ASSESSMENT OF LONG-TERM IMPACTS OF ORGANIC AND INORGANIC FERTILISERS ON SOIL EXTRACTABLE PHOSPHORUS AND CARBON IN MACHANG'A, MBEERE DISTRICT, KENYA

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November, 2005
DECLARATION

I, Salome Muriuki hereby declare that this thesis is my original work and has not been presented for a degree in any other University.

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This work is specially dedicated to my beloved parents Julius and Virginia, brothers Sammy and Reuben, sisters Patraycheers, Mercyline and Emily, my niece Rauleen and to my late brother George.
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TABLE OF CONTENTS

DECLARATION ................................................................................................................... ii
DEDICATION ..................................................................................................................... iii
ACKNOWLEDGEMENT ................................................................................................... iv
TABLE OF CONTENTS .................................................................................................. v
LIST OF TABLES ............................................................................................................... vii
LIST OF FIGURES .......................................................................................................... viii
ABREVIATIONS AND ACRONYMS ............................................................................... ix
ABSTRACT ...................................................................................................................... xi

INTRODUCTION .............................................................................................................. 1
  1.1 Background information ......................................................................................... 1
  1.2 Statement of the problem ....................................................................................... 3
  1.5 Justification ........................................................................................................... 5
  1.4 Research Hypotheses .............................................................................................. 6
  1.6 Research Objectives ............................................................................................... 6

LITERATURE REVIEW .................................................................................................. 7
  2.1 Soil fertility management in semi-arid areas ........................................................ 7
  2.2 Role of phosphorus in plant nutrition ................................................................. 8
  2.3 Forms of P in soil .................................................................................................. 10
  2.4 Sequential phosphorus pools ............................................................................. 10
  2.5 Combining inorganic and organic phosphorus inputs ........................................ 11
  2.6 Phosphorus sorption-desorption process ............................................................ 11
  2.7 Use of farmyard manure ..................................................................................... 12
  2.8 Residual effects .................................................................................................... 14
  2.9 Near infrared spectroscopy in soil quality assessment ....................................... 14
  2.9.1 Soil chromophores and reflectance spectra .................................................. 15
  2.9.2 Physical mechanism of photon absorption in soil minerals ......................... 16
  2.8.3 Quantitative soil spectroscopy ....................................................................... 17
  2.8.4 Calibrations ..................................................................................................... 18
  2.9 Knowledge gap ..................................................................................................... 19

METHODOLOGY .............................................................................................................. 20
  3.1 Study area description ......................................................................................... 20
  3.2 Experimental layout ............................................................................................. 21
  3.3 Soil sampling ......................................................................................................... 22
  3.4 Analytical methods ............................................................................................... 23
  3.4.1 Olsen P and organic carbon .......................................................................... 23
  3.4.2 Determination of soil phosphorus fractions .................................................. 23
  3.4.2.1 Conversion of soil measurement units ..................................................... 24
  3.5 Statistical analysis of soil chemical data .............................................................. 25
  3.6 Diffuse Reflectance Spectroscopy ....................................................................... 25
  3.6.1 Sample preparation and reflectance measurement ......................................... 25
  3.6.2 Processing of the raw spectral reflectance ..................................................... 26
RESULTS AND DISCUSSION ................................................................. 29
4.1 Treatment effects on soil extractable phosphorus .................. 29
4.2 Treatment effects on soil organic carbon ................................. 38
4.3 Treatment effects on soil phosphorus fractions ........................ 45
4.4 Diffuse reflectance spectroscopy analysis ................................. 53
4.4.1 Treatment reflectance spectra ................................................. 53
4.4.2 Principal component analysis for the spectral data ................. 56
4.4.3 Discriminant PLSR analysis of the spectral data .................. 61
4.4.4 Partial least squares regression analysis ............................... 65
4.4.4.1 Prediction of soil organic carbon ...................................... 65
4.4.4.2 Prediction of soil extractable P. ...................................... 72

CONCLUSION AND RECOMMENDATIONS ........................................ 74
5.1 Key findings and Conclusion ................................................... 74
5.2 Recommendations ................................................................. 77
5.3 Further research ................................................................. 78

REFERENCES .................................................................................... 79
APPENDICES .................................................................................... 91
LIST OF TABLES

Table 1. Manure experiment field treatments to test the effects of manure and P fertilizers on extractable P and SOC in Machang’a, Mbeere district ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ......
LIST OF FIGURES

Figure 1. Experiment 2 soil extractable phosphorus treatment means obtained from Machang’a over a period of 9 years .......................................................... 35

Figure 2a. Near infrared spectral reflectance averages for the different treatments illustrating variation in reflectance across the treatments over a period of ten years in Machang’a Mbeere district ...................................................... 54

Figure 2b. Derivative smoothing of data enhanced the visualization of the soil spectra and showed more clearly the significant wavebands as compared to the raw spectral data ................................................................. 55

Figure 3. Scatter plot showing spectral PC1 and PC2 scores for the different treatments ................................................................. 58

Figure 4. Plot showing the amount of explained variance in the spectral data for the different treatments collected from Machang’a over a period of 10 years ................................................................. 59

Figure 5. Loading plot showing the most significant wavebands in screening out differences among the treatments spectral values ................................................................. 59

Figure 6. Discriminant partial least squares regression calibration model showing the distribution of the measured versus predicted spectral scores for the M0, M1 and F samples collected from Machang’a, Mbeere district over a duration of 10 year ................................................................. 62

Figure 7. Discriminant partial least squares regression analysis plot showing the distribution of scores along PC1 and PC2 bioplot for the treatment samples obtained collected from Machang’a, Mbeere district from 1993 – 2002 ................................................................. 64

Figure 8. Scatter plot showing measured versus near infrared predicted organic carbon for the treatments; M0, M1 and M2 collected from Machang’a, Mbeere district from 1993-2002 ................................................................. 67

Figure 9. Scatter plot showing measured versus predicted organic carbon. Carbon validation model optimized and improved by jack-knifing and removal of outlying samples ................................................................. 68

Figure 10. Calibrated measured versus predicted % OC for the treatments control M1 and R1 obtained from Machang’a during the first three years of testing the residual value of manure ................................................................. 70

Figure 11. Measured versus predicted % OC for the treatments control, M1 and R1 obtained from Machang’a during the last three years of testing the residual value of manure ................................................................. 71
ABREVIATIONS AND ACRONYMS

ANOVA          Analysis of Variance
Ca             Calcium
C1             Cultivation with retention of crop residues
C2             Cultivation with addition of extra crop residues
C3             Cultivation with removal of crop residues
C1P            Cultivation with retention of crop residues plus inorganic fertilisers
C2P            Cultivation with addition of extra crop residues plus inorganic fertilisers
C3P            Cultivation with removal of crop residues plus inorganic fertilisers
C: P           Carbon to phosphorus ratio
CEC            Cation exchange capacity
CH₄            Methane
DAREP          Drylands applied research extension project
DPLSRA         Discriminant partial least squares regression analysis
DA             Discriminant analysis
F2             Bare fallow with regular hand tilling
F2P            Bare fallow with regular hand tilling plus inorganic fertiliser
FYM            Farm yard manure
HCL            Hydrochloric acid
K₂S₂O₃         Potassium disulphate
KARI           Kenya agricultural research institute
M0             No external input (control)
M1             Continuous manure at 10 t/ha/yr
M2             Continuous manure at 5 t/ha/yr
NaOH           Sodium hydroxide
NaHCO₃         Sodium hydrogen carbonate
N               Nitrogen
NIR             Near Infrared
NIRS           Near Infrared spectroscopy
OC             Organic carbon
OH             Hydroxyl ions
P               Phosphorus
PCA            Principle component analysis
PLSRA          Partial least squares regression analysis
PLSR           Partial Least Squares regression
R1             Residue manure at 10 t/ha/yr
R2             Residue manure at 5 t/ha/yr
r²             Correlation coefficient
RMSE           Root mean square error
SOM            Soil organic matter
SOC            Soil organic carbon
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWNIR</td>
<td>Shortwave Infrared</td>
</tr>
<tr>
<td>TSP</td>
<td>Triple superphosphate</td>
</tr>
<tr>
<td>UoR</td>
<td>University of Reading</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>USA</td>
<td>United States of America</td>
</tr>
<tr>
<td>VNIR</td>
<td>Visible near infrared</td>
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ABSTRACT

Decline in crop yields is a major problem facing smallholder farmers in semi-arid Kenya and the entire Sub-Saharan region. Soil organic matter is rapidly declining and phosphorus (P) and nitrogen (N) deficiencies are important constraint to food production in semi-arid areas. Inorganic fertilisers are unaffordable to most smallholder farmers at current producer prices, limiting their use on farms. While N can be replenished through biological fixation, there is no equivalent process for the introduction of P in soils. Consequently, phosphorus deficiency has become a major constraint to food production. To try to solve this problem, two long-term field experiments were established at Machang’a site to assess long-term effects of manure and inorganic P fertilisers on soil extractable P and organic carbon (OC). The first experiment began in 1989 and treatments were; control, continuous manure at 5 and 10 t/ha/yr, residual manure at the same rates and NP fertiliser at 51 and 12 kg/ha/yr respectively. This trial had 14 years of annual manure application. The second experiment began in 1994 and was planned to supplement the first experiment by giving information on the effects of a one time application of 250 kg/ha TSP on long-term P availability. Diffuse reflectance spectroscopy was used for rapid assessment of soil quality. While common wet laboratory methods for soil nutrient analysis are laborious, time consuming and costly, diffuse reflectance spectroscopy method was explored as an alternative analytical method. Since the current study was part of an on-going project, data accumulated from the project was used for purposes of current study. Soil sampling began in 1993 and samples analysed for OC and extractable phosphorus. Sub-samples of these soils were scanned using reflectance spectroscopy. Samples collected in year 2002 were analysed for sequential P fractions using a modified Hedley’s method. Laboratory data was analysed for variation by Genstat (1995), while the near infrared (NIR) spectral data was analysed using multivariate exploratory statistics. Partial least squares regression, principle component analysis and discriminant analysis were used to develop predictive calibration models. Results indicated that repeated manure application at 10t/ha/yr significantly increased the level of plant available P and maintained high OC. Residual manure did not have profound effects on P and OC compared with continuous manure. Though inorganic fertilisers raised the level of bioavialable P fractions, they had negligible influence on OC. The residual value of a one time application of 250 kg/ha TSP was observed to maintain high soil P-test values for close to 10 years. Robust near infrared calibration models developed, well predicted the level of OC by the various treatments. However, poor calibrations were obtained for soil extractable P. It is not expected that NIR spectroscopy will replace the nutrients analysis used in convention soil fertility assessment. However, infrared methods have the potential to rapidly and non-destructively predict soil quality changes caused by various management regimes, thus adding considerable value to soil analysis. The method is also economically attractive due to the low costs associated with it.
INTRODUCTION

1.1 Background information

Semi-subsistence farming in small landholdings is the principle livelihood for the majority of rural people in Sub-Saharan Africa. This economic activity is to a large extent hindered by soil fertility depletion, which is a fundamental biophysical constraint to crop production (Smaling, 1993; Mukwonye et al., 1996; Sanchez et al., 1997). While per capita food production is increasing for other parts of the developing world, it continues to decrease for Africa (World Bank, 1996, cited in Sanchez, 1997). In the semi arid areas, over 50% of the human population lives below the poverty line and has no guarantee of household food security due to harsh environmental conditions and the poverty trap of soil nutrient depletion.

Of Kenya’s total land area of 582,646 km², semi arid lands occupy approximately 78%, and are a sanctuary for 25% of the human population, 40% of livestock population and 50% of the wildlife population (Government of Kenya, 1992). Population pressure in these semi-arid lands has increased to such an extent that there is little possibility of increasing agricultural production by expanding the amount of land under cultivation without impacting on marginal areas. Most of the suitable land has already been put into production and the only option that is left is to increase yields on the existing cultivated fields to avoid environmental degradation expanding into marginal land. Although rainfall is limited, the biggest obstacle that the farmers face is the low and often decreasing soil fertility (Van der pol, 1992; Keulen van and Breman, 1990). Several studies have emphasized the role of soil organic matter
in maintaining soil fertility (Woomer et al., 1994). SOM plays a key role in nutrient retention and availability, soil structure maintenance and the soil water regime. Enhancement of soil productivity through SOM is therefore essential for sustained agricultural production system especially in semi-arid areas where farmers cultivate low potential sandy soils that are naturally infertile (Sanders et al., 1996). However, the intensification of agriculture in small landholdings has typically not been accompanied by sufficient input of nutrients to match the output through harvested products and other losses. The result has been widespread mining of nutrients and depletion of soil fertility (Smaling et al., 1997). Nonetheless, application of organic matter to the soil in form of plant litter, crop residues and livestock manure can lead to soil organic matter maintenance.

In semi-arid Eastern Kenya, nitrogen and phosphorus are the major soil nutrients constraints to food production. Soils in this region are deficient in available P (Sanchez et al., 1997; Deckers, 1993). This deficiency has often led to low crop yields, food insufficiency, malnutrition and absolute poverty (Sanchez, 1997). While N can be introduced to the soil through biological fixation, there is no equivalent process for the introduction of P into the farming system (Buresh et al., 1997). Consequently, P deficiency becomes a fundamental constraint that must be overcome if agricultural production is to be sustained (Bekunda et al., 1997; Bationo et al., 1996). Thus, there is an indisputable need to correct deficiency of soil P using resources available to farmers (Mukwonye et al., 1996; Smaling et al., 1997). However, to scale up research, results are needed for rapid quantitative assessment and monitoring of soil quality. Standard procedures for measuring soil properties are
complex, costly, time consuming and laborious (Duran et al., 2002) and hence present
difficulties for soil fertility monitoring. Furthermore, chemical procedures used in the
characterization of soils often complicate the interpretation as the extraction
procedures may change the soil equilibrium. There is thus the need for development
of techniques that give soil analytical information, while at the same time preserving
the basic integrity of the soil system as observed by Janik et al. (1998). Diffuse
reflectance spectroscopy is a non-destructive rapid analytical technique for studying
interactions between incident light and a materials surface (Batten, 1998). The
technique has been applied to the analysis of African soils and has been shown to be
able to detect changes in soil quality (Shepherd and Walsh, 2002). It is now widely
used in industries due to its simplicity, rapidity and the need for little or no sample
preparation.

1.2 Statement of the problem

The continuing supply of plant nutrients by soils is an essential part of long-term
sustainability of crop production. In semi-arid Machang’a, Mbeere District, SOM is
rapidly declining and farmers regard low soil fertility as a major constraint to food
production and therefore a priority for research (Micheni et al., 1999). Phosphorus
deficiency is particularly a major constraint and this is due to the low native P
reserves in the soils (Sanchez et al., 1997; Deckers, 1993) which is further
compounded by long-term P exports from the soils in crop harvests and crop residue
removal (Fairhurst et al., 1999). Moreover, the traditional shifting cultivation that
used to naturally restore soil fertility has been replaced by continuous cultivation due
to the increasing human population (Imbernon, 1999). Phosphorus is now a limiting
nutrient in the areas’ sandy-loamy soils. Replenishing P stocks requires the use of phosphorus fertilizers (Breman, 1990; McIntire and Powel, 1995). However, most smallholder farmers in the area are poor and lack the financial capacity to purchase sufficient fertilizers. Hence the use of mineral fertilizers on the farms is constrained and the end result has been the continued decline of soil P, loss of soil fertility and the resulting degradation of soil resources. Moreover, this problem has not been adequately addressed quantitatively due to lack of easily measurable soil attributes that reflect the capacity of the soil to perform environmental functions, and lack of reliable monitoring tools. Current conventional laboratory methods for soil analysis are costly, time consuming and laborious (Duran et al., 2002) and require large number of samples to characterize soils. This has led to difficulties and inefficiencies in soil fertility monitoring and consequently the decline in soil nutrients, crop production, food insufficiency, malnutrition, and absolute poverty in the region.

There is thus an indisputable need to correct P deficiency using resources available to the farmers (Mukwonye et al., 1996; Smaling et al., 1997), and the development of a technique that can rapidly and non destructively detect soil quality changes caused by management regimes. The study therefore aims to evaluate the contribution of manure and inorganic P fertilizers on soil phosphorus availability and organic matter, and their place in improving crop production and secondly, to determine the accuracy of using diffuse reflectance spectroscopy for assessment of soil quality changes due to manure and fertilizer use.
1.5 Justification

Phosphorus occupies a key place among nutrients because of its relative scarcity and its essential role on all life on earth (Sanchez et al., 1997). An understanding of the effects of organic and inorganic phosphorus fertilisation on the soil fertility and how it influences plant growth is necessary for effective soil management. Moreover, most farmers in the semi-arid Africa are unfamiliar with fertilizers and therefore unable to judge their importance for sustainable agricultural production. Effects of management practices on soil productivity are best evaluated using long-term experiments (Rasmussen et al., 1998). This is because annual changes in soil carbon are small, and therefore continuous data is needed to detect soil quality changes. Soil carbon is unduly accepted as a key soil quality indicator. Scientific information is thus continuously needed to guide the use of phosphorus in order to obtain maximum benefits without producing undesirable impacts on the environment. This knowledge will enable better nutrient management for sustainable agricultural production and uplift the livelihood of the rural poor who solely depend on this economic activity.

A rapid and economical soil analytical technique is needed before farmers and land managers can be able to fully utilize soil testing as an aid in precision farming and management of soil quality. Duran et al. (2002) and Shepherd et al. (2003) has demonstrated that diffuse reflectance spectroscopy methods have practical advantages over conventional laboratory soil analysis techniques. The method is non-destructive, accurate, cheap and allows very rapid analysis of increased sampling densities to adequately characterize soils. Information on the use of this technique to characterise soil nutrients and their availability to crops is therefore needed.
1.4 Research Hypotheses

1. Continuous manure and inorganic fertilizer application to the soil is needed to increase and maintain levels of soil extractable P and organic carbon.

2. Long-term manure and inorganic fertilizer application provides high residual available phosphorus in the soil for a number of years.

3. Diffuse reflectance spectroscopy method is a relatively accurate analytical method and can detect subtle changes in soil properties caused by manure but not inorganic fertilizer application over short-term durations.

1.6 Research Objectives

The general objective of the study was to assess the long-term effects of organic and inorganic phosphorus fertilizers application on plant available phosphorus and organic carbon in the semi arid Kenya. To achieve this, the specific objectives were:

1 To assess the effects of manure and inorganic fertilizer use on soil extractable P and soil organic carbon.

2 To determine the residual available phosphorus created by long-term manure and inorganic fertilizer application.

3 To assess the accuracy of diffuse reflectance spectroscopy as an alternative analytical tool for rapid assessment of soil quality changes caused by long-term manure and fertilizer use.
2.1 Soil fertility management in semi-arid areas

Inherently infertile soils and low use of organic and mineral fertilizers are a major biophysical constraint to increasing agricultural productivity in farming systems in the semi-arid region of Africa (Yates and Kiss, 1992). Soils in the semi-arid areas are rapidly declining in fertility. The vagaries of weather, especially rainfall, are also important limitations to agricultural production in these semi-arid areas. Soil nutrient imbalances and deficiencies are common and the ability of the soil to supply nutrients is finite. The inherently infertile soils require external inputs of fertilizer material for sustained fertility and productivity, especially under continuous cropping. The risk involved with cropping due to the possible failure of the rains results in returns from fertilizer use being less than in high potential areas. The result is that fertilizers are less used and soils become progressively depleted in nutrients (Badiano and Delgado, 1995).

The often-sandy soils of these dry areas predispose the soil to reduced effectiveness because of their low water holding capacity, low organic matter content, and low nutrient retention capacity. These soils are typically low in available nitrogen and commonly deficient in phosphorus, sulphur, magnesium, and zinc (Mukwonye et al., 1996). The sandy and clay loams derived from granite are reported to have low potential for crop production under continuous cultivation (Kumwendwa et al., 1995). If not managed well, poor land cover results in poor soil structure, limited rooting depth, and susceptibility to accelerated erosion. Management has to focus on
supplying inputs from external sources to improve organic matter content and the capacity to retain nutrients and water. Efficient recycling of organic material such as crop residue and manure in combination with mineral fertilizers and use of rotations with legumes can significantly contribute to soil fertility replenishment and therefore increase crop production (Giller et al., 1997).

The soils in these semi-arid areas are variable and generally low in fertility. A major part is covered by well drained, shallow to very deep, dark reddish brown, loose to friable loamy sand to sandy clay loam, with varying degrees of rockiness and stoniness (Van de Mbuvi, 1975; Sombroek et al., 1992), classified by FAO/UNESCO (1977) as Ferralic, Arenosols, Orthic Ferrosols, Alfisols and Luvisols. Rainfall is low (500-1000 mm) and base leaching limited, hence soils have relatively high soil pH and base saturation (Ssali, 1986). Particularly, Alfisols have a fairly optimal pH (pH 6.0 to 6.5). However, acidity may rapidly increase with farmer’s cultural practices (Pieri, 1985). Reduction of traditional fallow systems due to population growth and intensive cropping, lead to nutrient losses by run-off, Ca\(^{2+}\) and Mg\(^{2+}\) losses and nitrate leaching, which all tend to induce acidification in low buffered soils. Considering P deficiency and soil resource degradation by farmers’ practices, organic amendments and inorganic fertilizers are alternatives that can be exploited to improve crop productivity in semi-arid Mbeere.

2.2 Role of phosphorus in plant nutrition

Phosphorus is an essential macro-nutrient in plant nutrition and occurs in most plants in concentration between 0.1 and 0.4 % as simple and complex organic compounds.
Its major physiological and metabolic roles in the plant include energy storage and transfer in the form of Adenosine di and tri-phosphate (ADP and ATP) as a constituent of co-enzymes, nucleic acids (RNA and DNA), phospholipids, phosphoproteins and sugar phosphates (Tisdale et al., 1993). P is involved in carrying genetic information and translating it for protein synthesis, in creating biological compartments separated by semi-permeable membranes and in providing a form of energy transfer for physiological metabolisms. Inorganic phosphate controls several enzymatic reactions in pollen, seeds and tubers. P deficiency reduces leaf area of a plant, retards root development and depresses growth.

Plants absorb P in the form of primary or secondary orthophosphates (H$_2$PO$_4^-$ and HPO$_4^{2-}$) depending on the soil pH in an active energy dependent process. A water film around soil particles is thus required for roots to take up this nutrient. P availability for most crops is optimal at the pH range of 6.0 to 6.5. At high pH (>7.5), P in the soil is converted into insoluble Ca phosphate compounds while at low pH (<5.5), P reacts with Al and Fe to form phosphate compounds (Bohn et al., 1979). The orthophosphate ions can be sorbed on surfaces in a rapid exothermic followed by a slow endothermic reaction or can be taken up by soil organisms and plants (Frossard et al., 2002). Due to the high reactivity of P with the solid phase, less than 0.1 % of the total soil P is usually found in the soil solution (Fardeau, 1996). From an agronomic perspective, the strong reduction in the formation of reproductive organs and general plant development under P deficiency makes adequate P supply to plants an important condition to achieve sufficient crop yields.
2.3 Forms of P in soil

Phosphorus occurs in inorganic and organic forms in soils. Apatite, the most common primary P mineral is dissolved in the presence of hydrogen ions. Orthophosphate in solution can precipitate with Ca, Al or Fe to subsequently form various secondary P minerals. Organic P is an important reservoir of soil P ranging from 20 – 80 % of total soil P (Dalal, 1977) but frequently in the range of 60 – 80 % in East African soils. All soil organic P is derived from organisms but due to selective stabilization of some forms of organic P, the composition of organic P differs between living cells and soils (Magid et al., 1996) and only a small fraction of organic P is labile in the short term. While the majority of P in growing organisms is in nucleic acids, monoesters often represent more than 50 % of the extractable inorganic P. Total organic P decreases with continuous cropping without P fertilization (Adetunji, 1994) and tends to increase with soil age. Total P is however low in sandy soils of the semi arid tropics. Decline in SOM as traditional rotational systems containing fallows are replaced by continuous cropping can lead to reduced supply of plant available P, and thus the need for external inputs of P.

2.4 Sequential phosphorus pools

The sequential extraction procedure estimates inorganic and organic P fractions in the soil. Increasingly harsher treatments are used to extract P pools that are believed to be increasingly less available to plants (Hedley et al., 1982). The resin extractable soil inorganic P fraction (resin P) is regarded as freely exchangeable P (Tiessen and Moir, 1993) and thus easily exchangeable to plants. The sodium bicarbonate extractable
pool is considered as labile and the NaOH extractable fraction is moderately labile, and therefore these are biologically important. The HCL fraction is considered as a relatively stable pool which might contribute to P availability in the long-term. Though soil P from other pools can enter the available P pool, resin P is normally used as an index of P availability. The sum and distribution of the P fractions from the sequential extraction reflects the quality of the different P sources.

2.5 Combining inorganic and organic phosphorus inputs

Plants absorb phosphate ions, which come into solution through the dissolution of P bearing weatherable minerals, P fertilisers, sorbed P and the mineralization of soil organic P. Many P depleted soils have pH value above 6.2 which is too high for dissolution of P. Combining mineral fertilisers and compost has been shown to increase the availability of rock phosphate (Lompo, 1993; Ikerra et al., 1994). However, little is known about the influence of organic materials on P solubilisation and sorption-desorption processes when organic materials are applied along with inorganic fertilisers (Palm et al., 1997). The integration of locally available organic resources with commercial P fertilisers may be the key to increasing and sustaining levels of P in smallholder farms.

2.6 Phosphorus sorption-desorption process

Organic materials have been shown to reduce the P sorption capacity of the soil and increase P availability. The magnitude and duration of the effect varies with the soil type, the quality of the organic material and the amounts added (Iyamuremye et al., 1996). In general, only materials with > 2.5 g P/kg have been shown to reduce the P
sorption capacity of the soil (Singh and Jones, 1976). Organic anions chelate with Fe and Al ions in solution, preventing the precipitation of phosphate and also reducing Al and Fe toxicity. They also compete with P for sorption sites and also solubilize P from the insoluble Ca, Fe and Al phosphates. Studies by Hue (1991) and Gachengo (1996) showed that complexation and competition are more important than replacing sorbed P or solubilizing native P.

2.7 Use of farmyard manure

Considerable research has been carried out on use of farmyard manure to maintain soil fertility in Africa. Besides addition of nutrients, manure increases the water holding and infiltration capacity, pH, and decrease bulk density of the soil (Azevedo and Stout, 1992). Increase in exchangeable cations as well as organic N and available P have been obtained on soils receiving large applications of manure (Olsen et al., 1990). Excess application of manure has been shown to cause environmental pollution in North Western Europe, USA and increasing South East Asia. For instance, large plain areas in China show enormous nutrient surplus that range from 200 to >1000 kg of N per ha per year (FAO, 1997b). Specialized livestock production systems emit large quantities of wastes, resulting to excessive loading of manure on limited land areas. The spreading of manure on land can lead to N leaching, contamination of surface waters and damage to the aquatic and wetland ecosystems. Moreover, emission of ammonia, CO₂, CH₄ and nitrous oxide from manure affects the global atmosphere by contributing to global warming. However, a study by Lekasi et al. (2001) pointed out that although livestock is an important production asset and a characteristic of a farming system in semi arid areas, only a few households owns
cattle. This implies shortage of manure use on farms, and therefore environmental pollution resulting from manure use is not much of a problem in semi-arid Kenya.

For most farmers in semi arid Kenya, manure is an important resource and the only affordable concentrated source of plant nutrients and can therefore be a remedy to the low soil organic matter. Organic P may account for up to 50% of the total P in animal manure (Richardson et al., 2000). This supplies plant nutrients either directly or indirectly by alleviating Al toxicity, thereby increasing P availability especially in high P fixing soils (Nziguheba et al., 1998). A study by Parham et al. (2002) indicates that manure P is more mobile than chemical fertilizer P in soils.

Little has been done to understand the importance of organic P in manure and its relationship to biological activities in soil over a long time. P accumulation has been reported in soils with repeated short-term (1-2 years) heavy application of animal manure (Carpenter et al., 1998; Reed et al., 1998), but it is not apparent following long-term manure application (Parham et al., 2002). A study by Reed et al. (1998) showed that a one time application of 164 kg P/ha solid beef manure resulted in consistently higher soil Olsen P levels and P uptake by corn plants, when compared with soils treated with chemical fertilizers (Ginting et al., 1998a). However, it is not apparent to what extent, manure P accumulates in long duration. The current study aims to assess the residual available phosphorus due to long-term manure and fertilizer use on the soil.
2.8 Residual effects

P sorption is an important process controlling P availability in soils (Lajtha and Harrison, 1995) and it is a major constraint to crop production. However, P sorption may be an asset rather than a liability. The residual effect of large phosphate applications is due to the desorption process. The process is controlled by clayey surfaces and is only important in the topsoil where P fertilisers are applied. A study carried out in Cerrado region of Brazil showed that the duration of residual effects increases with increasing rate of P application (Goedert, 1985). Low P sorbing soils have a shorter residual effect than high P sorbing soils. Replenishing strategies for high sorbing clayey soils of Eastern Africa should therefore differ from strategies for low sorbing sandy soils, where smaller and more frequent applications are required (Bationo et al., 1996).

2.9 Near infrared spectroscopy in soil quality assessment

Current methods for determining the amount of nutrients available to growing crops are costly and labour intensive. The use of remote sensing techniques could decrease the amount of labour and the cost of analysis. Near infrared reflectance spectroscopy technique is simple, non-destructive and reliable and relies only on direct collection of reflected light from an illuminated soil sample. Spectral signatures of materials are defined by their reflectance or absorbance as a function of wavelength in the electromagnetic spectrum. The signatures result from electronic transitions of atoms and vibrational stretching and bending of structural groups of atoms that form molecules or crystals. Fundamental features in reflectance spectra occur at energy levels that allow molecules to rise to higher vibrational states. For instance the
fundamental features related to various components of SOM generally occur in the mid to thermal infrared range (2.5 – 25 μm) but their overtones occur in the near infrared (0.7 – 1.0 μm) and short wave infrared (1.0 – 2.5μm) region.

Near infrared spectroscopy has shown promise as a rapid, non-destructive method for determining agricultural and food constituents (Davies and Cho, 2002; Burns and Cuirczak, 2001). The technique has been used for protein determination in forage and grain analysis (Shenk et al., 2001), in determination of total N, C, lignin, cellulose and acid detergent fibres of tree species (Joffrey et al., 1992; Meuret et al., 1993; McLennan et al., 1991). Studies by Reeves and Van Kessel (2000), Qafoku et al. (2001) and Malley (2002) demonstrated the capability of NIRS for analysis of livestock manure and compost quality for moisture, organic matter of solids, total and potentially mineralisable N. However, there is limited research investigating the potential of using infrared spectroscopy to detect P and other nutrient deficiencies (Millen et al., 1996). The study aims to assess more subtle changes in soil organic carbon and extractable P caused by manure and fertiliser use.

2.9.1 Soil chromophores and reflectance spectra

A given soil sample consists of a variety of chromophores, which vary with environmental conditions. Chromophores are parameters or substances (chemical or physical) that significantly affect the shape and nature of a soil spectrum. A soil reflectance spectrum is a set of data that provides the relative intensity of reflected radiation as a function of wavelength. The reflected intensity is expressed relative to the intensity of the illuminating radiation. Reflectance values are determined by
taking a ratio of the energy reflected by a bright diffuse reference material. Discrete absorption bands caused by chemical activity allow unique identification of many of the soil chromophores. The spectral response is also a product of interaction between these parameters and a precise understanding of all chemical and physical reactions in the soil. There are strong chemical interactions between these components and in most cases are non linear and rather complicated. For instance, organic components mostly humus affects soil clay minerals in chemical and physical ways. Similarly, free iron oxides coat soil particles and affect photons that either absorb or reflect light. Additionally the coating material may collate fine particles into course aggregates that may physically change the soil behavior. Spectral signals related to a given chromophore overlap with signals of other chromophores and thereby hinder the assessment of the effect of a given chromophore. Multivariate techniques are thus essential in analyzing the data.

2.9.2 Physical mechanism of photon absorption in soil minerals

Organic matter plays a major role with respect to many chemical and physical processes in the soil environment and has a strong influence on soil reflectance characteristics. The hydroxyl group (OH) is spectrally active in the visible near infrared (VNIR) and shortwave infrared (SWIR) (Hunt, 1979). The OH group is found either as part of the mineral structure or as part of a thin water molecule. Three major spectral regions active for the clay minerals are 1.3 to 1.4 μm, 1.8 to 1.9 μm and 2.2 to 2.5 μm (Hunt and Salisbury, 1970). The assigned positions can however change slightly from one structure to another depending on chemical composition and
surface activity. Humus plays an important role in many of the soil properties such as aggregation, soil fertility, soil water retention, ion formation and soil colour and hence soil reflectance. Specifically, organic matter has spectral activity throughout the entire VNIR to SWIR region. Numerous absorption features exist that relate to the high number of functional groups of the organic matter such as C-H and N-H. These can all be explained spectrally by combinational and vibrational modes of organic functional groups (Elvidge, 1990; Chen and Inbar, 1994). Aber et al. (1990) observed that the organic matter including its decomposition stage affects the reflectance properties of mineral soil.

2.8.3 Quantitative soil spectroscopy

Soil and soil spectra are rather complex phenomena. It is postulated that although the soil is a complex material and soil spectra may appear featureless, a remarkable amount of information is hidden in the reflected photons, which under controlled conditions can be retrieved (William and Norris, 2001). Soil spectra carry unique and important information about many of the soil properties and analysis of the spectrum can yield useful information about the chemical characteristics of the soil even though many of the channels are inter-correlated and the soil matrix is complex. Because of the unknown interactions between soil chromophores, it is difficult to assess the most appropriate wavelengths for explaining the composition of a given sample. Spectral pretreatment minimizes the irrelevant information in the spectra in order to be able to develop more simple and robust models, which may yield quantitative information about soils. Clark and Rush (1984) noted that there is a potential for quantitative conversion of a reflectance spectrum of a multi-mineral abundance using physical
models. Because this situation is not simply applied to a soil system where complex relationships exists between chromophores, empirical quantitative approaches are developed to derive chemical-physical information from the soil spectra data. Manipulation of spectra using derivative transformation enables enhancement of weak spectral features and minimizes physical effects (Demetriades-Shah, 1990). For instance, first derivative removes confounding offset variations whereas the second derivative removes confounding linear trends. Regression equations are used to establish mathematical relationships between NIR and the reference method. Factor analysis is commonly used to reduce the components of the spectral data and avoid problems associated with the high correlation in reflectance among wavebands.

2.8.4 Calibrations

Near infrared spectroscopy is an indirect analytical method since it is based on the development of empirical models in which the concentration of a constituent can be predicted from a complex spectra data. Information content of a sample's NIR spectrum is very high because it provides a concise but very rich summary of the overall biochemical composition (Foley et al., 1998). Spectroscopic methods have been used in conjunction with extensive laboratory based chemical analysis to calibrate empirical models for predicting the composition of a given sample (Curran, 1989). Basically NIR method assumes that the concentration of a given constituent is proportional to the linear combination of several absorption features. The method has two stages; the calibration and the validation stages.
2.9 Knowledge gap

Of the extensive work devoted to studying P behaviour and the fate of manure P in the soil, relatively little has been directed towards understanding manure P behaviour in soil under long-term manure application in semi arid lands. While the agronomic effectiveness of composted goat manure and inorganic fertiliser materials in the field in the short term is known, the residual effectiveness of these fertilisers in the long term remains unknown. Available information is conflicting about the long-term influences of inorganic fertilisers on soil quality and productive capacity (Doran et al., 1996). This justifies a need for research on long-term effects of inorganic fertiliser application on soil quality and productivity. Soil visible near infrared spectroscopy has been shown to be able to predict soil properties across a range of soils and detect large changes in soil properties due to management in the long-term NARL experiment. The current study aims to assess whether NIRS can detect more subtle changes due to manure and P fertiliser effects.
METHODOLOGY

3.1 Study area description

The study is part of an on-going project by KARI-Embu and the University of Reading, UK. The site is located in Machang’a site, Mavuria location, Mbeere District in Eastern Kenya on a concave slope averaging 5%. The area predominantly experiences a semi-arid climate with an average annual rainfall of 800 mm, which is biomodally distributed. The two rainy seasons are the April season that runs from March to July and the November season, falling from October to January. Mean annual temperature is 23°C while mean annual evaporation is about 1998 mm. The site lies at 0°47’S latitude and 37°40’E longitudes and at 1050 m above the sea level, approximately 200 km NE of Nairobi.

The trial site soil types are sandy clay loam containing 56.5 %, 12.7 % and 30.8 % sand, silt and clay respectively with a pH of 6.55 (1: 2.5 in water). They are classified as Chromic Cambisols (Kenya soil survey; personal communication) overlying granitoid gneiss (Van de Weg and Mbuvi, 1975). Soils are shallow and loose organic matter and nutrient rich aggregates within 3 to 5 seasons of cultivation with inadequate inputs and protection from water erosion. They are poorly structured and easily compacted and eroded and contain approximately 0.61% OC, 0.06% total N, 0.94 mg/kg extractable P and 331 mg/kg exchangeable K. The typical farm size is 1.6 ha and about 70 % of the farmers use manures (J.W. Irungu, personal communication). Farmers in this area practice continuous cultivation with no efforts to replenish the removed nutrients.
3.2 Experimental layout

Two long-term field experiments were established at Machang’a fourteen years ago and designed to test the effects of manure and P fertilizers on crop productivity. The first experiment (manure experiment) was initiated in 1989 and the design was a complete factorial of three cropping systems by three manure treatments (0, 5 and 10 ton/ha). Manure was applied annually in the month of October and the quality did not change throughout the experimentation period (the mean analysis for manure was; 31 %C; 2.03 %N; 0.47 %P; 2.75 %K). Net plots measured 5.0 by 5.0 metres. Field treatments for the manure experiment were as indicated in Table 1. Treatments M0, M1 and M2 were maintained throughout from 1989 to 2002 while treatments R1 and R2 assessed the residual effects after a final manure application in 1992 (i.e. after four years of application). All treatments were replicated thrice and randomised within blocks. Planting of crops was done at the onset of rains.

Table 1. Manure experiment field treatments to test the effects of manure and P fertilizers on extractable P and SOC in Machang’a, Mbeere district, Kenya

<table>
<thead>
<tr>
<th>Field code</th>
<th>Treatment/Application</th>
<th>Cropping sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM0</td>
<td>Control</td>
<td>Intercrops</td>
</tr>
<tr>
<td>CM2</td>
<td>Continuous manure at 5 t/ha/yr</td>
<td>Intercrops</td>
</tr>
<tr>
<td>CM1</td>
<td>Continuous manure at 10 t/ha/yr</td>
<td>Intercrops</td>
</tr>
<tr>
<td>CF</td>
<td>51 kg N &amp; 12 kg P every October from 1993</td>
<td>Intercrops</td>
</tr>
<tr>
<td>CR2</td>
<td>Residual manure at 5 t/ha/yr</td>
<td>Intercrops</td>
</tr>
<tr>
<td>CR1</td>
<td>Residual manure at 10 t/ha/yr</td>
<td>Intercrops</td>
</tr>
<tr>
<td>CM0</td>
<td>No external inputs (control)</td>
<td>Sole crops in rotation</td>
</tr>
<tr>
<td>CM2</td>
<td>Continuous manure at 5 t/ha/yr</td>
<td>Sole crops in rotation</td>
</tr>
<tr>
<td>CM1</td>
<td>Continuous manure at 10 t/ha/yr</td>
<td>Sole crops in rotation</td>
</tr>
</tbody>
</table>
The second experiment (fertilizer experiment) began in 1994 and was planned to supplement the first experiment by giving information of the effects of a one time triple superphosphate (TSP) recapitalization. Field treatments are summarized in Table 2. All treatments were replicated thrice and randomised within blocks.

Table 2. Fertilizer experiment field treatments to test the effects of one time application of inorganic P fertilizers on extractable P and SOC in Machang’a Kenya

<table>
<thead>
<tr>
<th>Field code</th>
<th>Fertilizer application</th>
<th>Cropping</th>
<th>Residue management</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>No</td>
<td>Sorghum</td>
<td>Residues retained on plot</td>
</tr>
<tr>
<td>C1P</td>
<td>Yes</td>
<td>Sorghum</td>
<td>Residues retained on plot</td>
</tr>
<tr>
<td>C2</td>
<td>No</td>
<td>Sorghum</td>
<td>Extra residues from C3 in same block</td>
</tr>
<tr>
<td>C2P</td>
<td>Yes</td>
<td>Sorghum</td>
<td>Extra residues from C3P in same block</td>
</tr>
<tr>
<td>C3</td>
<td>No</td>
<td>Sorghum</td>
<td>Residues removed to C2 in same block</td>
</tr>
<tr>
<td>C3P</td>
<td>Yes</td>
<td>Sorghum</td>
<td>Residues removed to C2P in same block</td>
</tr>
<tr>
<td>F2</td>
<td>No</td>
<td>Bare fallow</td>
<td>Regular hand tilled</td>
</tr>
<tr>
<td>F2P</td>
<td>Yes</td>
<td>Bare fallow</td>
<td>Regular hand tilled</td>
</tr>
</tbody>
</table>

Where applied, triple superphosphate fertilizer was broadcast at 250 kg P/ha in March 1994 only

3.3 Soil sampling

Regular soil sampling commenced in 1993 to 2002 at 0-20 cm. Sampling was done either in February or September before cultivation and incorporation of residues and manure as described by Warren et al. (1997). Three sampling pits per plot were dug at 30 x 30 x 20 cm within steel frames driven into the soil, soils mixed and sieved (10 mm mesh) to remove stones. A composite sample was then taken, air dried, transported from site and archived at KARI-Embu and some at the University of Reading awaiting laboratory chemical and spectral analysis. Baseline soil sampling was however not done at the start of the experiment in each plot. This prevented a
rigorous before-after impact analysis, and the assumption had to be made that all plots had the same level of initial fertility and SOC content.

3.4 Analytical methods

3.4.1 Olsen P and organic carbon

Since the study is part of an on-going study, Olsen P and organic C data was already available for the current study. Soil samples were dried and crushed to pass through a 2 mm sieve. Extractable phosphorus was measured by the Olsen method (0.5 M NaHCO₃) at a pH of 8.5 as recommended by TSBF (Okalebo et al., 1993). Organic carbon was measured colorimetrically after fine grinding the soil and digesting it in H₂SO₄/H₃PO₄/K₂CrO₇ solution (Anderson and Ingram, 1995).

3.4.2 Determination of soil phosphorus fractions

A modified Hedley's fractionation scheme described by Tiessen and Moir (1993) and Agbenin and Tiessen (1994) was adopted. This fractionation technique uses a series of extractants to identify labile inorganic (Pi) and organic (Po) fractions followed by the more stable forms. The freely exchangeable fraction was extracted using anion exchange resin in the chloride form and NaHCO₃ (0.5 M, pH 8.5). The moderately labile pool was extracted with 0.1 M NaOH whereas 1 M HCl was used to remove the more recalcitrant Ca-bound P portion. In brief, 0.5g of air dried soil was placed in 50 ml centrifuge tube and sequentially extracted by each of the following extractants: HCO₃-exchange resin, 0.5 NaHCO₃ (pH 8.5), 0.1 M NaOH and 1 M HCl after shaking for 16 hours on a flatbed shaker at 175 rpm and centrifuging at 7000 rpm. The supernatant was filtered into 50 ml bottles through Whatman No. 5 filter paper
and used for subsequent P determination. Resin P sorbed onto the resin bags was recovered using 20 ml of 0.5 M HCl. 2 ml of the NaHCO₃ and NaOH extracts were oxidized using potassium persulfate (K₂S₂O₈) and then digested in an autoclave for 60 minutes, for total P analysis. Aliquots of the digests were then neutralized using 0.5 M NaOH and 1.2 M H₂SO₄ to bring the pH to about 6-8 before determination of P.

Inorganic P in the NaHCO₃ and NaOH extracts was determined by acidifying 4 ml of the aliquot in a 50 ml centrifuge tube with 0.6 ml of 1.2 M H₂SO₄ to precipitate the organic matter. The OM was removed by carefully decanting the supernatant after centrifuging at 7000 rpm. Inorganic P was determined colorimetrically at 880 nm absorbance by the molybdenum – ascorbic acid blue method of Murphy and Riley (1989). Organic P was estimated as the difference between total P and inorganic P.

HCl extraction was done on soils previously extracted with NaOH after decanting the NaOH since the sequence of alkaline followed by acid extraction gives reliable distinction between Al and Fe, and Ca associated Pi (Kurmies, 1972).

3.4.2.1 Conversion of soil measurement units

Phosphorus fractions P concentration was measured in mg P 1⁻¹ and converted to mg/kg (Pmgkg) as follows:

\[
P_{\text{mgkg}} = \frac{(P_{\text{conc}} - P_{\text{blnk}}) \times \text{Exvol}}{P_{\text{slwt}}}
\]

Where:  

- Pconc = P concentration for sample (mg P 1⁻¹)  
- Pblnk = P concentration for blank (mg P 1⁻¹)  
- Exvol = Volume of the extractant (ml)  
- Pslwt = Weight of the extracted soil (g)
3.5 Statistical analysis of soil chemical data

Analysis of variance between the treatment and seasonal means for organic carbon, Olsen P and sequential P fractions data was analyzed using Genstat for Windows Discovery Edition (Genstat, 1995). Variation between the treatment means and seasonal means were calculated and changes assessed by use of standard error of difference (SED) between treatment means and the F probability.

3.6 Diffuse Reflectance Spectroscopy

This technique was used for rapid characterization of soils (Shepherd and Walsh, 2002). The technique is simple, non-destructive and reliable and relies only on direct collection of reflected light from an illuminated soil sample. Light reflection is digitally captured over several hundred wavebands from the visible through the near and short wave infrared, and gives a spectral signature of a characteristic shape. Reflectance is a product of complex patterns of scattering and absorption by numerous structural and biochemical components. The shape of the spectral signature responds to the chemical and biophysical attributes of the soil.

3.6.1 Sample preparation and reflectance measurement

Soil samples were air dried and passed through a 2 mm sieve. No sample preparation was required beyond air drying and light grinding. About 100 g of soil sample was placed into a 7.4 cm (diameter) Duran glass petri dish to give a sample thickness of about 1 cm. The sample was scanned through the bottom of the petri dish using a high intensity source probe (Analytical Spectral Devices, Boulder Co., 1997) as described by Shepherd et al. (2003). The probe illuminated the sample and collected the
reflected light from a 3.5 cm diameter sapphire window through the fibre optic cable. To sample within dish variation, reflectance spectra were recorded at two positions, successively rotating the sample dish through 90° between readings. Reflectance readings for each spectrum were recorded at 0.35 - 2.5 μm wavelengths at 1 nm intervals and expressed relative to the average of the white reference reading.

3.6.2 Processing of the raw spectral reflectance

The raw spectra reflectance data derived from sample scanning was compiled in Ms-Excel spreadsheets by selecting every 10th value from 0.35–2.5 μm wavelength bands. This was done to reduce the volume of data for analysis and to match it more closely to the machine's spectral resolution (0.003-0.01 μm). Reflectance spectra were given codes according to sampling dates and field treatments and matched to the soil chemical results (organic carbon and Olsen P data). Data was checked for normality and several transformation approaches tried to give a probability distribution as close as possible to a normal distribution. The spectral variables were standardized by mean-centering to adjust the nonlinearity among samples caused by constituent absorption, scatter caused by sample particle size and sample surface reflection. Reflectance values were then transformed using several approaches to reduce variation due to grinding and optical set-up. First and second derivatives by Savitsk Golay algorithm (Fearn, 2002), standard normal variate and Norris transformation methods were tested to see how well they could normalize the data. Derivative transformation minimizes variation among samples caused by variation in grinding and optical set up (Martens and Naes, 1989).
3.6.3 Statistical analysis of spectral data

Exploratory statistics was used to identify important variables in the spectral data. Principal component analysis (PCA) and discriminant partial least squares regression analysis (DPLSRA) were conducted with the Unscrambler Version 7.5 (Camo Inc. 1998) to investigate the treatment effects on the soil spectral data. PCA searches for directions of maximum variability in sample groupings and uses them as new axes called principle components. In this way, relevant information for the system is contained in a reduced number of variables. The PCA data thus obtained is used as new variables in subsequent calculations instead of the original data. In this study, PCA was carried out to investigate the main variation in the sample spectral values.

Soil chemical data for P and C earlier obtained was calibrated to soil reflectance values using partial least squares regression (PLSR) (Naes et al., 2002). Partial least squares regression uses information on both spectral (X) and the Y variable in the estimation of the components or factors. Empirical models were computed for predicting the composition of a given sample. These predictive models were developed on the first derivative-transformed data. Wavebands in regions of low signal and displaying noise were omitted leaving 197 bands for analysis. Several approaches were checked to improve the stability of the models and hence to improve their predictive performance. A sample observed to be outlying (high residual standard deviation) from the general trend in the scatter plots was omitted from the calibrations. Elimination of non-significant wavebands (jack-knifing) during calibration was performed to simplify the final models and increase their predictive
performance. Models were developed using cross-validation. The calibration set was used to develop a predictive equation while the validation set was used to validate the same equation\(^1\). There was insufficient number of samples to be able to use a separate hold-out validation set, to evaluate the stability of the models and to estimate the prediction error. Prediction success of the calibration models was evaluated using statistical parameters commonly used for the NIR technique. These included; coefficient of correlation \((r^2)\), roots mean square error (RMSE) and bias.

\[ Y = \beta_0 + \beta X + \Sigma \]

Where: \( \beta_0 \) = Y intercept from regression,

\( \beta X \) = regression co-efficient

\( \Sigma \) = random error.
RESULTS AND DISCUSSION

4.1 Treatment effects on soil extractable phosphorus

Analysis of variance revealed that treatments in both the manure and fertilizer experiments affected the level of extractable P at 5% level of significance (p < 0.01). As Table 3 shows, results of manure experiment (Trial 1) indicates that continuous manure application appeared to have the highest effects on soil extractable P followed by N and P fertilizers applied at 51 and 12 kg/ha respectively. Continuous manure application at 10 t/ha/yr (M1) significantly increased the level of extractable P in all the 12 sampling seasons. In the fifth year after treatment application (1993), the level of P in M1 had significantly increased from 0.9 mg/kg to 3.6 mg/kg, steadily increasing in preceding years. P fluctuated annually and no significant yearly changes were observed. By year 2000, extractable P had increased to 9.0 mg/kg and by 2002 (fourteenth year), there was a significant P decline to 6.7 mg/kg, which was still highly significant as compared to the other treatments.

The high P levels by continuous manure application could be attributed to the higher P input coming from the large amounts of manure added, and the fact that manure being an organic resource might have increased microbial activity (by providing energy in carbon) and the potential for mineralization of SOM. Since manure is a high quality resource, this possibly increased the microbial carbon resulting to a low C:P ratio, as a result of nutrient immobilization. This consequently may have induced the transformation of soil organic P to inorganic P through microbial turnover, hence the high availability of solution P.
Table 3. Soil extractable P treatment means collected from Mbeere district, Kenya over a period of 10 years

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Treatment</td>
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M0-control, M1 and M2-continuos manure application at 10 and 5 t/ha/yr respectively, R1 and R2-residual manure at 10 and 5 t/ha/yr respectively and F-NP fertilizer at 51 and 12 kg/ha/yr respectively.
Microbial biomass dynamics and C:P ratios have been observed as important factors regulating nutrient availability (Smith et al., 1993). He et al. (1997) suggests that a decrease in microbial C:P ratio is a result of nutrient immobilization and has higher potential to release P through microbial turnover. Organic manures also supply substantial amounts of macro and micro nutrients that influences nutrient balance in soil resulting to enhanced P availability and uptake (Hue et al., 1994; Gachengo et al., 1999). Similar observations have been made by Ndayegamiyo and Anger (1990) who noted that mineralization of organic P is important in influencing soil P availability. Simard et al. (1995) noted that repeated manure application can lead to P accumulation in soils and saturation of P sorption sites.

Moreover, the application of manure to the soil could have improved soil structure and moisture holding capacities of the soil, enhancing microbial activity and consequently phosphorus turnover. Organic matter application increases soil aggregation (Phan and Thi Cong, 2002), reduces bulk density consequently enhancing P diffusion rates and hence P availability. These observations are in agreement with a study by McKenzie et al. (1992) who noted that manure applied for many years resulted in accumulation of inorganic and organic P in the soil. Since Machang’a is highly P deficient area, the increased availability of extractable P in manure treated plots was also perhaps due to the combined effects of rapid N and P mineralization. This is consistent with the findings of Murphy (1989), who observed that high concentration of ammonium N in the soil with fertilizer P may interfere with normal P adsorption reactions prolonging the effects of P fertilization.
Continuous manure at 5 t/ha/yr was found to significantly increase P in five out of the twelve sampling seasons. This variation as compared to application at 10 t/ha/yr was mainly attributed to the quantity of manure applied and consequently the nutrient concentration in the input. In 1997, a 53% increment in soil solution P was recorded followed by a 44% loss in 1998. A highly significant increase was again observed in 1999 to 2002 with a recorded value of 5.8 mg/kg, which then steadily declined to 3.0 mg/kg in 2002. The high build up of P observed in 1999 was attributed to rapid mineralization of organic P due to the increased moisture resulting from the high rainfall received in 1997. This was catalyzed by the effects of high temperatures experienced in the area.

Residual manure at both 5 and 10 t/ha/yr was observed to significantly increase available P only in the first year after manure application ceased. Though all the other preceding years recorded relatively high levels of P, these were not significant in any of the years (p < 0.01). This implies that the residual effects of manure on extractable P lasted only one year or at least were not detectable given the precision of the experiment. Loss of available P from 1994 was attributed mainly to transformation of inorganic P to organic P via plant and soil biota uptake (Bolan and Hedley, 1990).

Inorganic fertilizers at 51 and 12 kg/ha/yr N and P respectively had no influence on extractable P in the first year. Normally, it is expected that nutrients are readily available from inorganic fertilizers unlike in organic resources where decomposition
must first take place before the nutrients are released and made available in the soil. On the contrary, this was not the case and the effects of inorganic fertilizers were not immediately felt. Significant effects were observed in 1994 to 1999, and in the preceding three years, a slight decline was observed, with a value of 4.0 mg/kg being recorded in 2002. As compared to 1993, a 76% increase in available P was observed in 2002. The absence of significant effects in the first year of application of inorganic fertilizers was attributed to P immobilization by microorganisms. This agrees with a study by Walbridge (1991) who observed that where P is limiting, microbes can immobilize between 50% and 20% of P applied in surface soils.

Though adsorption-desorption reactions were thought to be low due to the almost neutral pH of the soil (pH=6.5), addition of the mineral fertilizers might have induced local acidification by reducing the inherent soil pH value of 6.5 and consequently the soil base saturation. This concurs with the findings of Kang and Wilson (1987), who observed that frequent application of N fertilizers resulted in rapid acidification of soils low in organic matter. Decrease in the soil pH could also be a function of the release of H⁺ associated with organic anions and nitrification process following plant litter decomposition and decreased CEC (Bolan, 1991). This meant increased exchangeable acidity, Al saturation and the amount of sesquioxides, which in turn might have complexed P and hence the low P values in 1993. Low pH causes surface hydroxyl groups to accept protons to form -OH groups. Since -OH are easier to displace than hydroxyls, lowering pH could have increased P sorption by facilitating ligand exchange reactions. This is in line with an observation that in ecosystems with
moderate weathering regime, most of the added P is adsorbed onto clay minerals. P fixation results from increase in the amount of sesquioxides that occurs during the weathering process in Ultisols and Alfisols (Sanchez and Logan, 1992). The significant effects and increase in the level of available P after the second sampling year, in the said treatment was possibly due to repeated P application and net mineralization of organic P from crop residues. Although the organic residues cannot provide a sufficient source of P, they may increase soil P levels and availability patterns through their effect on the microbial activity and P sorption capacity of the soil. Several studies have shown that organic residues reduced soil P adsorption through competition of adsorption sites, whereby the organic anions replace phosphates sorbed at metal hydroxide surfaces through ligand exchange reactions, and consequently increased P availability (Easterwood and Sartain, 1990; Hue, 1991; Gachengo, 1996; Hernandez et al., 1996). Iyamuremye et al. (1996a) and Nziguheba (2001) observed that organic matter complexes and dissolves the metal oxide surfaces that sorb P, and saturates adsorption sites. Application of high amounts of P fertilizers also acts to saturate the sorption sites (Garden et al., 1997; Mukwonye and Bationo, 2002).

Fertilizer experiment (Trial 2) results (Figure 1) indicated that throughout the nine yeas of the experiment, bare fallow (F2), retention of crop residues (C1), addition of extra crop residues (C2) and removal of residues (C3) recorded low P levels with insignificant yearly changes.
Figure 1. Soil extractable phosphorus treatment means obtained from Machang’a over a period of 9 years

F2; bare fallow, F2P; bare fallow + 250 kg/ha TSP, C1; continuous cultivation + retention of crop residues, C1P; C1 + 250 kg/ha TSP, C2; continuous cultivation + addition of extra crop residues, C2P; C2 + 250 kg/ha TSP, C3; continuous cultivation + removal of crop residues, C3P; C3 + 250 kg/ha TSP.

However, an initial application of 250 kg TSP to F2, C1, C2 and C3 was observed to hugely and significantly increase available P in the second season of first year and in the preceding years. There were no significant effects in the first season, and the highest increment was observed in the second season of the first year. A declining trend in the level of P was observed from the third year in bare fallow + TSP, retention of residues + TSP, addition of extra residues + TSP and in removal of residues + TSP. The decline was however drastic up to 1997, after which the level seemed to stabilize up to 1999, and gradually declining until the end of the experiment. P significantly increased in bare fallow + TSP (F2P) from 0.8 mg/kg to 31 mg/kg in the second season, slightly declining to 22 mg/kg in 1995. By the ninth
year (2002), P level had declined to 3.9 mg/kg. Likewise, available P increased in retention of residues + TSP (C1P) from 0.90 mg/kg to 33 mg/kg in the second season, significantly declining to 3.8 mg/kg in 2002. The highest level of available P in C2P (23 mg/kg) also occurred in 1994, sharply declining to 6.4 mg/kg in 1997 and an amount of 3.3 mg/kg recorded in 2002 was still significant as compared to F2 and C2. Extractable P in C3P increased from 0.7 mg/kg in the first season to 23 mg/kg in the second season and then gradually declined to 3.1 mg/kg in year 2002.

The relatively low levels of P in the first season following application of 250 kg/ha TSP in the fallow and cropped system was attributed to P immobilization by microbes immediately following application. The remarkably high P level one season later was probably due mineralization of phosphorus earlier immobilized by microorganisms. The huge amount of P applied and its high solubility could also have heightened the level of soil solution P. The drastic decline from the third year was due to the fact that no fresh application was made and consequently phosphorus was liable to losses by microbial immobilization, uptake by crops and losses in grain harvests, conversion to organic P and probably wind erosion losses. Between 1997 – 1999, P level appeared to stabilize and this was related to the relatively high rainfall that occurred in 1997, which caused relatively high soil moisture consequently enhancing microbial activities and P turnover.

Comparing the three residue management (retention, addition of extra, and removal of residues), it was observed that although C1P seemed to have high P levels
followed by C2P and lastly C3P, the differences were not statistically significant, implying that the method of residue management did not influence the P level. However, C1P appeared to have relatively more available P and this was attributed to the beneficial effects of organic residues, which, quickens phosphorus solubilization thereby enhancing its availability (Nziguheba et al., 1997). However, though the crop residues in C1P enhanced P availability, this was not the case where extra residues were added (C2P). Possible reasons could be that the extra residues added to the microbial substrate, increasing microbial population and consequently the conversion of some of the available P to microbial P. Phosphorus immobilization could also have occurred since a lot of material with high C:P ratios was added. This is consistent with the findings of Schomberg and Steiner, (1999) and Mafongoya et al. (2000) who reported that addition of plant residues significantly decreased P availability perhaps due to immobilization of P in the residues.

In general, even though inorganic P has generally been considered the major source of plant available P in the soil, continuous manure was observed to increase available P than the inorganic NP fertilizers. This emphasizes the importance of organic P in P cycling. The build up of available P by manure was to suggest that either the addition of manure converted part of the non-available P forms into available P forms or the P added from fertilizers was easily transferred into non-available forms, thus reducing their efficiency as P sources. This was consistent with the findings of Tate et al. (1991), who observed that in absence of fertilizer P, labile organic P mineralization was an important source of P in low fertility soils in New Zealand. The effect of crop
residual management on P availability was observed to be very minimal and almost negligible while residual effects of TSP lasted significantly (more than nine years). By the end of the experimentation period in 2002, the residual effects of 250 kg/ha applied in 1994 were still significantly different from the plots that never received fertilizer. Further work is hence necessary to determine the exact number of years that the residual value is effective.

4.2 Treatment effects on soil organic carbon

The influence of the different treatments in manure experiment on organic carbon (Table 4) revealed that treatments affected the level of soil organic carbon at 5% level of significance (p<0.01). Significant treatment differences were observed in the level of carbon throughout the 12 experimentation seasons.

Five years after the application of treatments (1993), organic carbon in continuous manure at 10 t/ha/yr (M1) increased from the inherent value of 0.6 % to 0.9 %. The level dropped in the sixth year to 0.7 %, increasing to 1 % in the ninth year. The highest level of OC was observed in 1999 (1.02 %) and by the year 2002, the level was still significant as compared to the control samples.
Table 4. Soil organic carbon treatment means obtained from Machang’á, Mbeere district, Kenya over a period of 10 years

<table>
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<tbody>
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<td>0.82</td>
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<td>0.75</td>
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<tr>
<td>R2</td>
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<td>0.78</td>
<td>0.72</td>
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<td>0.76</td>
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M0-control, M1 and M2-continuous manure application at 10 and 5 t/ha/yr respectively, R1 and R2-residual manure at 10 and 5 t/ha/yr respectively and F -NP fertilizer at 51 and 12 kg/ha/yr respectively
The effects of continuous manure at 5 t/ha/yr (M2) on the soil organic carbon portrayed the same trend as that of 10 t/ha/yr but the values for the former being only slightly lower than those of the latter. When compared though, the difference between the two manure rates on the SOC was observed to be insignificant in any of the sampling years. In 1993, SOC in M2 had significantly increased to 0.88 % and was maintained at 0.84 % in 1997. By the fourteenth year (2002) OC by M2 was still significant (0.8 %) as compared to the control (M0) though the level had slightly declined. The high OC level by continuous manure was attributed to the repeated organic input that balanced decomposition losses. It has been observed that application of manures is the main strategy for restoring SOM (Woomer et al., 1994; Smaling et al., 1997 and Vanlauwe et al., 2002).

Residual manure at 10 t/ha/yr (R1) significantly increased the level of OC in the first three years of testing the residual value more than any of the other treatments. A value of 0.99 % OC was observed in the first year, with a value of 0.84 % being recorded in the third year (1995). Likewise, residual manure at 5 t/ha/yr (R2) led to increased OC with a 40 % rise above the control being recorded in the third year. From the third (1995) to the sixth years (1998), OC appeared to stabilize and in 1999, just like in continuous manure at both rates, R1 hugely increased OC from 0.54 % to 0.85 %. Later the level gradually declined in each successive season, indicating that the residual value of manure on the SOC declined with time. By 2002, R2 was not any different from control. After 14 years, a maximum loss of 19 % in the initial level of OC by residual manure was noted and attributed to the reduced input of manure relative to decomposition rates, biota uptake and losses to wind erosion, which is prevalent in the
study area as observed by DAREP (1995). It was evident therefore that the residual value of manure lasted three years and therefore fresh application is inevitable. In addition to microbial assimilation, OC was perhaps converted into more stable humic compounds as decomposition progressed.

Inorganic NP fertilizer (F) did not significantly influence organic carbon in any of the years. Addition of nitrogen and phosphorus possibly increased SOM decomposition rate hence exposing carbon to losses since increased N availability stimulates a higher decomposition and mineralization rate as observed by Palm and Sanchez (1991) and Tian et al. (1995). When compared to manure, fertilizer effects on the soil organic carbon was very minimal. The 0.63 % recorded at the end of the experiment did not differ much from the inherent carbon value (0.61 %) indicating that N and P fertilizers did not improve the level of SOC. This is consistent with an observation by Bationo et al. (1995) that the use of inorganic fertilizer alone can lead to a decline in SOM while organics can maintain SOM levels. This contradicts the findings of Bache and Heathcote (1969), who reported that application of ammonium sulphate and single super phosphate over 15 years caused a small increase in soil organic carbon in the savanna zone of northern Nigeria.
Results in the fertilizer experiment (Trial 2) indicated that treatments affected the level of SOC in all years at 5% level ($p < 0.01$) (Table 5).

Table 5. Soil organic carbon treatment means obtained from Machang’a, Mbeere district Eastern Kenya, over a period of 4 years

<table>
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<tr>
<th>Year / Season</th>
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<td>0.97</td>
<td>0.90</td>
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<tr>
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<td></td>
<td>C2P</td>
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<td>0.90</td>
<td>0.83</td>
<td>0.78</td>
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</tr>
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</tbody>
</table>

F2; bare fallow, F2P; bare fallow + 250 kg/ha TSP, C1; continuous cultivation + retention of crop residues, C1P; C1 + 250 kg/ha TSP, C2; continuous cultivation + addition of extra crop residues, C2P; C2 + 250 kg/ha TSP, C3 continuous cultivation + removal of crop residues, C3P; C3 + 250 kg/ha TSP

Results indicated that fallow system (F2) recorded slightly high carbon values as compared to the cultivated cropped systems, though the difference was not significant. The level of OC in F2 was relatively high in 1994 (0.9 %), gradually declining in each consequent year and by 2002, the level had dropped to 0.7 %. Though initial addition of TSP to bare fallow (F2P) appeared to increase the level of carbon, this increment was not statistically significant. The relatively high carbon level (0.9 %) observed in year one presumably resulted from decomposition of the initial plant biomass before fallow maintenance took course.

In 1994, organic carbon in C3 increased from the inherent value of 0.6 % to 1.0 % maintaining the level to 1.0 % in 1995 and declining just slightly to 0.96 % in 1996. By
the end of the experimentation period, the level of OC had declined to 0.7 % recording a carbon loss of 24 %. This loss was attributed to intensive cultivation over the years, which disintegrated the soil aggregates giving way to intensified microbial attack and too little return of organic materials to the soil (Rawat et al., 1996). This holds true for the other cultivated cropped systems. Initial application of 250 kg TSP in C3 (C3P) in 1994 did not increase the level of OC in any of the preceding years, but instead decreased it significantly compared to cropping without fertilizer. This was attributed to increased soil micro-organisms due to the readily available nutrients in the fertilizer and consequently increased respiration leading to loss of organic carbon.

Cropping systems with crop residues retained (C1) recorded relatively high carbon level, which appeared to be constant for all the seasons except for a very slight decline in 2002. However, it was noted that both retention and addition of extra crop residues did not significantly differ from each other, nor did they lead to a significant increase in the level of OC. This was attributed to increased microbial activities and more rapid turn-over rates inferred from the high ratio of carbon inputs to microbial population.

Addition of soluble forms of carbon (crop residue) could also have resulted in the decomposition of the more recalcitrant plant components and SOM, the so called priming effect. Collins et al. (1990) found that the decomposition of mixes of wheat residues was greater than the predicted when parts with more soluble carbon were added. Vanlauwe et al. (1994) also confirmed that more soluble carbon fractions in plant materials enhanced the decomposition of the more recalcitrant fractions. Organic additions to the soil can also cause a shift in the distribution of nutrients in the organic
and inorganic soil fractions caused by microbial activity. This conflicts with an observation by Dhiman et al. (2000) that, incorporation of wheat and rice residues increased organic carbon compared to removal of straw. Addition of TSP in either of the cropping systems did not increase the level of carbon and it was generally evident that the addition of inorganic TSP had negligible influence on the level of soil organic carbon.

Organic carbon appeared to decline from 1996 down to 2002 in all the treatments. In the cropped plots this decline was attributed to continuous cultivation, which might have induced a lower equilibrium level of SOM. Continuous cultivation in conjunction with residue removal are known to induce a more rapid mineralization of SOM within the first year of cultivation by disrupting macro-aggregates and leading to mineralization of SOM within the physically protected aggregates. Bolan et al. (1992) observed a 33-45 % decrease in SOM after five years of continuous cropping. Six et al. (1998) also observed that cultivation reduces SOM and alters the distribution and stability of aggregates. Tillage could have increased SOM oxidation by disrupting soil aggregates, exposing new surfaces to microbial attack and changing the redox conditions within the profile.
4.3 Treatment effects on soil phosphorus fractions

Treatments in both manure and fertilizer experiments were found to influence sequential P fractions (p<0.01) after 14 years of experimentation (Table 6).

The largest difference among the amendments was observed in the resin P fraction. This is the fraction that is most labile, and hence directly and readily exchangeable with the soil solution. Continuous manure application at 10 t/ha/yr (M1) yielded the highest P level (17.5 mg/kg) in the said fraction and other subsequent inorganic P fractions; NaHCO₃ and NaOH. Resin P fraction significantly increased to 6.07 mg/kg in NP fertilizer (F), while continuous manure application at 5 t/ha/yr and residual manure at 10 t/ha/yr did not lead to significant build up of this fraction. The high level of available P by manure application at 10 t/ha/yr was perhaps due to the quantity of organic P added in manure and also because of the beneficial effects of organic amendments on phosphorus availability. Net P mineralization was also expected with the application of manure because P concentration in the manure (0.47 %) was higher than the critical level of 0.25 % for net P mineralization (A Kwabiah, personal communication). Iyamuremye et al. (1996 b) reported an increase in the resin P, NaHCO₃ Pi and NaOH Pi with manure and alfalfa residues both with greater than 0.24 % P.
Table 6. Sequentially extracted phosphorus fractions by treatments in manure experiment (a) and fertilizer experiment (b) at Machang'a, Mbeere district Kenya, in year 2002

### a) Manure experiment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>RP</th>
<th>NaHCO₃-Pi</th>
<th>NaHCO₃-Po</th>
<th>NaOH Pi</th>
<th>NaOH Po</th>
<th>NaOH Pt</th>
<th>HCL P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.44</td>
<td>1.70</td>
<td>6.70</td>
<td>8.40</td>
<td>8.70</td>
<td>40.49</td>
<td>49.17</td>
</tr>
<tr>
<td>M1</td>
<td>17.47</td>
<td>7.68</td>
<td>6.02</td>
<td>11.88</td>
<td>21.37</td>
<td>42.91</td>
<td>64.19</td>
</tr>
<tr>
<td>M2</td>
<td>3.60</td>
<td>4.70</td>
<td>1.20</td>
<td>5.90</td>
<td>10.77</td>
<td>43.88</td>
<td>54.60</td>
</tr>
<tr>
<td>F</td>
<td>6.07</td>
<td>5.08</td>
<td>6.51</td>
<td>11.60</td>
<td>41.51</td>
<td>58.54</td>
<td>2.62</td>
</tr>
<tr>
<td>R1</td>
<td>1.60</td>
<td>2.70</td>
<td>5.28</td>
<td>7.60</td>
<td>40.83</td>
<td>48.99</td>
<td>1.38</td>
</tr>
<tr>
<td>SED</td>
<td>1.26</td>
<td>0.56</td>
<td>0.97</td>
<td>0.74</td>
<td>1.05</td>
<td>1.96</td>
<td>2.53</td>
</tr>
</tbody>
</table>

### b) Fertilizer experiment

<table>
<thead>
<tr>
<th>Treatment</th>
<th>RP</th>
<th>NaHCO₃-Pi</th>
<th>NaHCO₃-Po</th>
<th>NaOH Pi</th>
<th>NaOH Po</th>
<th>NaOH Pt</th>
<th>HCL P</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1.04</td>
<td>2.16</td>
<td>5.64</td>
<td>7.80</td>
<td>5.98</td>
<td>60.00</td>
<td>66.00</td>
</tr>
<tr>
<td>C1P</td>
<td>3.20</td>
<td>7.54</td>
<td>3.88</td>
<td>11.40</td>
<td>17.57</td>
<td>62.82</td>
<td>80.33</td>
</tr>
<tr>
<td>F2</td>
<td>1.60</td>
<td>2.49</td>
<td>3.91</td>
<td>6.40</td>
<td>4.78</td>
<td>58.34</td>
<td>65.43</td>
</tr>
<tr>
<td>F2P</td>
<td>4.80</td>
<td>6.49</td>
<td>1.80</td>
<td>8.10</td>
<td>15.58</td>
<td>54.72</td>
<td>70.24</td>
</tr>
<tr>
<td>SED</td>
<td>0.43</td>
<td>0.41</td>
<td>0.66</td>
<td>0.61</td>
<td>0.88</td>
<td>3.35</td>
<td>3.74</td>
</tr>
</tbody>
</table>

RP-resin inorganic P, NaHCO₃-Pi-bicarbonate inorganic P, NaHCO₃-Po-bicarbonate organic P, NaHCO₃-Pt-bicarbonate total P, NaOH Pi-Sodium hydroxide inorganic P, NaOH Po-Sodium hydroxide organic P, NaOH Pt-Sodium hydroxide total P, HCL-hydrochloric acid extractable P, M0-control, M1-continuous manure at 10 t/ha/yr, M2-continuous manure at 5 t/ha/yr, F-NP fertilizers at 51 and 12 kg/ha/yr, R1-residual manure at 10 t/ha/yr, C1-Cropping without fertilizers, C1P-Cropping + 250 kg/ha triple super phosphate, F2-bare fallow, F2P-bare fallow + 250 kg/ha triple super phosphate
The findings conflict with the results of a study by McCoy et al. (1986) who found that biosolids P was four to seven times less available to plants than TSP. Tunney and Pommel (1987), reported that P in pig slurry was at least 90 % as effective as P in the mineral fertilizer. The absence of significant effects by residue manure was possibly due to P losses via plant and biota uptake and the reduced inputs of manure relative to decomposition. Bare fallow and continuous cultivation, with and without an initial P addition at 250 kg/ha TSP in 1994 was found to influence resin P at 0.05 % level. Earlier analysis revealed an absence of statistical meaningful difference with regard to Olsen extractable P between C1, C2 and C3 (Warren, 1997). For the purpose of this analysis therefore, a composite of the three treatments was taken and coded C1, and where P was added, this was coded C1P. Resin P in C1P increased to 3.2 mg/kg and this was relatively low compared to the build up in M1 (17.47 mg/kg). This was attributed to the fact that addition of TSP in C1P was only applied once in 1994 and the observed level was the residual value after nine years, unlike in M1 where there was repeated manure application. The low P level in C1P could also be due to transformation of inorganic P in fertilizer into more stable P forms, as portrayed by the high concentration of P in the more recalcitrant NaOH P fractions. Resin P level was significant in bare fallow + TSP (4.8 mg/kg) and this was higher than in cultivated plots. This was attributed to the non-till effects and an absence of P losses resulting from grain harvests.

Just like in the resin P fraction, NaHCO₃ inorganic P (Pi) fraction was highest in M1. The NaHCO₃ inorganic P has been defined as the labile pool that is highly related to
P uptake by plants (Fixen and Groove, 1990). This fraction significantly went up from 1.7 mg/kg in control to 7.7 mg/kg and 5.1 mg/kg in continuous manure at 10 t/ha/yr and inorganic fertilizer respectively, while no significant effects were recorded in R1. Likewise, negative effects on the bicarbonate extractable fraction, were observed in F2 and C1, while addition of TSP to F2 and C1 lead to a significant build up of this P fraction but at slightly lower level than in manure application. The relatively higher levels in this fraction by manure and TSP was perhaps due to their high P content (P>0.25 %) and high solubility, particularly for the inorganic fertilizers. As compared to resin P, bicarbonate P fraction was much less, implying that most of the labile P was held in the resin fraction, and hence was readily available for crop use. Generally, it was noted that labile inorganic P fractions (resin and bicarbonate) were higher where high amounts of P was applied. This was hugely because of the quantity of P added, thus indicating the dependency of labile P release on the application rate. The results show that animal manure can cause significant increases in the labile NaHCO₃ P fraction that is clearly related to plant available P. A similar observation of organic inputs on the NaHCO₃ extractable P fraction was reported by Iyamuremye et al. (1996) for high quality manure and Nziguheba et al. (2000) for different agroforestry prunnings.

Sodium bicarbonate organic P (NaHCO₃ Po) or the loosely sorbed P fraction did not appear to increase in any of the treatments and instead (Table 6) all treatments recorded relatively lower levels compared to control. As would be expected, addition of TSP did not increase this organic fraction but it was surprising that manure had
negative effects. The decrease in the organic P pool by manure was attributed to rapid mineralization of the organic amendments. This perhaps is to suggest that there was a net conversion of the organic P forms to inorganic forms and hence conversion of manure P to inorganic forms in the soil. NaHCO$_3$-Po is readily mineralisable and less stable compared to NaOH-Po (Buresh et al., 1997). This is because the major component of labile Po is a diester PO$_4$ (Tiessen et al., 1984), which prevents it from binding strongly to soil minerals and makes it susceptible to rapid mineralization. Negligible influence in this fraction (NaHCO$_3$ Po) was also observed in C1P and F1P, presumably because TSP was fast dissolved to the inorganic fraction which represents the more soluble P forms. The relatively higher level by retention of crop residue (C1) (5.6 mg/kg) was attributed to initial immobilization of the plant litter P which, later became slowly available with time as a result of net mineralization. During early stages of residue decomposition net immobilization of P can conserve a substantial amount of P in slowly available organic forms.

The treatments also influenced sodium hydroxide inorganic P (NaOH-Pi) fraction. The NaOH extractable inorganic P has been defined as the P capital that provides the main sink of excess P from fertilizers (Buresh et al., 1997. It is the P fraction strongly sorbed onto Fe and Al oxides and clay edges through chemosorption and is only slowly available to plants (Tiessen and Moir, 1993). Continuous manure (M1) recorded a value of 21.3 mg/kg, which was highly significant as compared to control (8.7 mg/kg). This fraction also increased significantly in NP fertilizers, F2P and C1P treated samples (17.1 mg/kg, 17.6 mg/kg and 15.6 mg/kg respectively), and this was
perhaps due to the dissolution of TSP. Residual manure at 10 t/ha/yr (R1) and continuous manure at 5 t/ha/yr (M2) did not lead to build up of the fraction. The low level of phosphorus in R1 and M2 resulting from mineralization of the manure had probably undergone some chemosorption transformation. Nevertheless, this fraction (NaOH Pi) appeared the dominant fraction related to availability of P. It appeared to include a slowly labile inorganic P pool which is otherwise an important source of available P, given time. This is in line with the results of a study by Beck and Sanchez (1994) who found that in an 18 year continuously cultivated and fertilized cropping system, NaOH Pi was the dominant fraction in P availability to plants in an Ultisol. Other studies on an Ultisol fertilized with P for 10 years (Schimidst et al., 1996) and 4 years (Linquist et al., 1997), found that NaHCO₃-Pi and NaOH Pi fractions were sinks for fertilizer P applied in excess of the plant uptake. The lower values for this fraction compared with sodium hydroxide organic P and total P, might indicate the conversion of this P pool into more stable NaOH-Po perhaps due to increased microbial activity.

None of the treatments in both trials significantly affected sodium hydroxide organic P (NaOH-Po) fraction. Neither the organic amendments nor the inorganic fertilizers had an effect on this fraction (p <0.01). NaOH-Po is more stable than NaHCO₃-Po but can be important P source. This fraction has more recently been identified as an important source of available P in tropical soils not receiving mineral P fertilizers (Tiessen et al., 1992; Beck and Sanchez, 1994). Just like in the case of NaHCO₃-Po, the absence of effects on this fraction presumably implied that the organic P in either
of the treatments (manure and crop residues) was rapidly mineralized into the inorganic P due to the deficiency of P in the soil solution. This differs with the findings of Tiessen et al. (1992) who reported an increase in NaOH Po following 8 years of bush fallow. This fraction has been shown to be an important source of P for crop growth in low input systems. On the other hand, M1 and F were observed to increase sodium hydroxide total P (NaOH Pt) and this was related to the increase in NaOH-Pi fraction. Treatments that did not increase the sodium hydroxide inorganic fraction had negligible influence on the NaOH-Pt fraction. C1P was observed to yield the highest NaOH-Pt fraction (80.33 mg/kg). This high level was partly the result of increase in the inorganic P fraction as well as the inherently high NaOH-Po fraction as observed in the control samples (40.49 mg/kg). Consequently, this implied that most of the phosphorus was held in stable humic compounds and perhaps by the Al and Fe oxides, and hence its deficiency. This is consistent with the observation of Cross and Schlesinger (1995), that NaOH organic P is associated with humic compounds and is often sorbed on Fe and Al sesquioxides.

Comparatively, the HCl extractable P fraction was observed to have the lowest phosphorus values (Appendix 11). This fraction is associated mainly with insoluble Ca-P (Mutuo et al., 1999) and since the soils used in this study were not alkaline and therefore had less calcium, this explains why this HCl-P fraction was comparatively low. Nonetheless, phosphorus level in this fraction significantly increased in M1 and F2, but the level was relatively higher in M1. Continuous manure at 5 t/ha/yr and residual manure at 10 t/ha/yr had negligible effects on the hydrochloric acid extractable P fraction. C1P and F2P likewise recorded significant effects on the HCl
fraction while C1 and F2 did not. The HCl-P fraction was therefore associated mainly with the undissolved native Ca-P.

All along, the fractionation scheme illustrated that continuous manure at 10 t/ha/yr, more than often yielded the most phosphorus in all the fractions that were affected by the amendments. Iyamuremye et al. (1996) also found increases in the resin P, bicarbonate Pi and NaOH Pi with manure and alfalfa residues. Inorganic P fertilizers recorded relatively low significant effects on the P fractions than in manure. The residual effects of TSP fertilizer were still significant after 9 years of cropping.
4.4 Diffuse reflectance spectroscopy analysis

4.4.1 Treatment reflectance spectra

Reflectance spectra covering the spectral range of the manure experiment soil samples (Figure 2) portrayed a similar pattern and appeared to follow the same basic shape observed by other researchers (Shepherd and Walsh, 2002). This is to be expected as the experiment was situated on the same soil types. Prominent absorption peaks and troughs tended to occur at the same wavelengths across all samples with three major absorption bands around 1400, 1900 and 2200 nm in the infrared light region of the electromagnetic spectrum. These bands correspond mainly to overtones and combinations of fundamental vibrations.

Given the complex nature of the soils, near infrared spectra (NIR) are a highly complex summation of individual constituent absorbance. The peak absorption by wavebands near 1400 and 1900 nm was attributed to absorbance by the hydroxyl ions (OH\(^{-1}\) group) in free, bound or adsorbed water, while the 2200 nm band was probably due to the lattice hydroxyl features (Hunt, 1980). Soils even if dried retain free water, hygroscopic water and bound water (Bendor, 2002). The overlaps observed in the spectra revealed that the soil is a non-ideal system that is chemically and mineralogically complex. This is due to the large number of co-existing components, sometimes with chemical interactions (Theng and Tate, 1989) each contributing partly to the observed spectra.
Figure 2a. Near infrared raw spectral reflectance averages for the treatments illustrating variation in reflectance across the treatments over a period of ten years in Machang’a Mbeere district, Kenya

M0 - control, M1- continuous manure at 10 t/ha/yr, M2 - Continuous manure at 5 t/ha/yr, F - NP fertilisers at 51 and 12 kg/ha/yr respectively, R1- residual manure at 10 t/ha/yr and R2-residual manure at 5 t/ha/yr
Figure 2b. Derivatised near infrared spectral reflectance averages for the treatments, showing the significant wavebands in absorbance across the treatments over a period of ten years in Machang'a Mbeere district, Kenya.

M0 - control, M1 - continuous manure at 10 t/ha/yr, M2 - continuous manure at 5 t/ha/yr, F - NP fertilisers at 51 and 12 kg/ha/yr respectively, R1 - residual manure at 10 t/ha/yr and R2 - residual manure at 5 t/ha/yr.
Control samples had the highest reflectance across all wavebands while manure treated samples had the lowest. The manure treated samples contained dark humic compounds hence absorbed much of the incident light and reflected only a fraction and consequently the low reflectance. Inorganic fertilizer samples portrayed a similar pattern but the reflectance was a little bit higher than in manure samples but lower than the control. This was due to the fact that mineral fertilizers lack organic matter but at the same time increased biomass production and hence organic matter accumulation at a rate lower than organic manure. Soils rich in OM contain humic substances, which are a series of relatively high molecular weight brown to black coloured substances formed by secondary reactions in soil and tend to absorb more light. This observation concurs with the higher SOC levels in the manure treatments compared with fertilizer and control. Derivative smoothing of data (Figure 2b) enhanced the visualization of the soil spectra and showed more clearly the significant wavebands as compared to the raw spectral data.

4.4.2 Principal component analysis for the spectral data

Principal component analysis was conducted on the first derivative spectral data for the different treatments for the years 1993-2002. A principal component (PC) is a mathematical representation of a systematic type of variation in a data set. It is a latent variable that cannot be measured directly. Instead, principal components are computed from linear combinations of a set of manifest input variables, and they reflect the largest eigenvalues for the co-variances. They are called principal because
they summarize the main sources of variation. The first few principal components usually account for most of the variation in whole data table and avoid data redundancy. The first PC explains most of the variability in the data as measured by their variance. The second and subsequent PCs are orthogonal (at right angles) to the previous PC and to each other and describe the maximum amount of the remaining variability. The principal components replaces the original spectral variables (strongly redundant) by linear combinations of the latter, which contain almost the totality of the information and have the advantage of being uncorrelated. Simple geometry allows the expression of values of individual samples in terms of PCs as linear summations of the original data multiplied by a co-efficient which describes the PC. These new values are known as scores and each sample will have a score for each PC. The PCA model score plot (Figure 3) show the distribution relationship between samples receiving different treatment. The distribution of the samples in the biplot gave an indication of the variation within the soil samples.

Results (Figure 4) indicated that the first and second principle components (PC1 and PC2 respectively) explained more than 85 % of the total amount of variation in the spectral values over the entire data set. PC1 explained 79 % of the variation while PC2 explained only 6 % of the total variation. The third PC explained very little variation and any additional PC was insignificant and most likely due to noise. Hence, PC1 and PC2 came out clearly as most important in explaining the variance within the spectral data. Subsequently, the variation was an indication that the
spectral data with regard to the soil properties was not homogenous. This was attributed to treatment effects on general soil properties.

Figure 3. Scatter plot showing PC1 and PC2 scores for the treatments spectral data obtained from Machang’a, Mbeere district, Kenya over a period of 10 years. The distribution of the samples in the biplot gave an indication of the variation within the soil samples due to treatments.
Figure 4. Plot showing the amount of explained variance in the different treatments spectral data collected from Machang’a over a period of 10 years. PC1 and PC2 are shown to explain more than 85% of the total variation in the soils' spectral values, indicating that the samples were not homogenous.

Figure 5. Loading plot showing the most significant wavebands in screening out differences among the treatments spectral values of soil samples collected from Machang’a for a 10 years duration. Loadings of the various constituents on PC1 and PC2 that explained the variability in the spectral and constituent data modeled together are illustrated. Most of the information is in the near infrared region implying the visible range added little information.
The loading plot (Figure 5), just as in derivative smoothing (Figure 2a), depicted 1400, 1900 and 2200 nm as the most significant absorption features in screening out differences among the spectral values. This indicated that NIR spectra contains analytical information, that is in typically broad and extensively overlapping bands.

An ANOVA done between PC1 and PC2 scores obtained from the PCA model indicated that the treatments had an influence on the principle components scores (Table 7). All the treatments influenced PC1 scores at p<0.03. The organic amendments (continuous manure and residual manure at both 10 and 5 t/ha/yr) were significantly different from control and NP fertilizers, while the latter was not significantly different from control. Therefore the resulting 79 % variance by PC1 scores could be attributed to the manure effects on the soil parameters.

Table 7. Principle components 1 and 2 average scores for the various treatments spectral values for soil samples obtained from Machang’a, Mbeere over at 10 years duration

<table>
<thead>
<tr>
<th>Treatments</th>
<th>PC1 scores</th>
<th>PC2 scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0 (control)</td>
<td>-0.00553</td>
<td>0.00175</td>
</tr>
<tr>
<td>M1</td>
<td>0.00154</td>
<td>-0.00151</td>
</tr>
<tr>
<td>M2</td>
<td>0.00245</td>
<td>-0.00112</td>
</tr>
<tr>
<td>F</td>
<td>-0.00349</td>
<td>0.00058</td>
</tr>
<tr>
<td>R1</td>
<td>0.00297</td>
<td>0.00145</td>
</tr>
<tr>
<td>R2</td>
<td>0.00252</td>
<td>0.0009</td>
</tr>
<tr>
<td>SED</td>
<td>0.003299</td>
<td>0.000910</td>
</tr>
</tbody>
</table>

M0-control, M1-continuous manure at 10 t/ha/yr, M2- continuous manure at 5 t/ha/yr F-NP inorganic fertilizers, R1-residual manure at 10 t/ha/yr, R2 residual manure at 10 t/ha/yr
ANOVA between PC2 scores revealed that PC2 scores were unaffected by the treatment ($p < 0.01$). This implies that PC2 was only responsible for explaining very little variation, as earlier depicted in the PCA model. Hence the PC1 scores could be used as an indicator of SOC changes under different manure management regimes.

**4.4.3 Discriminant PLSR analysis of the spectral data**

Discriminant partial least squares regression (Martens and Naes, 1989) was used to screen spectral differences and hence spectrally discriminate group of samples based on how similar the samples were among treatments. This approach differs from PCA in that in PCA, the underlying patterns in the data can be revealed without any prior knowledge of the sample characteristics. Three key treatments that were known to be statistically different with regard to soil organic carbon were picked. These treatments; control, continuous manure at 10 t/ha/yr and NP fertilizers were coded numerically as $-1$, $0$ and $+1$ respectively. A PLSR calibration model was then computed using the spectral reflectance as the X variable and the coded treatments as the Y variable (Figure 6).

The models’ predictive ability was acceptable with a correlation co-efficient of 0.88 for the calibration set and 0.78 for the validation set. Results indicated that though there were some considerable overlaps between treatments, almost distinct clusters were formed (Figure 7) and these were widely spread across PC1 and PC2. In other words, the composition of the samples varied. Moreover, some of the overlap in the clusters may have been due to similarity in soil properties before treatments were
established. If baseline soil samples had been available, then spectral differences before and after treatments would have been used as the X-matrix. The majority of the control samples scored low values as compared to organic manure and inorganic fertilizers, and appeared to lay along PC1 in the score plot with only a few appearing in PC2. On the other hand, continuous manure and inorganic fertilizers samples were more concentrated along PC2, indicating a clear separation from control samples. Moreover, a representative number of manure samples were more clustered in a furthest corner, still confirming the variability between the treatments spectral data.

Figure 6. Discriminant partial least squares regression calibration model showing the distribution of the measured versus predicted spectral scores for the treatments M0, M1 and F samples collected from Machang’a, Mbeere district over a duration of 10 years

A further ANOVA between PC1 and PC2 treatment scores obtained from the discriminant partial least squares regression model computed (Table 8) revealed that
the three treatments had an effect on the principle components scores (p<0.01). PC1 depicted manure and NP fertilizers to be highly significant from control, while manure was also significantly different from fertilizer. However, PC2 showed that manure and fertilizer were not statistically different, indicating that most of the variation was captured by PC1. This is in line with the findings of principal component analysis, which likewise showed that PC1 was more important in explaining the variation in the samples spectral data. The results further illustrates that by computing the principal components, these can show the variation in the soil spectral data presumably caused by the treatments and thereby reduce the need for wet chemistry analysis.

Table 8. Mean PC1 and PC2 scores as revealed by discriminant PLSR analysis for three treatments collected from Machang’a, Mbeere district from 1993 - 2002

<table>
<thead>
<tr>
<th>Treatment</th>
<th>PC1 scores</th>
<th>PC2 scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0 (control)</td>
<td>-0.00409</td>
<td>-0.0034</td>
</tr>
<tr>
<td>M1</td>
<td>0.00387</td>
<td>0.00141</td>
</tr>
<tr>
<td>F</td>
<td>0.00018</td>
<td>0.00246</td>
</tr>
<tr>
<td>SED</td>
<td>0.00178</td>
<td>0.00104</td>
</tr>
</tbody>
</table>

M0- control, M1- Continuous manure application at 10 t/ha/yr and F- NP inorganic fertilizers

The results indicated that M1 had a bigger magnitude on scores than fertilizer samples. The effect of M1 was from -0.004 in control to 0.004, while that of F was from -0.004 to only 0.0002. This is in line with earlier results which revealed manure to significantly lead to an increase in the level of SOC, while fertilizer application did not lead to any significant increment.
Figure 7. Discriminant partial least squares regression analysis plot showing the distribution of scores along PC1 and PC2 bioplot for the control (-1), continuous manure at 10 t/ha/yr (0) and NP fertilisers at 51 and 12 kg/ha/yr respectively (+1) samples obtained collected from Machang’a, Mbeere district from 1993 – 2002
The discussed results show that principle component analysis and discriminant partial least squares regression analysis of the spectral data alone provides a sensitive measure of differences between soil samples resulting from different management regimes. This was the case for organic and inorganic amendments. Because both approaches portrayed considerable differences between the samples, this can form a basis for investigating the causes of the variation. The approaches are also advantageous in that they are rapid and inexpensive and hence can be employed in monitoring soil fertility dynamics. Hence they present a potential powerful tool for monitoring soil fertility changes and sustainability of agricultural production and food security. The main challenge rests on interpretation of spectral data and the development of meaningful spectral indicators.

4.4.4 Partial least squares regression analysis

4.4.4.1 Prediction of soil organic carbon

Robust Partial least squares regression calibration models were obtained and organic carbon accurately predicted (Figure 8). Models were developed on a calibration which was validated using hold-out-one cross-validation. The result reported are predictions for the control treatments (MO), continuous manure at 10 (M1) and 5 t/ha/yr (M2) and residual manure at 10 t/ha/yr (R1). Two combinations of data were tried; the first included control versus continuous manure application while the second focused on the control, residual and continuous manure.
The $r^2$ between the reference laboratory and the predicted organic carbon for the global calibration model covering M0, M1 and M2 was 0.76 with a root mean square error (RMSE) of 0.09 and a bias of 0.002. Values for the cross-validated model were only a little bit lower; $r^2 = 0.72$, RMSE = 0.09 and a bias of -0.002, indicating the stability of the calibrations. Removal of the non-significant wavebands (jack-knifing) did not improve the calibrations; $r^2 = 0.75$, RMSE = 0.09, and bias = -0.003.

Recalibration after omitting a manure sample observed to be outlying from the general trend of the model improved the predictions by raising the $r^2$ from 0.76 to 0.80, with RMSE reducing to 0.08 (Figure 8). The cross-validated model indicated a robust model with an $r^2$ of 0.77 (Figure 9). The above statistics implies therefore that there was a close correlation between the measured carbon values and the predicted values, and this shows the potentiality of NIR spectroscopic analysis. From the regression scatter plot, low organic carbon values were predicted for the control samples while manure at 10 and 5 t/ha/yr samples were predicted to have high level of OC. There was however no observable difference in the predictive ability between the two manure rates since the scores for the two were almost overlapping. In other words, there was no difference in the predictive ability of NIR for soils receiving manure at the two rates and hence the effects on the SOC were basically similar. This concurred with the ANOVA results earlier discussed that revealed an absence of statistically significant difference between the two manure rates.
Figure 8. Scatter plot showing measured versus near infrared predicted organic carbon for the various treatments collected from Machang'a, Mbeere district from 1993 – 2002. Control (M0), continuous manure at 10 t/ha/yr (M1) and 5 t/ha/yr (M2). $r^2$ between the measured and the predicted % OC = 0.80.
Figure 9. Scatter plot showing measured versus predicted organic carbon for the various treatments collected from Machang’a, Mbeere district from 1993 – 2002. Carbon validation model was optimized and improved by jack-knifing and removal of outlying samples. $r^2$ between the measured and the predicted % OC =0.77
Likewise, a global model including control, continuous manure at 10 t/ha/yr and residual manure at the same rate was computed and the predictive ability tested for the first three years of the trial when the residual effects were large, and the last three years when residual effects on the SOC small. The global calibration model for the first three years (Figure 10) was very accurate; $r^2 = 0.94$, RMSE = 0.001 and bias of 0.00. The cross-validated model indicated a robust model with an $r^2$ of 0.84 and RMSE of 0.003. Similarly the calibration model for the period 2000 - 2002 predicted accurately with an $r^2$ of 0.86 and RMSE of 0.007 (Figure 11). The cross-validated model for the same data set had an $r^2$ of 0.82 and RMSE of 0.009. The results imply that soil organic carbon new samples from the same population could be predicted from their reflectance spectra, thereby reducing the need for wet chemistry analysis, which is both time consuming and expensive. This further illustrates the potential and ability of near infrared spectroscopy for predicting current and residual effects on the soil organic carbon due to management.

Overall, partial least square regression, discriminant analysis and principle component analysis illustrated the potential of NIR spectroscopy for rapid assessment and monitoring of soil quality. The method can therefore be used to offset the high costs associated with the standard laboratory wet analytical methods.
Figure 10. Measured versus predicted % OC for the control, M1 and R1 obtained from Machang’a, Mbeere district, Kenya during the first three years of testing the residual value of manure. R1 is portrayed to yield high OC values which are distinctly different from control, implying that the residual effects were still high during this period.
Figure 11. Measured versus predicted % OC for the control, M1 and R1 obtained from Machang’a during the last three years of testing. The cross-validated model indicated a robust model with an $r^2$ of 0.84 and RMSE of 0.003.g the residual value of manure. R1 is portrayed to yield low OC values, which are distinctly different from M1, but almost at the same range with M0, signifying that the residual value of manure on the SOC had declined over-time.
4.4.4.2 Prediction of soil extractable P

Partial least squares regression calibration models gave poor predictions of extractable P. Calibration set $r^2$ was 0.58 with a RMSE of 2.8 and a bias of 0.00 while the cross-validated model statistics were $r^2=0.52$, RMSE = 3.16 and a bias of 0.003. The performance of the calibrations was basically poor implying that there was poor correlation between the observed and the predicted Olsen P.

While spectroscopic scanning deals directly with the whole soil matrix, determination of bicarbonate extractable P by the Olsen method usually involves lengthy equilibrations of solutions of known initial concentrations, with soil suspensions. Hence chemical determination of soil extractable P does not deal directly with the soil matrix, but with nutrient availability that are more dependent on a more transient criterion. Consequently, near-infrared prediction of bicarbonate extractable phosphorus was poor probably because the extractable P is more related as much to the level of phosphorus in solution rather than to the soil chemistry. This is unlike in situations where excellent NIR predictions are expected in total phosphorus. This is because total P is dependent on the soil matrix minerals such as carbonates and iron oxhydroxides and organo Al complexes which are known to strongly sorb phosphate anions. Results of a study by Shepherd and Walsh (2002) showed that NIR predicts SOM, clay mineralogy, particle size, iron oxides and total P well, which are the main determinants of available P to plants. Consequently, further research needs to be done to determine whether excellent NIR calibrations can be obtained for soil extractable phosphorus.
On the other hand robust calibrations for OC were obtained with excellent correlation between the predicted and the observed values. This was mainly because organic carbon being a complex mixture of plant debris, humic substances and recalcitrant material (Theng et al., 1992), typically contains proportions of chemical groups such as H$_2$O, CH$_2$-1 and CH$_3$, (alkyl), C-OH, C = O (carbonyl), and aromatic C = C and CH (Janik and Skjemstand, 1995; Parfitt et al., 1997) which are best known to absorb radiation in the visible and near infrared wavelengths. SOM consists of decayed and undecayed plant and animal tissue, their decomposition products and the more stable organic matter. Particularly, humic substances comprise a large proportion of SOM. These are complex aromatic macromolecules with amino acids, amino sugars, peptide and aliphatic compounds involved in linkages between the aromatic groups. Thus the structure of humic acids and hence organic carbon contains free and bound phenolic OH- groups, N and COOH groups variously placed on the aromatic rings, which well absorb infrared radiation and the consequent reflection.
CONCLUSION AND RECOMMENDATIONS

5.1 Key findings and Conclusion

Continuous supply of plant nutrients by soils is an essential part of long-term sustainability of crop production. In semi-arid Machang’a, Mbeere District, SOM is rapidly declining and farmers regard low soil fertility as a major constraint to food production and therefore a priority for research (Micheni et al., 1999). Phosphorus deficiency is particularly a major constraint and this is due to the low native P reserves in the soils (Sanchez et al., 1997; Deckers, 1993) which is further compounded by long-term P exports from the soils in crop harvests and crop residue removal (Fairhurst et al., 1999). The result has been declining food production over the years and the ultimate degradation of the soil resource. There is thus an indisputable need to correct loss of fertility in Machang’a soils. Soil organic matter is unduly accepted as a key soil quality indicator. This study was carried out with the intention of determining appropriate and accurate strategies for remedying organic matter, and phosphorus deficiency in Machang’a site located in semi-arid Eastern Kenya. The key objectives for the study were;

1. To assess the effects of manure and inorganic fertilizer use on soil extractable P and soil organic carbon.

2. To determine the residual available phosphorus created by long-term manure and inorganic fertilizer application.

3. To assess the effectiveness of diffuse reflectance spectroscopy as an alternative analytical tool for rapid assessment of soil quality changes caused by long-term manure and fertilizer application.
The results of the study demonstrated that the decline in soil organic carbon and available phosphorus can be remedied through application of organic and inorganic soil amendments. A high quality goat manure applied at 10 t/ha/yr was observed to highly increase the amount of plant extractable phosphorus as well as maintain the level of soil organic carbon. Though application at 5 t/ha/yr had almost the same effects on the level of SOC, this treatment was found not to significantly increase the available P level. NP fertilizers applied at 51 and 12 kg/ha/yr respectively also proved effective in checking the decline in plant available phosphorus, but at a relatively lower level than in manure. However, this treatment was less effective in remedying soil organic carbon in any of the sampling seasons. A one time application of 250 kg/ha TSP significantly increased the level of P throughout the nine years that the experiment lasted, but no influence on organic carbon (OC) was noted. The application of organic inputs (manure) in many cases proved an effective soil carbon and available P remedy, but only at a higher application rate of 10 t/ha/yr manure.

With regard to the soil phosphorus fractions, the labile and moderately labile soil phosphorus increased in continuous manure at 10 t/ha/yr while that at 5 t/ha/yr was negligibly influenced. Overall, as compared to resin P, bicarbonate P fraction was much less implying that most of the directly exchangeable P was held in the resin P fraction and hence readily bioavailable for crop use. Though soil P from other pools can enter the available P pool, resin P is normally used as an index of P availability. Since resin P pool was highest in manure treated samples, this then implied that manure increased plant available P the highest. Manure also led to an increase in NaOH Pi, which is regarded as a sink for excess phosphorus. This fraction has
therefore the potential for supplying crop available phosphorus in the long-term. Continuous NP inorganic fertilizers and initial recapitalization of P using TSP also raised the labile P fractions but the influence was not as pronounced as in continuous manure. Residual manure was found to be less effective in remedying phosphorus deficiency since the effects lasted only one year after application. Generally, it was noted that bio-available P fractions (resin and bicarbonate) were higher where P was applied at 10 t/ha/yr than at 5 t/ha/yr. Repeated manure application, thus, offered a better option in remedying P deficiency as compared to inorganic fertilizers.

Near infra-red spectroscopy proved an excellent analytical tool with regard to SOC prediction. Robust calibration models were developed to predict the level of SOC by various treatments with a high degree of accuracy. The method is also known to have a high degree of repeatability (precision). Values for the validated models were only a little bit lower as compared to those of the calibrations, indicating the stability of the model, and hence implying that the model can be used to predict for unknown samples. Exploratory studies using principal component analysis and discriminant analysis showed that treatments effects on spectral data could be discerned. However, poor NIR predictive models were obtained for the soil extractable phosphorus.

In conclusion therefore, Infrared spectroscopy particularly when used with multivariate analytical methods was shown to be able to predict soil management treatment effects on soil organic carbon with a high degree of accuracy. It can achieve this rapidly with a minimum of sample preparation, an important advantage for large
soil sets. The low cost and accuracy of the infrared method opens up its possible use in broad-scale precision farming and soil resources monitoring and assessment. So, can diffuse reflectance spectroscopy be an alternative soil analytical tool? In general, the technique should be viewed as mostly adding value to or expanding existing extraction methods. While it is not expected that NIRS will replace the extractable nutrients analysis used in conventional soil fertility assessment, infrared methods have the potential to rapidly and non-destructively predict soil quality changes caused by various management regimes, adding considerable value to soil analysis. The main challenge limiting the use of this technology is to design spectral indicators of soil fertility that can be used independently of wet chemistry data.

5.2 Recommendations

The following are the recommendations emanating from this study:

- Since goat manure is a readily available resource in Mbeere district, farmers can use it to ameliorate the soils in their farms. This would increase organic carbon and phosphorus availability. However, to be able to effectively remedy the declining soil fertility and sustain agricultural production, application of manure at 10 t/ha/yr is recommended. Farmers in the area should therefore integrate livestock in their farming systems for sustained production of manure, which will help meet the recommended quantities and therefore ensure a continuous input to the farms.
• A combination of continuous manure at 10 t/ha/yr and 250 kg TSP/ha can also be applied to the farms. This is economically attractive since buying costs of fertilizers are only incurred once and the beneficial residue value can last up to approximately ten years. A one time application also reduces labour. However, this would require large capital outlay for which farmers would need to purchase the fertilizers and is logistically difficult. Environmental service payments should be considered in the area as strategy for motivating farmers to observe and maintain healthy environment. Maintaining SOC is an important environmental objective. Micro-finances should also be established in the area to empower the farmers and hence raise their purchasing power.

5.3 Further research

• Further research should develop spectral indices of soil fertility that can be used to assess and monitor effects of management. The main challenge is to design generalisable indicators that can be used at a watershed scale beyond a single experiment as done here.

• Further research and exploratory statistics need to be carried out to determine the applicability of NIR spectroscopy for determination of bioavailable soil P, and in particular to relate crop response directly to soil spectral information.

• Lastly, in long-term experiments, baseline soil sampling should be done at the start of the experiment to enable rigorous before and after impact analysis.
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APPENDICES

Appendix I. Laboratory spectrophotometer that was used for scanning the soil samples
Appendix II. Graph showing the annual rainfall averages recorded in Machang’a from 1998 to 2002
Appendix III. Trial 1 Soil phosphorus fractions

![Sequential P fractions graph]

**Phosphorus (mg/kg)**

**Sequential P fractions**

- RP
- NaHC
- O$_3$-Pi
- NaHCO$_3$
- M1
- NaHC
- O$_3$-Pt
- NaOH
- IP
- NaOH
- Po
- NaOH
- Pt
- HCL P

Legend:
- Control
- M1
- M2
- F
- R1
Appendix IV. Trial 2 Soil phosphorus fractions

![Graph showing sequential P fractions](image-url)
Appendix  Map of Kenya showing the site of the study