 8.00 to 70.00%, respectively.

4.2. Lime requirements (LR) by various methods

Lime requirement values of soils measured by various methods to pH 6.5 are presented in Table 2. The results of lime requirements to pH 6.5 show that the buffer methods gave different ranges of lime requirements from those of the standard $(Ca(OH)_2$ -titration). Where $Ca(OH)_2$ -titration method shows a range from 10.0 to 21.0 me, SMP-SB method shows a range from 10.0 to 25.0 me; SMP-DB method a range from 10.0 to 24.0 me; Mehlich I method a range from 16.0 to 17.0 me; while Mehlich II method shows a range from 10.0 to 11.0 me. At lime requirements above

TABLE It SOME CHARACTERISTICS OF THE SOILS USED FOR THE STUD*

Soli	pH	tc	C.E.C.	Exch. Al me/100 g	Exch. Hn	% Clay	Textural Name	FAO/UNESCO 1974 Classification	USDA EQUIVALENT
Cltuanba I (prcvlovaly limed)	4.5	4.08	31.50	3.80	0.20	40	Clay Loam	Humlc Andosols	Oxlc Dystrandapt
Gltuamba II (unlimed)	4.5	4.56	32.00	4.20	0.31	41	Clay	Humlc Cleysol	N m
Yala II	4.6	3.00	36.50	3.40	0.95	51	Clay	Humlc Cleysol	-Humaqueptic Fluvaquent
Yala I	4.8	4.16	39.50	2.20	0.86	62	Clay	m m	
Kerlcho	4.5	2.37	35.25	1.20	0.92	39	Clay	Humlc Nltosol	Orthoxlc Palehumult
Marlene	4.4	1.74	25.50	4.40	0.69	59	Clay	H m	Typic Palehumult
Zaraton	4.9	2.73	31.00	3.40	0.43	46	Clay	H m	Orthoxlc Talchumult
Koru	4.8	1.89	38.50	2.20	0.27	57	Clay	Eutrlc Nltosol	Typic Palehumult
Kltale 74/4-12	5.3	1.38	12.50	0.10	0.02	21	Sandy Loam	Gleylc Luvlsol	Typic Tropaqualf
r.ltalo Pt. 15	5.3	1.47	12.50	0.20	0.p5	46	Clay Loam	Orthlc Ferralsol	Typic llaplustox
Kltale PC. 25	5.3	1.5*	12.50	0.60	0.04	43	w m		
La net	5.5	1.41	16.50	0.00	0.40	47	Clay	Gleylc Camblsol	m m
N.A.L.	5.4	1.74	21.00	0.30	0.16	70	Clay	Humlc Nltosol	Oxlc Paleustult
Eldoret	5.2	1.28	19.50	0.60	0.46	56	Clay	Plinthlc Ferralsol	Tropeptic Eustrustox
Alupe	5.8	1.56	23.00	0.10	0.01	49	Clay	Plinthlc Acrlsol	Typic Pllnthudult
Kltul Valley Side	5.5	1.16	11.00	0.10	0.03	50	Clay Loam	Ferral-Chroralc Luvlsol	Udlic Paleustalf
Kltul Bottom Land	5.6	0.86	10.00	0.00	0.03	33	Sandy Clay Loam	N *	M
Oljoro Orok	5.8	1.67	26.50	0.10	0.01	45	Clay	Ferric Luvlsol	Oxlc Paleustalf
Kakamcga	5.8	2.08	25.25	0.10	0.01	58	Clay	Eutrlc Nltosol	Typic Paleudalf
Kolo	5.6	1.99	22.50	0.00	0.01	35	Clay Loam	Molllc Andosol	Typic Eutrandedpt
Hjoro	6.0	1.77	24.50	0.00	0.01	46	n	N m	N
Klsll	5.9	2.37	31.50	0.00	0.02	47	Clay	Eutric Nltosol	Oxlc Tropudalf
Marlakani	6.0	0.76	7.00	0.00	3.62	8	Sandy Clay Loam	Orthlc Solonctz	Typic (Aquil) Natrargld
Ramsl	5.7	0.52	3.50	0.00	0.01	16	-	Orthlc Ferralsol	Oxlc Haplustalf
Mtwapa	6.2	0.70	7.50	0.00	0.03	9	Loamy Sand	w m	Typic Eustrustox
Matuga	6.2	0.39	5.25	0.00	0.03	13	Sandy Loam	Rhod-Acrlc Ferralsol	Typic Acrustox

TABLE 2: LIME REQUIREMENTS OF 26 SOILS TO pH 6.5 DETERMINED
BY VARIOUS METHODS (in me/100g soil)

Soil	Ca(OH) ₂ titration	SMP-SB	SMP-DB (adjusted)	Mehlich I	Mehlich II
Eituarra II	21.80	25.64	24.10	17.13	11.42
dtuanf>a I	20.20	25.64	24.20	17.13	11.42
Yala II	21.20	20.58	18.78	17.13	11.42
Mariene	19.90	19.84	20.60	17.13	11.42
Kericho	19.30	22.34	19.80	17.13	11.42
Baraton	18.80	21.10	17.40	15.75	10.50
Yala I	18.30	17.88	18.72	15.75	10.50
Koru	15.00	18.76	17.50	15.75	10.50
Eldoret	10.80	9.98	9.70	7.35	4.90
Lanet	7.60	8.12	5.92	6.33	4.22
Kitale Pt. 25	7.40	11.90	8.94	6.33	4.22
Kitale Pt. 15	6.30	8.96	7.80	6.33	4.22
Alupe	6.80	5.38	6.00	4.47	2.98
Kakamcga	6.50	9.68	8.94	5.37	3.58
Molo	6.40	7.04	6.00	5.37	3.58
Kisii	6.40	10.36	9.26	5.37	3.58
NAL	5.70	10.54	6.06	10.65	7.10
Njoro	5.00	8.24	6.90	6.33	4.22
Ol Joro Orok	4.40	7.28	6.00	5.78	3.85
Kitale 74/4-12	4.40	4.24	6.00	4.47	2.98
High LR soils (over 4 me/100 g) means:	11.61	13.68	12.46	10.35	6.90
Kitui valley side	3.90	4.12	5.12	3.60	2.40
Mariakani	3.30	0.74	1.64	2.79	1.86
Kitui bottom land	2.42	1.58	1.64	2.79	1.86
Mtwapa	1.60	0.50	0.84	2.01	1.34
Ramisi	0.80	0.14	0.84	1.29	0.86
Matuga	0.80	0.20	0.80	2.01	1.34
Low LR soils below 4 me/100 g means:	2.14	1.21	1.81	2.42	1.61
Means of all soils:	9.42	10.80	10.00	8.52	5.68

4.0 me/100g soil but below 10.0 me/100g soil, where Ca(OH)^{\wedge} -titration method shows a range from 4.0 to 10.0 me, SMP-SB method shows a range from 4.0 to 10.0 me; SMP-DB method a range from 6.0 to 10.0 me; Mehlich I method a range from 4.0 to 11.0 me; and Mehlich II method a range from 3.0 to 7.0 me. At lime requirements below 4.0 me/100g soil, where Ca(OH)_2 -titration method gives a range from 0.8 to 4.0 me, SMP-SB method gives a range from 0.2 to 4.0 me; ~~SxMP-~~DB method a range from 0.8 to 5.0 me; Mehlich I a range from 2.0 to 4.0 me; while Mehlich II method gives a range from 1.0 to 2.0 me. These results imply that the Mehlich methods are not sensitive enough for soils of high lime requirements since they virtually give the same lime requirement value where the standard gives a lime requirement range from 10.0 to 21.0 me. Their sensitivity, however, improves for soils of low and intermediate lime requirements.

The mean lime requirement values to achieve pH 6.5 for soil of high lime requirements (i.e. > 4.0 me/100g soil) obtained with SMP-SB and SMP-DB methods were 17.8 and 7.3%, respectively, above that obtained with the standard (Ca(OH)_2 -titration) while the mean lime requirement values obtained with Mehlich I and xMehlich II methods were 10.9 and 40.6%, respectively, of that obtained with Ca(OH)^{\wedge} -titration. For soils of low lime require-

ment (< 4.0 me/100g soil), the mean lime requirement value obtained with Mehlich I method was 13.0% above that obtained with Ca(OH)_2 -titration, while values obtained with SMP-SB, SMP-DB and Mehlich II methods were 43.5, 15.4 and 24.8%, respectively, of that obtained with Ca(OH)_2 -titration. For all the 26 soils the mean lime requirement values to pH 6.5 obtained with SMP-SB and SMP-DB methods were 14.6 and 6.2%, respectively, above that obtained with Ca(OH)_2 -titration, while the values obtained with Mehlich I and Mehlich II methods were 9.6 and 39.7%, respectively, of that obtained with Ca(OH)_2 -titration. Thus overall the SMP-DB method gives the least variation from the reference method (Ca(OH)_2 -titration) throughout the entire range.

Lime requirement values of soils measured by various methods to pH 6.0 are presented in Table 3. For soils of high lime requirements (> 4.0 me/100g soil), where CaCO_3 -incubation method shows a range of lime requirement from 4.0 to 20.0 me, SMP-SB method shows a range from 5.0 to 18.0 me; SMP-DB method a range from 4.0 to 19.0 me; Mehlich I method a range from 11.0 to 17.0 me; while Mehlich II method shows a range from 7.0 to 11.0 me. For soils of low lime requirements (≤ 4.0 me/100g soil), where CaCO_3 -incubation method shows a range from 0.0 to 3.0 me, SMP-SB method shows a range from 0.2 to 6.0 me; SMP-DB method a range from 0.0 to 4.0 me;

TABLE 3: LIME REQUIREMENTS OF 15 SOILS TO pH 6.0 DETERMINED
BY VARIOUS METHODS (in me/100 g soil)

	CaCO ₃ ~ incubation	SMP-SB	SMP-DB	Mehlich I	Mehlich II
Gituajnba I	20.16	17.72	18.80	17.13	11.42
Yala II	19.60	16.12	17.78	17.13	11.42
Yala I	19.60	16.00	14.60	15.75	10.50
Gituamba II	18.38	17.72	17.12	17.13	11.42
Keric'io	14.72	16.46	17.90	17.13	11.42
Baraton	13.38	13.20	12.40	15.75	10.50
Mariene	12.84	16.52	16.00	17.13	11.42
Kcru	10.70	12.80	12.00	15.75	10.50
NAL	4.46	4.70	4.28	10.65	7.10
High LR soils (over 4 me/100 g)					
Means:	14.87	14.58	14.54	15.95	10.63
Lanet	2.80	5.68	4.00	6.33	4.22
Kitale Pt. 15	1.96	4.52	4.10	6.33	4.22
Kitale 74/4-12	1.96	4.22	3.88	4.47	2.98
01 Joro Orok	1.96	3.36	2.30	5.78	3.85
Kitui bottom land	0.16	1.16	0.60	2.79	1.86
Mtwapa	0.00	0.20	0.00	2.01	1.34
Low LR soils (below 4 me/100 g)					
Means:	1.47	3.19	2.48	4.62	3.08
Means of all Soils:	9.51	10.03	9.72	11.42	7.61

Mehlich I method a range from 2.0 to 6.0 me; while Mehlich II method shows a range from 1.0 to 4.0 me. Once again the Mehlich methods lack sensitivity for soils of high lime requirements and their sensitivity improves for soils of low lime requirements.

The mean lime requirement value to pH 6.0 for soils of high lime requirements (4.0 me/100g soil) obtained with Mehlich I method was 7.3% above that obtained with CaCO⁻-incubation, while the values obtained with SMP-SB, SMP-DB and Mehlich II methods were 2.0, 2.2 and 28.5%, respectively, of that obtained with CaCO⁻-incubation. For soils of low lime requirements (5. 4.0 me/100g soil), the mean lime requirement values to achieve pH 6.0 obtained with SMP-SB, SMP-DB, Mehlich I and Mehlich II methods, were 117.0, 68.7, 214.3 and 109.5 %, respectively, above that obtained with CaCO⁻-incubation. For all the 15 soils the mean lime requirement values to achieve pH 6.0 obtained with SMP-SB, SMP-DB and Mehlich I methods were 5.5, 2.2 and 20.1%, respectively, above that obtained with CaCO⁻-incubation, while the value obtained with Mehlich II method was 20.0% of that obtained with CaCO⁻-incubation. The variation from the reference method (CaCO⁻-incubation) is thus again the least with SMP-DB method throughout the entire range.

Lime requirement values for the 15 soils measured by various methods to pH 5.5 are presented in Table 4. The lime requirement values to raise soil pH to 5.5 show that while CaCO_3 -incubation method gives a lime requirement range from 7.0 to 16.0 me for soils of high lime requirements, SMP-DB method gives a range from 6.0 to 16.0 me; Mehlich I method a range from 16.0 to 17.0 me; and Mehlich II method a range from 10.0 to 11.0 me. For soils of low lime requirements, while CaCO^{\wedge} -incubation method gives a range from 0.0 to 2.0 me, SMP-DB method gives a range from 0.0 to 2.4 me; Mehlich I a range from 2.0 to 10.0 me; while Mehlich II method gives a range from 1.0 to 7.0 me. These results once again imply lack of enough sensitivity with the Mehlich methods for soils of high lime requirements whereas their sensitivity increases for soils of low lime requirements.

The mean lime requirement values for soils of high lime requirements to pH 5.5 obtained with SMP-DB and Mehlich I methods were 1.4 and 47.8% respectively, above that obtained with CaCO^{\wedge} -incubation while the value obtained with Mehlich II was 1.4% of that obtained with CaCO^{\wedge} - incubation. For soils of low lime requirements, the mean lime requirement values obtained with SMP-DB, Mehlich I and Mehlich II methods were 6.3, 756.3 and 470.3% respectively, above that obtained with CaCO^{\wedge} incubation method. For all the 15 soils the mean lime requirement

TABLE 4: LIME REQUIREMENTS OF 15 SOILS TO pH 5.5 DETERMINED
BY VARIOUS METHODS (in me/100 g soil).

Soil	CaCO ₃ - incubation	SKP - DB	Mehlich I	Mehlich II
Yala II	16.42	16.00	17.13	11.42
Gituamba 1	15.16	16.50	17.13	11.42
Gituamba	14.10	16.20	17.13	11.42
Yala I	10.70	8.64	15.75	10.50
Kericho	8.92	9.24	17.13	11.42
Marlene	8.92	10.22	17.13	11.42
Baraton	8.48	8.00	15.75	10.50
Koru	7.14	6.40	15.75	10.50
High LR soils (over 4 me/100 g) means:	11.24	11.40	16.61	11.08
NAL	1.60	2.40	10.65	7.10
Kitale Pt. 15	1.20	0.60	6.33	4.22
Lanet	1.12	1.40	6.33	4.22
Kitale 74/4-12	0.54	0.40	4.47	2.98
Ol joro Orok	0.00	0.00	5.78	3.85
Kitui bottom land	0.00	0.00	2.79	1.86
Mtwapa	0.00	0.00	2.01	1.34
Low LR soils (below 4 me/100 g) means:	0.64	0.68	5.48	3.65
means of all soils:	6.29	6.40	11.42	7.61

values to pH 5.5 obtained with SMP-DB, Mehlich I and Mehlich II methods were 1.7, 81.6 and 21.0%, respectively, above that obtained with CaCO_3 -incubation. The least variation from the reference method (CaCO_3 -incubation) is once more given by the SMP-DB method throughout the entire range.

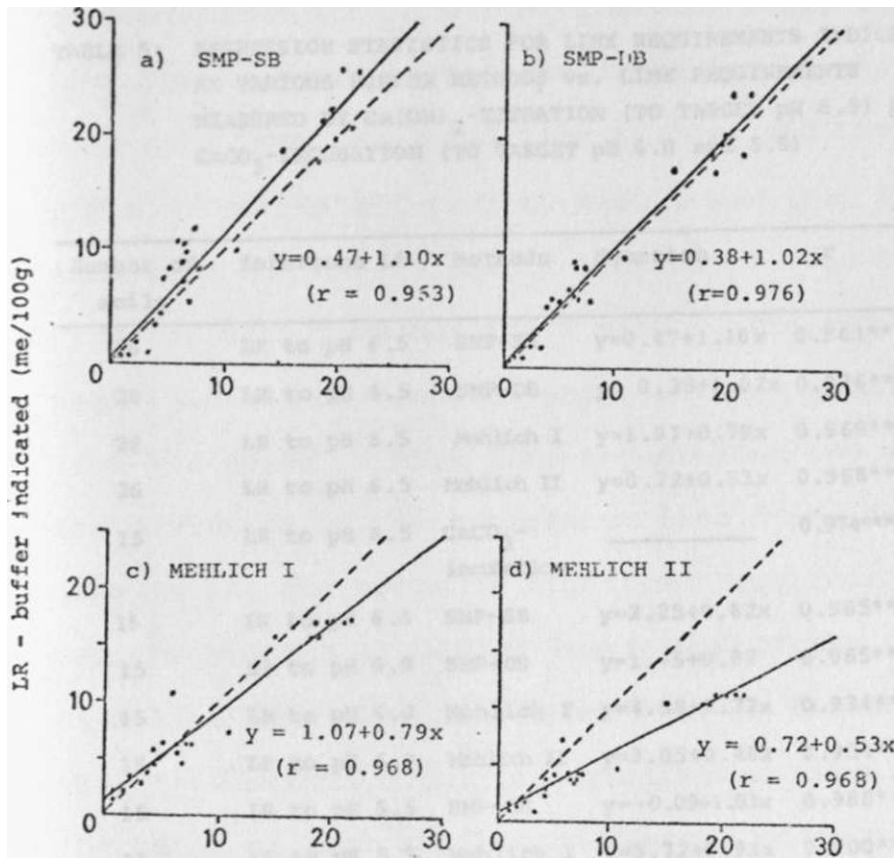
For all buffer methods highest and lowest indicated lime requirement values (to pH 6.5, 6.0 and 5.5) were for same soils. These results were consistent with the wide range of acid properties exhibited by these soils. The Coast Province soils (sandy soils) which had the lowest lime requirement values had the lowest cation exchange capacity, clay and organic matter contents (Table 1). The values of lime requirement to pH 6.5 were approximately twice as large as those to pH 5.5. It is probable that, in addition to exchange acidity neutralized to pH 5.5, large amounts of pH-dependent acidity were neutralized above this pH level (Kamprath, 1970; Hutchinson, 1970).

The buffer methods gave different lime requirement ranges for the three pH targets (pH 6.5, 6.0 and 5.5). Generally, the SMP-DB method gave the widest lime requirement ranges for a given pH target, while the Mehlich methods gave the narrowest, particularly for soils of high lime requirements. At low lime requirements the lime requirement ranges given by the Mehlich methods were approximately as wide as those given by the SMP-SB and SMP-DB methods. The results

also showed that at the three pH targets the mean lime requirement values obtained with the SMP-DB method generally deviated less from the mean values obtained with the reference methods (Ca(OH)_2 titration and CaCO_3 -incubation), especially at low pH targets, than was the case with other methods.

4.3. Regression - correlation analysis

Lime requirement values measured by Ca(OH)_2 titration to pH 6.5 are plotted against the four buffer-indicated values (Fig. 1 a-d) while the regression statistics are presented in Table 5. The correlation coefficients (r) were relatively high and highly significant ($P = 0.001$) for all the four buffer methods involving the 26 soils. The correlation coefficient for data for SMP-DB method, however, was the highest ($r = 0.976$). For the SMP-SB method (Fig. 1 a) the regression line indicates that this method slightly underestimates amount of lime required for soils of low lime requirements by as much as about 1.0 me/100g soil and overestimates amount of lime required for soils of high lime requirements, hence a big deviation of the regression line from the ideal line, especially at high lime requirement levels. Furthermore, the uncertainty of measurement indicated by the standard error of estimate ($S_{y.x}$) is quite large for this method (Table 5). For the SMP-DB method (Fig. 1, b) the regression line indicates



LR - Ca(OH)₂ titrated (me/100g)

Fig. 15 Lime requirements (LR) to pH 6.5 of 26 acid soils as measured by Ca(OH)₂ titration vs. those measured by various buffer methods (dashed lines indicate what the perfect correlations would have been).

TABLE 5: REGRESSION STATISTICS FOR LIKE REQUIREMENTS- INDICATED BY VARIOUS BUFFER METHODS vs. LIME REQUIREMENTS MEASURED BY Ca(OH)⁺TITRATION (TO TARGET pH 6.5) AND CaCO₃-INCUBATION (TO TARGET pH 6.0 and 5.5)

Number of soils	Reference LR	Methods	Equation	r	Sy.x
26	LR to pH 6.5	SMP-SB	y=0.47+1.10x	0.963***	2.24
26	LR to pH 6.5	SMP-DB	y= 0.38+1.02x	0.975***	1.65
26	LR to pH 6.5	Mehlich I	y=1.07+0.79x	0.968***	1.49
26	LR to pH 6.5	Mehlich II	y=0.72+0.53x	0.968***	0.99
15	LR to pH 6.5	CaCO ₃ - incubation		0.971***	
15	LR to pH 6.0	SMP-SB	y=2.25+0.82x	0.965***	1.82
15	LR to pH 6.0	SMP-DB	y=1.45+0.87	0.965***	1.94
15	LR to pH 6.0	Mehlich I	y=4.58+0.72x	0.934***	2.24
15	LR to pH 6.0	Mehlich II	y=3.05+0.48x	0.934***	1.50
15	LR to pH 5.5	SMP-DB	y= -0.09+1.03x	0.938***	1.02
15	LR to pH 5.5	Mehlich I	y=5.72+0.91x	0.900***	2.74
15	LR to pH 5.5	Mehlich II	y=3.81+0.60x	0.900***	1.83

*** significant at P = 0.001

— not determined

that this method estimates approximately equal amounts of lime for soils of low lime requirements as the standard (Ca(OH)_2 -titration) but slightly overestimates the amount of lime for soils of high lime requirements. Thus the deviation of the regression line from the ideal line is less and the standard error of estimate ($S_{y.x}$) is also lower than that for data from the SMP-SB method (Table 5). The regression line for data from Mehlich I method (Fig. 1, c) shows that this method tends to underestimate amount of lime for soils of high lime requirement and as such the deviation of the regression line from the ideal line is big for soils of high lime requirements. For the Mehlich II method deviations of the regression line from the ideal line (Fig. 1, d) indicate that this method highly underestimates amount of lime for soils of high and intermediate lime requirements but estimates approximately equal amounts of lime as the standard (Ca(OH)_2 -titration) for soils of very low lime requirements.

Lime requirement values measured by CaCO_3 -incubation to pH 6.0 are plotted against those indicated by four buffer methods (Fig. 2 a-d) while the regression statistics are presented in Table 5. The correlation between Ca(OH)_2 -titration and CaCO_3 -incubation was high ($r = 0.974$) and highly significant ($P = 0.001$), thus justifying the use of lime requirements measured by CaCO_3 -incubation as the

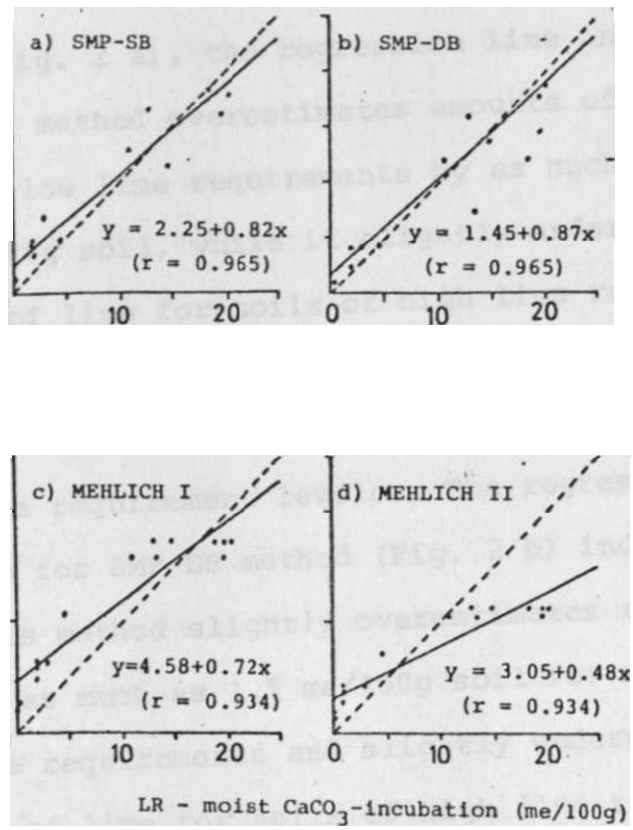


Fig. 2: Lime requirements (LR) to pH 6.0 of 15 acid soils as measured by CaCO_3 + Incubation vs. those indicated by various buffer methods (dashed lines indicate what perfect correlations would have been).

standard for lower pH targets (pH 6.0 and 5.5). The correlation coefficients (r) show that they were high and highly significant ($P = 0.001$) for all the methods involving the 15 soils. Once again the correlation coefficient for data for SMP-DB method was the highest ($r = 0.965$). For the SMP-SB method (Fig. 2 a), the regression line indicates that this method overestimates amounts of lime for soils of low lime requirements by as much as about 4.0 me/100g soil, while it slightly underestimates amounts of lime for soils of high lime requirements. The deviation of the regression line from the ideal line is, therefore, big especially at low and very high lime requirement levels. The regression line for data for SMP-DB method (Fig. 2 b) indicates that this method slightly overestimates amounts of lime by as much as 1.5 me/100g soil for soils of low lime requirements and slightly underestimates amounts of lime for soils of high lime requirements. The difference between the regression line and the ideal line is, thus, smaller than is the case with the other methods. For Mehlich I method the regression line (Fig. 2, c) indicates that this method overestimates amount of lime by as much as about 5.0 me/100g soil for soils of low lime requirements and underestimates amount of lime for soils of high lime requirements, hence the difference between

the regression line and the ideal line is quite big for this method, especially at low and intermediate lime requirement levels. For Mehlich II method the deviation of the regression line from the ideal line (Fig. 2 d) indicates that this method overestimates amount of lime by as much as about 3.0 me/100g soil for soils of low lime requirements and underestimates amount of lime for soils of intermediate and high lime requirements.

Lime requirement values measured by CaCO_3 -incubation to pH 5.5 are plotted against the values obtained with the buffer methods (Fig. 3a-c) while the regression statistics are presented in Table 5. Once again the correlation coefficients (r) were high and highly significant ($P = 0.001$) for all the buffer methods involving the 15 soils. The correlation coefficient for data for SMP-DB was, again, the highest ($r = 0.988$). The regression line (Fig. 3a) for SMP-DB method indicates that this method estimates approximately equal amounts of lime as the standard (CaCO_3 -incubation) throughout the entire range, hence the deviation of the regression line from the ideal line is very small throughout the lime requirement range. For Mehlich I method (Fig. 3 b) the deviation of the regression line from the ideal line indicates that this method overestimates the amounts of lime throughout

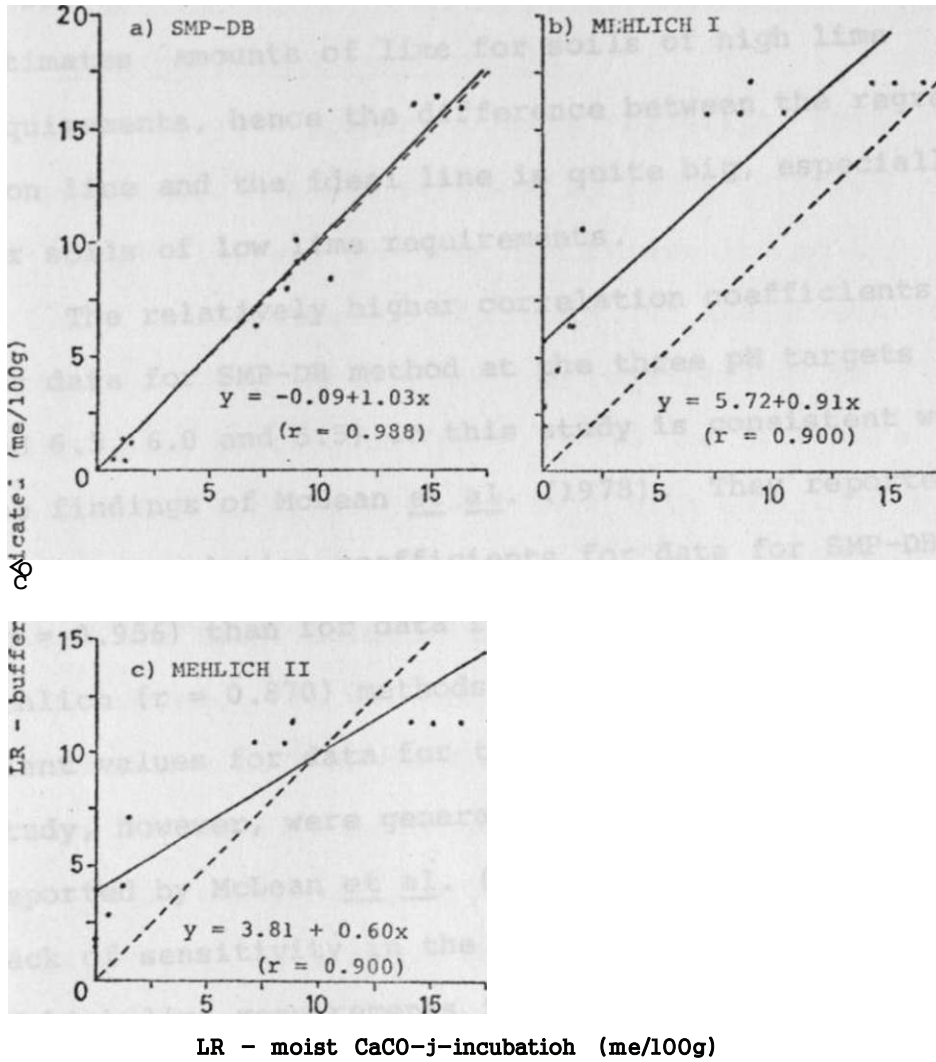


Fig. 3 - Lime requirements (LR) to pH 5.5 of 15 acid soils as measured by CaCO₃ + incubation vs. those indicated by various buffer methods (dashed lines indicate what Derfect correlations would have been).

the entire lime requirement range. The regression line (Fig. 3c) for Mehlich II method indicates that this method overestimates amounts of lime for soils of low and intermediate lime requirements and underestimates amounts of lime for soils of high lime requirements, hence the difference between the regression line and the ideal line is quite big, especially for soils of low lime requirements.

The relatively higher correlation coefficients for data for SMP-DB method at the three pH targets (pH 6.5, 6.0 and 5.5) in this study is consistent with the findings of McLean et al. (1978). They reported higher correlation coefficients for data for SMP-DB ($r = 0.956$) than for data for SMP-SB ($r = 0.550$) and Mehlich ($r = 0.870$) methods. The correlation coefficient values for data for the buffer methods in this study, however, were generally higher than those reported by McLean et al. (1978). There was generally lack of sensitivity in the Mehlich methods for soils of high lime requirements indicating that these methods might be inadequate for these soils. On the other hand, the SMP-DB method gave the least variation from the reference methods, the highest correlation coefficients at all the three pH targets and was particularly impressive at the lowest target pH (5.5). These results indicate that this method might be the best choice as a lime requirement index

for these soils, especially as it might not be necessary to lime these soils to high pH levels.

4.4. Relationship between soil properties and reference lime requirements

Various soil properties were correlated with lime requirement values measured by $\text{Ca}(\text{OH})$ titration (to pH 6.5) and by CaCO_3 incubation (to pH 6.0 and 5.5). Correlation coefficients (r) are presented in Table 6. These show that lime requirements to all the three pH targets (pH 6.5, 6.0 and 5.5) were significantly correlated ($P = 0.001$) with soil carbon, exchangeable aluminium; exchange acidity; residual acidity; and total acidity; but rather poorly correlated to clay content. In all cases the highest correlation coefficients with lime requirements were for total acidity, followed by exchange acidity and residual acidity. This relationship between lime requirements and soil properties is similar to observations elsewhere. Keeney and Corey (1963) observed that organic matter content was well correlated ($r = 0.62$) with the amount of lime required to achieve pH 6.5, and highly correlated ($r = 0.95$) with amount of lime required to achieve pH 6.8 in 26 Wisconsin and 9 Michigan soils, respectively. Webber et al. (1977) also observed that lime requirements to pH 6.0 and 5.5 of Canadian soils correlated

TABLE 6: CORRELATION COEFFICIENTS (r) FOR REFERENCE LIME REQUIREMENTS VS. SOIL PROPERTIES⁺

Soil properties	LR to pH 6.5 ⁺⁺ (26 soils)	LR to pH 6.0 ["] (15 soils)	LR to pH 5.5 ⁺⁺⁺ (15 soils)
Soil pH	-0.925***	-0.882***	-0.868***
Soil organic carbon	0.829***	0.862***	0.866***
Exchangeable aluminium	0.834***	0.878***	0.892***-
Exchangeable manganese	0.729***	0.709***	0.680**
Exchange acidity	0.961***	0.918***	0.980***
Residual acidity	0.912***	0.872***	0.960***
Total acidity	0.967***	0.926***	0.980***
Clay content	0.485*	0.39 INS	0.306NS

+ measured before pH adjustments were made

++ as measured by Ca(OH)₂-titration

+++ as measured by CaCO₃-incubation

* significant at P = 0.05

** significant at P = 0.01

*** significant at P = 0.001

NS not significant at P = 0.05

highly with exchangeable aluminium ($r = 0.80, 0.82$); exchange acidity ($r = 0.92; 0.83$); and organic matter ($r = 0.76, 0.63$); but poorly correlated to clay content ($r = 0.42, 0.35$). The relatively high correlation coefficients between the amount of lime required to raise soil pH to 6.5, 6.0 and 5.5, and soil exchangeable aluminium, organic matter and exchangeable manganese in this study indicate that these soil properties contribute to lime requirement of these soils. The higher correlation coefficient values for total acidity for all the three pH targets over the corresponding values for exchange acidity and residual acidity suggest that both forms of acidity should be considered when estimating the lime requirements of these soils. This finding is similar to that of Mehlich (1976) who worked with mineral acid soils of North Carolina.

4.5. Relationship between soil acidity components and liming of soils

The results on the effect of liming on some soil properties are presented in Table 7. The results show that exchange acidity decreases with increasing rates of lime while residual acidity increases slightly with increasing rates of lime. Residual acidity was the highest component of soil acidity at all pH levels for all soils. These

TABLE 7j EFFECT OF LIMING ON SOME SOIL PROPERTIES*
I

Soil	Soil properties	Lime Levels	
		0.00	2.00
Yala I	pH	4.40	4.60
	Exch. acidity (me/100 g)	4.00	2.20
	Res. acidity (me/100 g)	12.40	12.00
	Exch. Al (me/100 g)	1.30	0.60
	Exch. Mn (me/100 g)	0.31	0.39
Gituanba (previously limed)	pH	4.40	4.60
	Exch. acidity (me/100 g)	5.80	4.80
	Residual acidity (me/100 g)	16.80	17.00
	Exch. Al (me/100 g)	2.00	0.80
	Exch. Mn (me/100 g)	0.48	0.16
Lanet	pH	4.70	6.00
	Exch. acidity (me/100 g)	2.40	1.60
	Residual acidity (me/100 g)	5.80	5.60
	Exch. Al (me/100 g)	0.30	0.10
	Exch. Mn (me/100 g)	0.23	0.05
Kitale (Point 15)	pi:	5.20	6.00
	Exch. acidity (me/100 g)	1.80	1.40
	Residual acidity (me/100 g)	3.80	3.40
	Exch. Al (me/100 g)	0.02	0.00

(in me CaCC>₃/100 g soil)

<u>4.00</u>	<u>6.00</u>	<u>9.00</u>	<u>12.00</u>	<u>16.00</u>	<u>20.00</u>
4.70	4.80	4.90	5.30	5.60	5.90
1.60	2.40	1.40	0.20	0.10	0.10
10.80	11.00	11.30	12.00	12.10	12.30
0.30	0.04	0.01	0.00	0.00	0.00
0.22	0.10	0.14	0.01	0.01	0.00
4.80	4.90	5.00	5.20	5.50	5.80
4.00	2.90	2.40	1.00	0.60	0.40
17.20	18.00	16.60	17.20	18.70	18.90
0.30	0.10	0.06	0.01	0.00	0.00
0.15	0.28	0.16	0.11	0.01	0.00
6.50	6.70	7.00	7.20	7.50	7.60
1.20	1.20	0.60	0.40	0.20	0.10
5.80	6.00	6.00	5.90	5.80	6.10
0.02	0.01	0.00	0.00	0.00	0.00
0.01	0.00	0.00	0.00	0.00	0.00
6.40	6.80	7.20	7.60	7.70	7.80
1.20	1.40	0.60	0.20	0.08	0.03
3.40	3.70	3.90	4.20	4.10	4.20
0.00	0.00	0.00	0.00	0.00	0.00

TABLE 7: continued

Kltale (74/4-12)	pH
	Exch. acidity (mc/100 g)
	Residual acidity (me/100 g)
	Exch. Al (me/100 g)
	Exch. Mn (me/100 g)
Oljoro Orok	pH
	Exch. acidity (me/100g)
	Residual acidity (me/100 g)
	Exch. Al (me/100 g)
	Exch. Mn (me/100 g)
Kitui (bottom land)	pH
	Exch. rcidity (me/100 g)
	Residual acidity (me/100 g)
	Exch. Al (me/100 g)
	Exch. Mn (me/100 g)
Gituamba (original)	pH
	Exch. acidity (me/100 g)
	Residual acidity (me/100 g)
	Exch. Al (me/100 g)
	Exch. Mn (me/100 g)
Kericho	pH
	Exch. acidity (me/100 g)
	Residual acidity (me/100 g)
	Exch. Al (me/100 g)
	Exch. Kn (me/100 g)
Mariene	pri
	Exch. acidity (me/100 9)
	Residual acidity (me/100 g)
	Exch. Al (me/100 g)
	Exch. Mn (me/100 g)

5.30	6.00	6.60	7.20	7.50	7.60	7.70	7.80
1.20	0.80	0.60	0.30	0.10	0.08	0.08	0.01
2.30	2.10	2.20	2.20	2.40	2.60	2.90	2.80
0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00
5.50	6.00	6.20	6.60	7.00	7.40	7.60	7.70
1.90	1.60	1.00	0.50	0.20	0.10	0.01	0.01
4.40	4.20	4.10	4.00	4.30	4.60	4.70	4.70
0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00
5.90	6.90	7.20	7.50	7.60	7.70	7.80	8.10
0.60	0.40	0.10	0.03	0.01	0.01	0.00	0.00
1.40	1.30	1.20	1.40	1.30	1.50	1.60	1.70
1.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
4.50	4.80	4.90	5.10	5.50	5.70	5.90	6.20
7.80	5.70	3.60	2.40	1.60	1.20	0.60	0.40
15.20	15.00	15.30	14.20	15.20	16.00	16.70	17.40
2.60	1.00	0.60	0.20	0.01	0.00	0.00	0.00
0.24	2.40	0.90	0.94	0.84	0.70	0.40	0.20
4.40	4.60	5.00	5.40	5.50	5.70	6.10	6.60
6.00	4.10	2.20	1.00	0.40	0.20	1.10	0.10
11.70	10.50	11.70	11.00	11.70	12.00	12.00	12.90
2.50	1.10	0.10	0.06	0.01	0.00	0.00	0.00
0.70	0.50	0.60	0.40	0.40	0.20	0.10	0.01
4.20	4.40	4.60	5.00	5.50	5.90	6.20	6.70
5.80	5.20	4.70	4.20	3.80	1.60	1.40	0.80
8.10	8.30	7.60	7.80	8.00	8.10	8.50	8.60
3.20	1.60	0.80	0.40	0.07	0.01	0.00	0.00
0.67	0.40	0.14	0.06	0.00	0.00	0.00	0.00

TABLE 7: continued

Yala II	pH	4.20	4.40
	Exch. acidity (me/100 g)	5.20	3.40
	Residual acidity (me/100 g) ^g	11.90	11.70
	Exch. Al (me/100 g)	2.50	1.20
	Exch. Mn (me/100 g)	0.85	0.76
NAL	PH	5.00	5.40
	Exch. acidity (me/101 g)	3.80	2.40
	Residual acidity (me/100 g) ³⁾	5.10	5.00
	Exch. Al (me/100 g)	0.60	0.10
	Exch. Kn (mc/100 g)	0.13	0.02
Baraton	pH	4.40	4.70
	Exch. acidity (me/100g)	6.60	4.40
	Residual acidity (me/100 g)	9.70	9.70
	Exch. Al (me/100 g)	1.80	1.20
	Exch. Mn (me/100 g)	0.01	0.42
Koru	PH	4.60	4.80
	Exch. acidity (me/100 g)	4.30	3.80
	Residual acidity (me/100 g)	8.00	7.80
	Exch. Al (me/100 g)	0.90	0.30
	Exch. Mn (me/100 g)	0.31	0.29

+ equilibration period with Ca[<]
in the laboratory.

4.50	4.70	4.90	5.40	6.00	6.40
3.00	2.00	1.00	0.20	0.10	0.10
11.70	12.20	11.80	11.80	12.40	12.30
1.00	0.20	0.04	0.01	0.00	0.00
0.14	0.13	0.15	0.12	0.02	0.01
5.90	6.20	6.70	7.00	7.20	7.60
1.40	1.20	0.60	0.20	0.10	0.10
5.40	5.30	5.40	5.40	5.00	5.70
0.04	0.01	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00
5.00	5.20	5.30	5.80	6.20	6.50
3.00	2.20	1.20	0.50	0.20	0.10
9.80	9.60	9.70	10.00	10.10	10.30
0.40	0.10	0.01	0.00	0.00	0.00
0.03	0.04	0.06	0.02	0.00	0.00
5.00	5.20	5.60	6.10	6.40	6.60
1.80	1.40	0.80	0.30	0.10	0.00
7.60	5.20	6.10	8.00	8.10	8.20
0.10	0.04	0.01	0.00	0.00	0.00
0.11	0.11	0.06	0.01	0.00	0.00

0. was 3^ months

results were similar to those obtained by Mehlich (1976) and confirm earlier findings (Kamprath, 1970; Pearson, 1975) that neutralization of exchange acidity of mineral soils requires lime in excess of exchange acidity for crops with high lime requirements.

In the same incubation study, results (Table 7) show that exchangeable aluminium decreases with increasing rates of lime. Generally, liming of the soils in the pH range of 5.1 - 5.3 reduced the amount of aluminium extracted with 1N KCl to less than 0.1 me/100g soil. Little or no aluminium was detected in the KCl-extract when soils were limed to pH 6.0. These results also agree very well with the published findings (Kamprath, 1970; Hoyt and Nyborg, 1972; and McLean et al. 1972) that liming acid soils to pH 5.2 - 5.3 eliminated or greatly reduced soluble aluminium.

The results on the effect of liming on exchangeable manganese (Table 7) show that increase in lime rates generally reduces the amount of exchangeable manganese. Exceptional results, however, were obtained with Gituamba (unlimed) soil where exchangeable manganese initially tended to increase with increased lime rates. As this soil was high in organic matter (Table 1) it is probable that at low pH levels some of the manganese is complexed by organic matter and, increase of pH might have

resulted in the release of the complexed manganese. The differences in exchangeable manganese between the unlimed and previously limed Gituamba soils suggest that a long equilibration time is required to neutralize the manganese so released.

4.6. Relationship between various forms of acidity and lime requirement of soils measured by various methods

Correlation coefficients of lime requirements of soils to pH 6.5 (LR 6.5), 6.0 (LR 6.0), and 5.5 (LR 5.5) measured by various methods versus various forms of acidity are presented in Table 8. Lime requirement values to the pH 6.5 target measured by various methods were highly correlated with exchange acidity, residual acidity and total acidity indicating that not any one of the acidity components can be disregarded when considering liming of these soils. All correlation coefficients (r) were highly significant ($P = 0.001$). The differences in correlation coefficient (r) for each of the acidity component versus lime requirements to pH 6.5 were generally small for all the methods indicating that not any one of the buffer methods is better as a measure of any of these acidity components than the other. The correlation coefficient between exchange acidity and lime requirements to pH 6.5 measured by all the methods

TABLE 8: CORRELATION COEFFICIENTS OF LIME REQUIREMENTS (LR) DETERMINED BY VARIOUS METHODS VERSUS VARIOUS FORMS OF SOIL ACIDITY*

Methods	LR to pH 6.5 (26 soils)			Lfl to pH 6.0 (15 soils)			LR to pH 5.5 (15 soils)					
	Ace	Acr	Act	Ace	Acr	Act	Ace	Acr	Act			
SMP-SB	0.953***	0.922***	0.954***	0.968***	0.978***	0.879***	0.950***	0.980***	—	—	—	—
SMP-DB	0.961***	0.915***	0.958***	0.970***	0.975***	0.911***	0.954***	0.981***	0.937***	0.862***	0.906***	0.940***
Mehlich I	0.963***	0.910***	0.952***	0.973***	0.964***	0.898***	0.940***	0.970***	0.964***	0.898***	0.940***	0.970***
Mehlich II	0.963***	0.910***	0.952***	0.973***	0.964***	0.898***	0.940***	0.970***	0.964***	0.898***	0.940***	0.970***
Ca(OH) ₂ -titration	0.964***	0.903***	0.947***	0.972***	—	—	—	—	—	—	—	—
CaCO ₃ -incubation	—	—	—	—	0.958***	0.863***	0.917***	0.960***	0.942***	0.876***	0.912***	0.947***

+ measured before pH adjustments were made

++ correlation coefficients of lime requirements vs Ace and Acr through a multiple regression

Ace Exchange acidity

Act total acidity

Acr residual acidity

— not determined'

*** significant at P => 0.001

were highest, followed by those of total acidity and then those of residual acidity. For all the methods at pH target 6.5 there was an improvement in correlation coefficient (R) with a multiple regression using exchange acidity and residual acidity over single regression using exchange acidity, residual acidity or total acidity alone. These results are similar to those reported by Mehlich (1976) when dealing with mineral acid soils of North Carolina. He, too, reported higher correlations with a multiple regression for lime requirements measured by Shoemaker - McLean - Pratt (SMP) and Adams - Evans buffer methods using exchange acidity and residual acidity than with simple regression using exchange acidity, residual acidity or total acidity alone.

The trends in results with respect to correlation coefficients with single regression and with a multiple regression at lower pH targets (5.5 and 6.0) were similar to those at pH 6.5 target presented above.

The improvement in correlation coefficients (R) with a multiple regression in this study indicates that exchange acidity and residual acidity should be considered simultaneously when estimating lime requirements of these soils. The fact that not any one method gave a significantly higher correlation coefficient for each of the acidity component than the other at all the three pH targets indicates

that all methods are equally good as a measure of any of these components in these soils.

4.7. Pot experiment

Establishment of plants were generally good in all the three soils used for the pot experiment. In the case of Mariene and Gituamba soils, especially at low pH levels, plants were not healthy. They were rather stunted and showed small and sometimes wrinkled leaves and stems. In the case of Gituamba soil, at low to medium lime rates, chlorosis and some black specks on the leaves were observed.

Soil analysis (Table 10) indicated that aluminium and manganese levels were high for Gituamba and Mariene soils and that exchangeable manganese increased at low lime rates in the case of Gituamba soil. The poor growth of plants observed at low pH levels in these two soils was probably due to high exchangeable aluminium and/or manganese levels at these pH levels. In the case of Gituamba soil, chlorosis and black specks observed on the plants at low to medium lime rates were probably due to manganese and/or aluminium toxicity at the lowest pH levels and due to high manganese levels at low lime rates.

The mean dry matter yield of beans and maize and mean dry weight of nodules for beans are presented in Table 9. For all soils nodule dry weight signi-

TABLE 9.1 EFFECT OF LIMING ON THE MEAN DRY MATTER YIELD (DMY) OF BEANS AND MAIZE AND MEAN DRY WEIGHT OF NODULES FOR BEANS GROWN IN THREE SOILS.

			NAL SOIL				
CaCO ₃ added (in me/100 g soil)	0.0	P ⁺	2.0	4.0	9.0	14.0	18.0
Soil pH	5.0	-	5.4	5.9	6.7	7.2	7.5
Mean D.M.Y. of beans (g/pot)	2.7ab	3.1b	3.2b	3.3b	3.3b	2.6a	2.2a
Mean D.M.Y. of maize (g/pot)	1.9bc	-	2.0c	2.2c	1.7bc	1.4ab	1.1a
Mean nodule dry weight (me/plant)	6.8a	8.2a	12.6ab	32.1bc	23.9bc	16.4ab	8.0a
			MAPTENE SOIL				
CaCO ₃ added (in me/100 g soil)	0.0	P ⁺	4.0	7.0	11.0	14.0	18.0
Soil pH	4.2	-	4.4	5.2	5.7	6.0	6.4
Mean D.M.Y. of beans (g/pot)	2.0a	2.7ab	3.3bc	3.8c	-4.1c	7.9c	4.0c
Mean D.M.Y. of maize (g/pot)	1.5a	-	1.8a	1.8a	2.0a	2.5b	1.6a
Mean nodule dry weight (mg/plant)	1.3a	1.8a	14.9ab	11.9ab	29.5c	10.5ab	23.8bc
			GITUAMBA SOIL				
CaCO ₃ added (in me/100 g soil)	0.0	P ⁺	6.0	9.0	14.0	22.0	
Soil pH	5.5	-	5.1	5.5	5.8	6.5	
Mean D.M.Y. of beans (g/pot)	2.9a	3.3b	3.7bc	3.8bc	4.2c	4.0c	
Mean D.M.Y. of maize (g/pot)	1.3a	-	1.4ab	1.5b	1.7b	1.5b	
Mean nodule dry weight (mg/plant)	3.5a	16.9b	15.3b	18.1b	9.4ab	7.0a	

+ pelleted seed with CaCO[^] powder
not determined

means followed by the same letter (within given row) are not significantly different (P = 0.05) using sequential studentized range test.

tyl
^

TABLE 10s EFFECT OF LIMING ON SOME PROPERTIES⁺ OF THE THREE SOILS
USED IN THE POT STUDIES

	N.A.L. SOIL					
CaCO ₃ added (in me/100 g soil)	0.00	2.00	4.00	9.00	14.00	18.00
Soil pH	5.00	5.40	5.90	6.70	7.20	7.50
Exchange Acidity (me/100 g)	3.80	2.40	1.40	0.60	0.10	0.10
Residual Acidity (me/100 g)	5.10	5.00	5.40	5.40	5.50	5.60
Exchangeable Aluminum (me/100 g)	0.60	0.10	0.04	0.00	0.00	0.00
Exchangeable Manganese(me/100 g)	0.13	0.02	0.00	0.00	0.00	0.00
	MARIENE SOIL					
CaCO ₃ added (in me/100 g soil)	0.00	4.00	7.00	11.00	14.00	18.00
Soil pH	4.20	4.40	5.20	5.70	6.00	6.40
Exchange Acidity (me/100 g)	5.80	4.70	4.00	3.20	1.60	1.00
Residual Acidity (me/100 g)	8.10	7.00	7.80	8.00	8.20	8.50
Exchangeable Aluminum (me/100 g)	3.20	0.80	0.40	0.02	0.01	0.00
Exchangeable Manganese(me/100 g)	0.67	0.14	0.06	0.00	0.00	0.00
	CITUAMBA SOIL					
CaCO ₃ added (in me/100 g soil)	0.00	6.00	9.00	14.00	22.00	
Soil pH	4.50	5.10	5.50	5.80	6.50	
Exchange Acidity (me/100 g)	7.80	2.40	1.60	0.60	0.01	
Residual Acidity (me/100 g)	15.20	14.20	15.20	16.20	17.40	
Exchangeable Aluminum (me/100 g)	2.60	0.20	0.01	0.00	0.00	
Exchangeable Manganese (me/100 g)	0.24	0.94	0.84	0.40	0.00	

⁺ equilibration period with CaCO₃ was 3V months in laboratory.

ficantly increased with increase in pH up to a certain level and then decreased at higher pH levels. The nodule weight in NAL and Mariene soils increased significantly up to pH 5.9 and 5.7, respectively, and then decreased beyond these pH levels. In Gituamba soil the increase in nodule weight was up to pH 5.5 and then decreased beyond this level. In all the three soils pelleting of inoculated seed, where no lime was applied, generally increased nodulation in beans. In Gituamba soil there was nearly a six-fold increase in nodule dry weight as a result of seed pelleting. Manganese levels were low in this soil at lowest pH levels and it is probable that seed pelleting might have reduced soil exchangeable aluminium around the seedling to sub-toxic levels, hence the increase in nodule production in this soil. The response of beans to lime with respect to nodule weight in this study was similar to that reported by other workers (Hoyt and Nyborg, 1972; McLean et al., 1972) that liming acid soils to pH 5.2 to 5.3 eliminated or greatly reduced soluble aluminium resulting in increased nodulation. Munns (1970) has also shown that at pH 5.2 or greater alfalfa was well nodulated provided adequate calcium levels and rhizobium population were maintained. Date (1970) indicated that the optimum soil pH for rhizobium survival and adequate nodule population was about 6.0

and that in soils below pH 6.0 there was poor survival, and hence poor nodule production.

Soil analysis (Table 10) indicated that soil exchangeable aluminium was essentially zero and manganese levels were low, except in Gituamba soil where exchangeable manganese were still high (but below 1.0 me/100g soil), at pH 5.9, 5.7 and 5.5 in NAL, Mariene and Gituamba soils, respectively. At these pH levels in the three soils maximum nodulation was obtained and rates of CaCO_3 added to the soils were above the exchange acidity. These observations are similar to those of Mehlich (1976) that lime rates in excess of exchange acidity are required in mineral acid soils for maximum crop production.

The results of mean dry matter yield of beans and maize (Table 9) also show that increase in pH increased dry matter yield of beans and maize in all the three soils up to a certain pH level and then decreased as pH increased beyond this level. In case of beans the optimum pH levels, where the highest dry matter yield was obtained in NAL, Mariene and Gituamba soils, were 5.9, 5.7 and 5.8, respectively. Optimum pH levels, where the highest dry matter yield of maize was obtained in NAL, Mariene and Gituamba soils, were 5.9, 5.7 and 5.8, respectively. In all the three soils the increase in dry matter yield of beans and maize over the control (no lime) was highly significant ($P = 0.01$). The

response of beans to lime in all the three soils was generally higher than that of maize indicating that beans are more sensitive to soil acidity and aluminium and/or manganese toxicity than maize. On the other hand, maize takes longer than beans to mature and since these two crops were allowed the same growing period (up to when 50% of beans had flowered), the effects of liming might have been more pronounced at later stages of growth.

Soil analysis (Table 10) indicated that soil exchangeable aluminium and manganese were essentially zero at pH 5.9, 5.7 and 5.8 in NAL, Mariene and Gituamba soils, respectively. At these pH levels in the three soils the highest dry matter yield of beans and maize was obtained and rates of CaCO_3 added to the soils were above the exchange acidity.

The results obtained from this study were similar to those reported for a green house study by de Freitas and Pratt (1969) with latosols and four red-yellow podosols of Sao Paulo. They found that the dry matter yield of alfalfa was increased in most soils up to pH 7.0. They established optima of pH 6.1 for Phaseolus, and 6.4 for Stylosanthes and alfalfa. With application of ~~YWTW-WS~~ these to two of the limed soils they observed manganese toxicity at low pH levels. As a result they concluded that tropical legumes were intolerant of manganese toxicity. Kamprath (1972) also cites work in South

America (Sao Paulo, Brazil) where a latosol with 58% exchangeable aluminium saturation at pH 4.6 gave an increase of 952 kg dry beans/ha at a reaction of pH 5.4. Studies with similar soils of Brazil ("Campo Cerrados") by McClung et al. (1957) and by Mikkelsen et al. (1963) with one lime application to pH 6.0, showed soyabeans response to lime to vary with fertility, yields increasing significantly where lime, P and K were applied together. In another study carried out by Mongi(1974) in Tanzania it was found that previous lime applications were associated with highly significant yield increases in navy beans: yield increased linearly and was highly significant up to 10.0 tons lime level/ha but decreased sharply with lime increase to 12.5 tons/ha.

The significant increase in dry matter yield of beans and maize, and nodule production in the three soils referred to in this study was directly related to an increase in soil pH, a result in changes in soil acidity components. Arnon et al. (1942), and Albrecht and Smith (1952) regarded pH, per se, as an unimportant factor in the range usually encountered in soils. Under these circumstances, lime benefits were mainly a function of decreasing the toxicity of aluminium and/or manganese, increasing availability and uptake of native and

applied phosphate, and increasing nitrogen fixation owing to increase in the availability of molybdenum, and population and activity of nitrogen fixing bacteria in the soil. In this study a reduction of exchangeable aluminium and/or manganese to non-toxic levels as a result of liming could have taken an upper hand in the increase of dry matter yield of beans and maize, and nodule production and nitrogen fixation in beans.

It is also worthwhile to note that the increase in dry matter yield of beans and maize, and nodule production with lime was up to certain pH levels, and then there was a decrease beyond these pH levels. It is probable that at high lime levels there was a nutrient imbalance as a result of excess C-i^{2+} ions from the lime added to the soil. Saturating cation exchange sites in the soil with Ca^{2+} ions from the lime added to the soil is likely to render other nutrients such as magnesium and potassium deficient. When the proportion of magnesium and calcium was varied experimentally by Vlamis (1949) and Walker et al. (1955), it was found that common plants not specifically adapted to serpentine-deprived soils (soils characteristically high in magnesium) did not respond to calcium above a degree of saturation of 20 to 25% an indication that nutrients need to be kept in balance in order to promote healthy

growth in plants. In this study yields started to decline in NAL, Mariene and Gituamba soils when calcium was 47.6, 54.9 and 43.8% of the cation exchange capacity, respectively. At the highest lime levels, calcium was 85.7, 78.8 and 71.8% of cation exchange capacity in NAL, Mariene and Gituamba soils, respectively. These proportions of calcium to cation exchange capacity in all the three soils were very high and they might have affected the yields of beans and maize in this study considerably. Induced deficiencies of available iron, copper or zinc coupled with interference in the uptake and utilization of boron by plants are also likely to have been caused by the excess lime.

In view of these results, therefore, it would be advantageous not only to know the conditions of soils but also to understand the influence of lime on the crop to be grown. The application of lime in amounts more than necessary for optimum growth of a particular crop may not only lead to reduced production but also to the waste of the farmers' money.

S U M M A R Y A N D C O N C L U S I O N

CHAPTER V

SUMMARY AND CONCLUSIONS

Four buffer methods were evaluated using Ca(OH)_2 -titration to pH 6.5 and CaCO_3 -incubation to pH 6.0 and 5.5 as reference methods through regression analysis and using 26 soils representing the major agricultural acid soils in Kenya. The four buffer methods selected were Shoemaker - McLean - Pratt single buffer (SMP-SB), Shoemaker - McLean - Pratt double buffer (SMP-DB), Mehlich I (for crops with high lime requirements) and Mehlich II (for crops with low lime requirements). Exchange acidity (Ace) residual acidity (Acr) and total acidity (Act) were also correlated with lime requirements measured by the above methods to raise soil pH to 6.5, 6.0 and 5.5. The effect of lime on the nodulation of beans and growth of maize and beans was also studied in the greenhouse using three selected soils.

The results based on regression analysis indicated that lime requirement values measured by the reference methods (Ca(OH)_2 -titration to pH 6.5 and CaCO_3 -incubation to pH 6.0 and 5.5) were well correlated with the values measured by the four buffer methods. The lime requirements to the three pH targets (6.5, 6.0 and 5.5) measured by the buffer methods were also well correlated with amounts of exchangeable aluminium, exchange acidity, residual

acidity, total acidity and organic carbon. The SMP-DB method, however gave the highest correlation coefficient values with the reference methods, the least variation from the ideal line for all the three pH targets, and was particularly impressive at the lowest target pH (5.5). The sensitivity of the SMP-DB and SMP-SB methods for soils of high and low lime requirements for the three pH targets was comparable, while lime requirement values measured by Mehlich methods indicated that these methods were only sensitive for soils of low and intermediate lime requirements but not sensitive enough for soils of high lime requirements.

All the soil acidity components were well correlated with lime requirements measured by the buffer methods and reference methods to raise soil pH to 6.5, 6.0 and 5.5. The correlation coefficients between total acidity and measured lime requirements for all three pH targets were the highest, followed by those of exchange acidity and then those of the residual acidity. Not any one of the buffer methods gave a significantly high correlation coefficient for each of the acidity components than the other methods for all the three pH targets. There was an improvement in correlation coefficient values when a multiple regression using exchange acidity and residual acidity was used over simple

regression using exchange acidity, residual acidity or total acidity alone. These results indicate that the methods used estimated the acidity components equally well and that it was better to consider all acidity components rather than taking them singly.

In the greenhouse experiment the highest dry matter yield of maize and beans was obtained at pH 5.9, 5.7, 5.8 in NAL, Mariene and Gituamba soils, respectively, while the highest nodulation of beans was obtained at pH 5.9, 5.7 and 5.5 in NAL, Mariene and Gituamba soils, respectively. The dry matter yield of beans and maize and nodule production in beans started to decline at pH levels beyond these. At all these levels in the three soils, exchangeable aluminium and manganese levels were essentially zero.

In view of these results, therefore, it was concluded that liming of these soils to achieve pH 5.5 to 6.0 would be ideal. Within this pH range most of the exchangeable aluminium and manganese is reduced to zero. In case of NAL soil which was low in exchangeable aluminium and manganese, there was a positive response of beans and maize to lime: the dry matter yield of maize and beans, and nodulation of beans increasing significantly up to about 9.0 me/100g soil lime level. This positive response to lime in such soils, therefore, indicates

that exchangeable aluminium and/or manganese should not be taken as the only criterion for liming of these soils. There are indications that overliming of soils to high pH levels is likely to cause a nutrient imbalance resulting in a decline in yields. Hence, there is a need to estimate lime requirements of these soils to avoid adding too little or too much lime.

Although SMP-buffers were equally sensitive for soils of high and low lime requirements, the SMP-DB gave higher correlation coefficients with reference methods and least variations from the ideal lines, and was particularly impressive at the lowest pH target (5.5). The SMP-DB method has an added advantage over the SMP-SB method because it does not require established tables, hence any pH target can be selected. The green house results indicate that liming these soils to a pH between 5.5 to 6.0 would be sufficient. From these results the SMP-DB method appears to be the best choice as a method of estimating lime requirements of Kenya acid soils, followed by the SMP-SB method.

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