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ABSTRACT

Land degradation remains a major threat to the provision of environmental services and the ability of smallholder farmers to meet the growing demand for food. Understanding patterns of land degradation is therefore a central starting point for designing any sustainable land management strategies. However, land degradation is a complex process both in time and space making its quantification difficult. There is no adequate monitoring of many of the land degradation issues both at national and local scale in Kenya. The objective of this study conducted between 2009 and 2012 was to assess the land degradation patterns in Kenya as a basis for making recommendations for sustainable land management. The correlation between vegetation and precipitation and the change in vegetation over the period 2001-2009 was assessed using 250 m resolution Moderate Resolution Imaging Spectroradiometer - Normalized Difference Vegetation Index (MODIS/NDVI) and time-series rainfall data. The assessment at national levels revealed that, irrespective of the direction of change, there was a significant correlation between vegetation (NDVI) and annual precipitation for 32% of the land area. The inter-annual change in vegetation cover, depicted by the NDVI slope, was between -0.067 and +0.068. A negative NDVI slope (indication of degradation) was observed for areas around Lake Turkana and several districts in eastern Kenya. Positive NDVI trends were observed in Wajir and Baringo, which are located in the dry land areas, showing that the vegetation cover was increasing over the years. NDVI difference between the baseline (2001-2003) and end line (2007-2009) showed an absolute change in NDVI of -0.42 to +0.48. But the relative change was between -74% for the degrading areas and +238% for the improving areas with most of the dramatic positive changes taking place in the drylands. Relative to the baseline, 21% of the land was experiencing a decline in the vegetation cover, 12% was improving, while 67% was stable. Classification of Landsat imagery for the period 1973, 1988 and 2003 showed that there were significant changes in land use land cover (LULC) in the western Kenya districts with the area under agricultural activities increasing from 28% in 1973 to 70% in 2003 while those under wooded grassland decreasing from 51% to 11% over the same period. Detailed field observations and measurements showed that over 55% of the farms sampled lacked any form of soil and water conservation technologies. Sheet erosion was the most dominant form of soil loss observed in over 70% of the farms. There was a wide variability in soil chemical properties across the study area with values of most major properties being below the critical thresholds needed to support meaningful crop production. Notable was the high proportion (90%) of farms with slightly acidic to strongly acidic (pH <5.5) soils. Over 55% of the farms had less than 2% soil organic carbon. There was a wide variability in the potential nutrient supply and uptake of the soils with the plots classified as high fertility (HF) having three times higher potential supply of nitrogen and phosphorus compared to the low fertility (LF) plots. The estimated maize yield potential of the soils was between 1.6 t/ha and 2.8 t/ha. However, the actual yield at farm level was less than 1 t/ha. There was a general consensus among the land owners that the productivity of the land, livestock, forests and water resources had declined. Combining methods and approaches for land degradation monitoring and assessment enabled capturing different aspects of the problem of land degradation, and thus important information for the design of sustainable land management strategies. Addressing the multiple nutrient deficiencies and low productivity requires adoption of integrated soil fertility management practices.

Erfassung und Bewertung verschiedener Erscheinungsformen von Landdegradation in West Kenia: Konsequenzen für Restaurierungs- und Rehabilitierungsmaßnahmen

Kurzfassung

Landdegradation stellt eine der größten Gefahren für die Bereitstellung von Umweltdienstleistungen dar und für die Kleinbauern hinsichtlich des wachsenden Bedarfs an Nahrungsmitteln. Die Entwicklung nachhaltiger Landnutzungsstrategien beginnt daher mit dem Erkennen und Verstehen von Landdegradationsmustern. Die komplexen Prozesse der Landdegradation über Raum und Zeit erschweren jedoch eine Quantifizierung. Bisher existiert in Kenia kein adäquates Monitoring der Landdegradation, weder auf nationaler noch auf lokaler Ebene. Das Ziel des von 2009 bis 2012 durchgeführten Studie war die Erfassung von Landdegradationsmustern in Kenia, um Empfehlungen für nachhaltige Landmanagementstrategien geben zu können. Die Korrelation zwischen Vegetation und Niederschlag und der Vegetationsveränderungen im Zeitraum 2001 bis 2009 wurde mittels einer MODIS/NDVI (Moderate Resolution Imaging Spectroradiometer (250 m-Auflösung) - Normalized Difference Vegetation Index) ermittelt. Die Untersuchungen auf nationaler Ebene ergaben, dass, unabhängig von der Richtung des Änderungsprozesses, eine signifikante Korrelation zwischen Vegetation (NDVI) und jährlicher Niederschlagsmenge für 32% der Landfläche besteht. Die Änderung der Vegetationsdecke über mehrere Jahre, dargestellt durch die NDVI-Linie, lag zwischen -0.067 und +0.068. Eine abfallende NDVI-Linie (als Indikator für Degradation) konnte für Flächen rund um Turkana See und in mehreren Distrikten Ost-Kenias beobachtet werden. Positive NDVI-Trends traten in den Trockengebieten Wajir und Baringo auf; dies deutet darauf hin, dass die Vegetationsdichte hier über die Jahre zunahm. Die Differenz des NDVI zwischen Ausgangswerten (2001-2003) und Endwerten (2007-2009) zeigte eine absolute NDVI-Veränderung von -0.42 bis +0.48. Die relative Veränderung war jedoch -74% für degradierende Flächen und +238% für Flächen mit zunehmender Vegetationsbedeckung, wobei die höchsten positiven Veränderungen in den Trockengebieten festgestellt wurden. Im Vergleich zu den Basisdaten fand auf 21% der Flächen eine Abnahme der Vegetationsbedeckung statt, 12% der Landflächen erfuhr eine Verbesserung und 67% verzeichnete keine Veränderungen. Die Klassifizierung der Landsat-Aufnahmen von 1973, 1988 und 2003 zeigte signifikante Veränderungen in der Landbedeckung bzw. Landnutzung in den Distrikten West Kenias . Der Anteil der landwirtschaftlich genutzten Fläche stieg von 28% im Jahre 1973 auf 70% in 2003 an, während der Flächenanteil der Baum- und Strauchsavanne im gleichen Zeitraum von 51% auf 11% abnahm. Detaillierte Felduntersuchungen ergaben, dass mehr als 55% der untersuchten Farmen keine Boden- oder Wasserschutzmaßnahmen durchführen. Bodenerosion stellte die Hauptursache von Bodenverlust dar und konnte bei über 70% der Farmen festgestellt werden. Die chemischen Bodeneigenschaften im Untersuchungsgebiet waren sehr variabel; viele der wichtigsten Bodeneigenschaften lagen unter den kritischen Grenzwerten, die für erfolgreichen Pflanzenbau notwendig sind. Auffällig war der hohe Anteil an Farmen (90%) mit leicht bis sehr sauren Böden (pH<5.5). In den Böden von über 55% der Farmen lag der organischer Kohlenstoffgehalt unter 2%. Potentieller Nährstoffvorrat und -aufnahme der Böden waren sehr variabel. Flächen, die als sehr fruchtbar klassifiziert wurden, hatten ein dreifach höheres Vorratspotential an Stickstoff und Phosphor im Vergleich zu Flächen mit geringer Fruchtbarkeit. Der geschätzte potenzielle Maisertrag der Böden lag zwischen 1.6 t/ha und 2.8 t/ha. Der aktuelle Ertrag lag mit weniger als 1 t/ha jedoch darunter. Insgesamt waren die Farmer der Meinung, dass die Produktivität der Landnutzung, Tierhaltung, und Forst- und Wasserressourcen gesunken sei. Durch die Kombination verschiedener Erfassungs- und Monitoringmethoden konnten verschiedene Aspekte der Landdegradation und damit wichtige Informationen für die Entwicklung nachhaltiger Landnutzungsstrategien erfasst werden. Um Bodennährstoffmangel und niedrige Bodenproduktivität positiv zu verändern, müsste ein integriertes Bodenmanagement zur Erhöhung der Bodenfruchtbarkeit umgesetzt werden.

TABLE OF CONTENTS

1	INTRODUCTION	1
1.1	General	1
1.2	Objectives	4
1.3	Thesis layout	4
2	BACKGROUND	6
2.1	Challenges of meeting Africa's food demand	6
2.2	Land degradation in perspective	6
2.3	Land degradation processes	7
2.4	Land degradation drivers, pressures, types and indicators	7
2.4.1	Direct drivers (pressures)	7
2.4.2	Indirect drivers	8
2.4.3	Types of land degradation	10
2.4.4	Indicators of land degradation	12
2.5	Land use and land cover (LULC) change and degradation	13
2.5.1	Assessment of LULC change	14
2.6	Land degradation assessment	16
2.7	Measurement of land degradation	17
2.7.1	Direct field measurements	17
2.7.2	Geospatial remote sensing technique	18
2.7.3	Radionuclides and land degradation	18
2.7.4	Modeling	19
2.8	Soil testing	19
2.9	Theoretical framework of land degradation assessment	20
3	STUDY AREA AND GENERAL METHODOLOGY	23
3.1	Kenya in perspective	23
3.2	Study area	25
3.2.1	Location of the study area and rational for site selection	25
3.2.2	Agro ecology	26
3.2.3	Soils	27
3.2.4	Population	27
3.2.5	Economy	28
3.3	General methodology	29

3.3.1 Description of the land degradation assessment approach ... 30
3.3.2 Data analysis ... 35

4 MAPPING LAND DEGRADATION PATTERNS USING NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI) AS A PROXY ... 36

4.1 Introduction ... 36

4.2 Methodology ... 39

4.3 Results ... 42
4.3.1 Correlation between biomass (NDVI) and inter-annual rainfall ... 45
4.3.2 Pixel-based linear slope of inter-annual NDVI ... 48
4.3.3 Land degradation patterns in Western Kenya ... 53

4.4 Discussion ... 57

4.5 Conclusion ... 62

5 LAND USE LAND COVER (LULC) CHANGE AND IMPLICATIONS FOR LAND DEGRADATION ... 65

5.1 Introduction ... 65

5.2 Study area and description ... 67

5.3 Materials and methods ... 68
5.3.1 Image pre-processing ... 70
5.3.2 Computation of NDVI ... 71
5.3.3 Image classification ... 72
5.3.4 Image post-classification ... 74

5.4 Results ... 77
5.4.1 Land cover change classification based NDVI values ... 77
5.4.2 Land use land cover change classification based supervised and unsupervised classification ... 79

5.5 Discussion ... 82
5.5.1 Classification based on NDVI ... 82
5.5.2 Classification based on Landsat image band combination ... 83

5.6 Conclusion ... 84

6 EVALUATING INDICATORS OF LAND DEGRADATION IN SMALLHOLDER FARMING SYSTEMS OF WESTERN KENYA ... 86

6.1 Introduction ... 86

6.2 Methodology ... 89
6.2.1 Study area and sampling framework ... 89
6.2.2 Plot and sub-plot level measurements ... 90
6.2.3 Land degradation indicator and attribute mapping ... 92

6.2.4 Soil sampling and analysis ... 93
6.2.5 Data analysis ... 95
6.3 Results ... 96
6.3.1 Attributes and indicators of land degradation ... 96
6.3.2 Calibration and prediction of soil chemical properties ... 101
6.3.3 Principal components analysis (PCA) of soil properties ... 109
6.4 Discussion ... 112
6.5 Conclusions ... 115

7 POTENTIAL NUTRIENT SUPPLY, UPTAKE AND CROP PRODUCTIVITY IN SMALLHOLDER CROPPING SYSTEMS OF WESTERN KENYA ... 117

7.1 Introduction ... 117

7.2 Methodology ... 120
7.2.1 Study area ... 120
7.2.2 Soil sampling and analysis ... 121
7.2.3 Interpretation of the soil chemical properties ... 122
7.2.4 Predicting nutrient supply, uptake, yield gap and productivity using QUEFTS ... 123
7.2.5 Statistical analysis ... 127

7.3 Results ... 127
7.3.1 Interpretation of threshold values of soil chemical properties ... 127
7.3.2 Prediction of nutrient supply, uptake and production potential under high, medium and low soil fertility ... 129

7.4 Discussion ... 135

7.5 Conclusions ... 140

8 LAND DEGRADATION FROM THE LAND USERS PERSPECTIVE: A CASE OF WESTERN KENYA ... 142

8.1 Introduction ... 142

8.2 Methodology ... 143
8.2.1 Description of study area ... 143
8.2.2 Survey ... 143
8.2.3 Data analysis ... 144

8.3 Results ... 144
8.3.1 Household socio-economic characteristics ... 144
8.3.2 Perception of changes in land productivity ... 149
8.3.3 Types of land degradation ... 150
8.3.4 Causes of degradation ... 151
8.3.5 Vulnerability of the household to impacts of land degradation ... 152
8.3.6 Soil and water management technologies ... 154

8.4 Discussion ... 154

8.4.1 Implication of household characteristics on land degradation 154
8.4.2 Perception of land degradation 158
8.4.3 Direct causes of land degradation 160
8.4.4 Indirect causes of land degradation 161
8.4.5 Vulnerability and adapting to land degradation 163

8.5 Conclusions 164

9 SYNTHESIS AND CONCLUSION 166

9.1 Introduction 166

9.2 Major findings 166
9.2.1 Mapping land degradation patterns 166
9.2.2 Land use land cover change 167
9.2.3 Evaluating indicators of land degradation 168
9.2.4 Implication of land degradation on land users 169

9.3 Research and policy implications 169

REFERENCES 172

APPENDICES 198

ACKNOWLEDGEMENT 211

1 INTRODUCTION

1.1 General

Kenya is an agricultural nation with over 80% of its population directly and indirectly dependent on agriculture. Agriculture is the second contributor to the gross domestic product (GDP) of the country. Unfortunately, food production has failed to keep pace with the ever-increasing human population. Despite the country having been food self-reliant at independence (1963), it has become a net food importer and heavily relies on food imports and aid. On average, production of the major cereal, maize, is less than 1 MT/ha on most smallholder farmers' fields compared to up to 8 MT/ha on experimental stations or under good management (Muasya and Diallo 2001). The low production has been attributed to low use of external inputs as well as declining soil fertility resulting from increased nutrient mining and land degradation. Other factors include increasingly adverse weather and poor macro-economic and sectoral policy.

Studies show that nutrient balances on most smallholder farms in 37 countries in sub-Saharan Africa (SSA) were negative (-22 kg N, -2.5 kg P and -15 kg K per hectare) over the last 30 years (Stoorvogel and Smaling 1990; Smaling et al. 1993; Stoorvogel et al. 1993). The annual loss is equivalent to US$ 4 billion in fertilizer (IAC 2004). The full potential of improved crop varieties cannot be realized when the soils are depleted of nutrients. Studies indicate that fertilize use efficiency is usually low in degraded land (Vanlauwe et al. 2006; Tittonell et al. 2007). This explains why food production remains low despite farmers investing in the use of inorganic fertilizers. It is therefore logical that improving food production calls for addressing the problem of land degradation, specifically soil erosion and nutrient depletion.

Land degradation is a major threat to ecosystem functioning in the areas classified as having both high and low agricultural potential in Kenya. More recent studies extrapolating on local findings of spatial and temporal patterns estimate that land degradation is increasing in severity and extent in many areas of the country and that over 20% of all cultivated areas, 30% of forests, and 10% of grasslands are subject to degradation (Muchena 2008). Unfortunately, the areas, which experience the highest degradation risk, coincide with the most productive areas in the country. These areas include the Central Kenya Highlands, the eastern Districts of Machakos, Kitui and Embu, Western Kenya, the Lake Victoria basin and some parts of the coastal zone. These areas also continue to experience increased fragmentation and deforestation due to increasing pressure for new cultivation and grazing lands as well as for settlement. Land scarcity has caused increased migration of people to the fragile arid and semi arid areas in search of land for cultivation and settlement. Cultivation of such arid areas characterized by little and unreliable rainfall results in frequent crop failures and leaves most of the land bare for long periods hence increasing the vulnerability of the land to soil erosion (Mwasi 2001). Recent attention to the issue of global environmental change has focused on the interrelationship among climate change, food security and land degradation. According to a study reported in (CBD 2011), climate change and land degradation are interconnected, not only through effects of climate change on land management but also through changes in ecosystem functioning that affect climate change. Maintaining and restoring healthy ecosystems will therefore play a key role in adapting to and mitigating impacts of climate change.

There have been significant changes in the land use and land cover (LULC) across the country and western Kenya in particular. Major shifts have been increase in areas under agriculture and decreases in natural vegetation formations such as forests, bush land, grasslands and wetlands (Githui et al. 2009). These changes are a result of the increasing human population and increased demand for food and fuel wood. With such changes, the potential for land degradation is high especially where such LULC changes have occurred.

Assessment of land degradation is a complex process driven by both natural and anthropogenic forces. Secondly, land degradation occurs at varied temporal and spatial scales making its quantification a great challenge. High costs of soil analysis equally hamper assessments and management of land degradation. Whereas direct measurement is considered the most accurate approach of land degradation assessment, this approach is limited in terms of the representativeness of the data obtained (Pickup 1989), the spatial resolution and patterns and potential to provide information on long-term rates of land degradation. Direct measurement approaches are also labor intensive, time consuming and costly especially for large areas (Loughran 1989; Hill et al. 1995). Recent advances in science have led to development of techniques capable of rapidly and effectively mapping out areas under threat of degradation. These techniques include remote sensing and geographical information systems (GIS), environmental radionuclides as tracers and use of infrared spectroscopy. The opportunities offered by the above advances can be used to map out patterns of land degradation at various scales relatively faster and with reasonably low cost (Sanchez et al. 2009).

Various studies have been undertaken to understand LULC changes and land degradation. The studies at continental and/ or national scale (Bai and Dent 2006; Bai et al. 2008; Vlek et al. 2008) are at course resolution and the results from such studies are good for modeling environmental change and for general policy recommendations. There is need to undertake studies at landscape level to ascertain the actual status, causes and impacts of land degradations as a basis for recommending practical sustainable land management (SLM) practices to the land users. Other studies in the region have been resource specific in nature, mainly focusing on forests (Kokwaro 1988; ICRAF 1996; Lung and Schaab 2004; Mitchell 2004; Schaab et al. 2009) and wetlands (Owino and Ryan 2007). There is a need to undertake comprehensive land degradation studies that take into consideration the full range of resources and their uses at landscape level. Few comprehensive soil surveys have been conducted in the study area in the past, and much of the existing data were not georeferenced. Like many other studies, wide varieties of laboratory tests and analytical procedures have been used to generate the chemical and physical data in the different projects. This makes it difficult to harmonize and compare over time. As a result, there is a need for the adoption of standardized sampling and analytical procedures to facilitate a comprehensive assessment of soil health and degradation prevalence for the region. Beyond the biophysical assessments, it is necessary to understand the socio-economic factors and how they influence land use and hence land degradation patterns and how the communities adapt to the changing environmental conditions.

This study therefore employed a systematic framework that takes into account spatial and temporal changes in land degradation while at the same time taking into consideration the anthropogenic factors influencing land degradation. The study results increase knowledge on the extent and patterns of land degradation in Western Kenya. Results of this study are tenable for comparison with similar studies in the region and hence can be used in defining recommendation domains of conservation practice not only in the study area but other similar regions in the country.

1.2 Objectives

The overall objective of the study is to assess land degradation patterns in Kenya as basis for making recommendations for sustainable land management.

Specific objectives

1. To map patterns and quantify the extent of land degradation,
2. To assess long-term land-use and land-cover changes,
3. To evaluate causes of the observed land degradation patterns, and
4. To assess the impacts of land degradation as a basis for enhancing the awareness and capacity of stakeholders for restoration and rehabilitation.

1.3 Thesis layout

Chapter 1 of the thesis presents a general introduction and problem statement as well as the objectives of the study. Chapter 2 reviews relevant literature on the problem of land degradation highlighting entry points for the current research. The third chapter presents a general description of the study area, methodology and data analysis approaches. Chapter 4 examines patterns of land degradation at national level based on Normalized Difference Vegetation Index (NDVI) as a proxy. The results of the NDVI trend analysis are used to demarcate benchmark sites for more detailed field assessments. General trends in land use and land cover (LULC) change for the study area are discussed under Chapter 5. Chapter 6 presents a discussion on the attributes and indicators of land degradation at selected benchmark sites. Chapter 7 presents predictions of supply and uptake of soil nutrients and potential productivity of the soils in the croplands as estimated using QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model. The study further evaluates the land degradation problem as perceived by the land users as an attempt to understand the socio-economic dimension of the problem and to bridge the scientific and indigenous knowledge (Chapter 8). The final chapter (9) is a synthesis that brings together major issues and key findings cutting across all the preceding sections and highlights policy implications, development needs and future research needs.

2 BACKGROUND

2.1 Challenges of meeting Africa's food demand

Africa remains the only continent in the world that has failed to meet the food demand for its growing human population (Sanchez 2002). Agriculture contributes about 9% to the gross domestic product (GDP) and more than 50% of the total employment (Pinstrup-Aderesen 2002). Statistics show that over 70% of the food insecure population in Africa lives in the rural areas and produce over 90% of the continent's food requirements (UNDP 2003). Previously, the continent was characterized by extensive traditional farming systems based on shifting cultivation. But rapid demographic and economic changes have irreversibly changed the ecological balance upon which these extensive systems depended (Matlon and Spencer 1984). The cultivated area has expanded onto marginal soil types, and fallow periods are being systematically reduced due to increased land fragmentation and change in tenure systems. The situation has been made worse by the persistent droughts in much of the region. These circumstances have severely constrained the regions capability to feed its own population and meet its development goals.

2.2 Land degradation in perspective

Land degradation remains a major threat to the world's ability to meet the growing demand for food and other environmental services. It is complex and involves the interaction of changes in the physical, chemical and biological properties of the soil and vegetation (NRC 1994). The complexity of land degradation means that its definition differs from area to area, depending on the subject to be emphasized. A review of literature reveals a wide range of definitions of land degradation (GLASOD 1988; UNCCD 1994; Hill et al. 1995; Bai et al. 2008). All these definitions point to a state of the land losing its capacity to provide the services intended. This study adopted the defining of land degradation as presented by Reynolds (2001) which states that: 'land degradation is a persistent reduction in the biological and economic productivity of terrestrial ecosystems, including soils, vegetation, other biota, and the ecological, biogeochemical and hydrological processes that operate therein'.

2.3 Land degradation processes

Mechanisms that initiate land degradation include physical processes such as decline in soil structure leading to soil compaction, erosion and desertification); chemical processes such as acidification, leaching, salinization and fertility depletion; and biological processes such as reduction in total and biomass carbon, and decline in land biodiversity (Lal 1994b). Causes of land degradation are the agents that determine the rate of degradation and include biophysical (land use and land management, including deforestation and tillage methods), socio-economic (e.g., land tenure, marketing, institutional support, income and human health), and political (e.g., incentives, political stability) (Eswaran et al. 2001). Climate change is also emerging as a major underlying cause of land degradation (Vlek et al. 2008).

2.4 Land degradation drivers, pressures, types and indicators

2.4.1 Direct drivers (pressures)

The main direct drivers (pressures) contributing to land degradation in sub-Saharan Africa (SSA) are non-sustainable agriculture, overgrazing by livestock, and overexploitation of forests and woodlands. The need to produce more food for the rapidly increasing human population has led to the rapid expansion of agricultural land and the shortening of the fallow periods in traditional, extensive land-use systems, which have reduced the regeneration of soil fertility through natural processes (Finegan and Nasi 2004). Today, close to 33% of the earth's land surface is devoted to pastures or cropland (de Sherbinin 2002). Much of the recent increase in area under agricultural land continues to occur mostly in developing countries, mainly Africa and Latin America (Houghton 1994).

The increased use of fire as a clearing tool especially in the savanna and forest margins has further led to loss of nutrients in many systems (Pivello and

Coutinho 1992). Nutrient losses through fire are proportionally much larger for nitrogen than for phosphorus and other nutrients (Van de Vijver et al. 1999). Fire is also considered as a non-selective herbivore that ‘feeds’ uniformly on vegetation (Bond and Keeley 2005) and hence contributes significantly to vegetation loss.

Rangelands are experiencing high grazing pressure, which affects overall rangeland productivity. Vegetation studies show that high grazing pressure leads to changes in species composition, which may reduce the resilience of rangelands for droughts (Hein and Weikard 2008). Recent years have seen droughts with severe impacts on livestock and local livelihoods in arid and semi-arid lands of East Africa. The rangelands are also experiencing a rapid decline in tree cover. The demand for timber and wood products for construction and energy (fuel wood and charcoal), especially in neighboring urban centres is increasing.

Most forests and woodlands of SSA continue to suffer from rapid deforestation. This is driven by a number of processes, such as continued demand for agricultural land, local use of wood for fuel wood, charcoal production and construction purposes, large-scale timber logging, often without effective institutional control of harvest rates and logging methods, and population movement and resettlement schemes in forested areas (Boucher et al. 2011). The rapid expansion of agricultural land as discussed above has come mainly at the expense of forests and rangelands.

2.4.2 Indirect drivers

Beside the direct drivers of land degradation, there are indirect causes such as population growth, poverty and climate change. Currently, the SSA population is growing at 2.1% per year, and, in the next 15 years, the region will have to accommodate at least 250 million (33%) more people (UNEP et al. 2005). Most areas experiencing rapid population growth and density have shown evidence of land degradation. Only isolated cases have been documented regarding the positive contribution of high population on sustainable land management (SLM) (Tiffen et al.

1994). In most other cases, high population has been associated with increased pressure on natural resources leading to land degradation in various forms.

Poverty has been identified as another indirect cause of land degradation. Between 1981 and 2001, the number of people in SSA living on less than US$ 1 a day increased by 93%, from 164 million to 316 million (UNEP et al. 2005) accounting for about 46% of the population of the region (Chen and Ravallion 2004). The majority of the poor are smallholder farmers located in the rural areas. These farmers depend on the already degraded lands to meet their food requirements. Often, the farmers will expand their farming system to other new and sometimes fragile ecosystems, and without incentives will engage in unsustainable farming practices that contribute to degradation of these areas. As such, the poor farmers are trapped in a vicious cycle of poverty and land degradation (Bationo et al. 2007a).

Recent studies have shown that climate change also contributes to land degradation. For example, the recent (2011) drought in East Africa, which directly affected an estimated 10 million people in Ethiopia, Kenya and Somalia, served to remind us that Africa is the continent most vulnerable to climate change. The continent has a long history of rainfall fluctuations of varying lengths and intensities (Singh 2006). Droughts and floods are two important climatic events responsible for land degradation. The continent has experienced droughts since the 1910s (Gommes and Petrassi 1994). The most prolonged and widespread droughts occurred in 1973 and 1984, when almost all African countries were affected, and in 1992, when all southern African countries experienced extreme food shortages. With the advent of droughts, net primary productivity is reduced and with intense grazing, most of the land is left exposed to agents of erosion, i.e., wind and water. The recurrent droughts have in some instances made it impossible for the natural vegetation to regenerate to its original state. In 1998, many parts of East Africa experienced record rainfall (up to ten times the usual amount) as a result of the El Nino phenomena, and this caused disastrous flooding. When such floods occur immediately after a drought, large volumes of soil are washed away from the exposed land leading to degradation. The International Panel on Climate Change (IPCC) predicts that the frequency and intensity of droughts and floods in SSA is likely to increase in the coming years due to climate change. Studies have shown that future warming will intensify the inter-annual variability of East Africa's rainfall thereby impacting on how land is used (Wolff et al. 2011).

2.4.3 Types of land degradation

It is estimated that 65% of SSA's agricultural land is degraded because of water and soil erosion, chemical and physical degradation (Oldeman et al. 1991; Scherr 1999). Of the total degraded area, overgrazing, agricultural mismanagement, deforestation and overexploitation of natural resources are said to account respectively for 49, 24, 14 and 13% (Oldeman et al. 1991; Batjes 2001). Other types of land degradation include salinization and depletion and pollution of water resources.

Soil erosion

Soil erosion is a major factor in land degradation and has severe effects on soil functions such as soil's ability to act as a buffer and filter for pollutants, its role in the hydrological and nitrogen cycle, and its ability to provide habitat and support biodiversity. Water and wind erosion, respectively, account for 46% and 38% of all the degradation (GLASOD 1988). Bielders et al., (1985) noted that wind erosion can remove up to 80 tons of soil on one hectare in a single year. Furthermore, the deposition of sand on top of plant seedlings causes crop losses. Whereas soil erosion is a natural geomorphic process, human activities such as cultivation, overgrazing and deforestation accelerate the process beyond the acceptable levels. With an increasing human population, farming and livestock keeping is being expanded into remote, steep and hilly slopes thus increasing the potential for accelerated rates of erosion. Excessive erosion is associated with diverse negative on- and off-site impacts, including loss of soil nutrients, leading to a reduction in crop yields, decreasing stream competence and capacity because of sedimentation, and siltation of reservoirs (Tamene 2005). Additionally, agricultural chemicals transported with soil particles have significant impacts on water quality.

Soil nutrient depletion

Smallholder farmers continue to lose nutrients from their farms mainly through crop harvest and soil erosion without the use of sufficient quantities of manure or fertilizer to replenish the soil. This has resulted in very high average annual nutrient depletion rates estimated at 22 kg nitrogen (N), 2.5 kg phosphorus (P), and 15 kg potassium (K) per hectare of cultivated land at continental level (Stoorvogel and Smaling 1990; Smaling et al. 1993). These losses are estimated to be equivalent to US$ 4 billion in fertilizer (Sanchez et al. 1997; IAC 2004). Similar depletion rates are also replicated at sub-national levels. For example, annual losses of 112 kg N/ha, 2.5 kg P/ha, and 70 kg P/ha were observed on smallholder farmers' fields in the western Kisii highlands of Kenya (Smaling et al. 1993; Smaling et al. 1997).

Unfortunately, external fertilizer use in Africa has not kept pace with the increased land-use intensification, or compensated for nutrient losses through crop harvests and soil erosion. Fertilizer use in SSA averages only 8 kg/ha, compared with 96 kg/ha in East and Southeast Asia and 101 kg/ha in South Asia (Morris et al. 2007). Africa accounts for less than 1% of global fertilizer consumption. The response of the poor farm households to declining land productivity has been the abandonment of the degraded pasture and cropland and the move to new land for grazing and cultivation. However, with the increasing human population and changes in the land tenure system, opportunities for sifting cultivation have also reduced. As a result, land users now have to cultivate the same pieces of land each year. Without the opportunity to invest in improved soil fertility management technologies, such an impoverished community remains trapped in a vicious cycle of poverty and land degradation (Barbier 2000).

Deforestation

The FAO Global Forest Assessment provides regular statistics of forest cover. The assessments showed that globally, around 13 million hectares of forest were converted to other uses or lost through natural causes each year in the last decade (2000s) compared with 16 million hectares per year in the 1990s (FAO 2010). It is estimated that Africa lost 3.4 million hectares of forest annually between 2000 and 2010 (FAO 2010). In 1975, the estimated forest area in SSA was about 710 million hectares, but this reduced to 595.6 million hectares in 2010 (FAO 2010). In Kenya, the forest cover reduced from 3.7 million to 3.4 million hectares between 1990 and 2010 (FAO 2010). Besides a reduction in the area covered by forests, many remaining forests show degradation in terms of crown cover and species diversity. Deforestation has major implications for biodiversity, production of wood and non-wood forest products and river discharge patterns. Fragmentation and habitat loss are causing local overcrowding of wildlife in restricted areas, leading to increasing human-wildlife conflicts.

Rangeland degradation

Rangelands comprise about 50% of the world's land area (Kamau 2004). Degradation of these areas is driven primarily by overgrazing, which is leading to a loss of vegetation (and hence livestock) productivity, and a loss of resilience of the rangeland to droughts. Overgrazing accounts for about 50% of all land degradation and reduced rangeland productivity in semi-arid and arid regions of Africa (Oldeman et al. 1991; WRI 1992).

2.4.4 Indicators of land degradation

The complexity of soil degradation processes makes it difficult to encapsulate the problem in a few simple measures, hence the need to use indicators of land degradation (Doran and Parkin 1994; FAO 1999; Hess et al. 2000; de Paz et al. 2006). Indicators are variables which may show that land degradation has taken place – they are not necessarily the actual degradation itself. Among the widely used indicators of land degradation are crop yields and soil quality indicators (visual, physical, chemical, and biological) (USDA 1996) and vegetation/biomass (Tucker 1979). Other notable indicators include presence of soil erosion features, soil acidity as manifested by the raised levels of iron (Fe) and aluminium (Al), infestation by parasitic weeds such as Striga, and plant fertility indicators, especially weeds.

Some studies have used remotely sensed data to derive indicators of land degradation. For example, the Normalized Difference Vegetative Index (NDVI) is a commonly used proxy of land degradation derived from remotely sensed data (Kidwell 1997). The NDVI is calculated from remote sensing imageries as the ratio between measured reflectivity in the red and near-infrared portions of the electromagnetic spectrum (Tucker et al. 1985b; NOAA 1988; Vrieling 2007). The NDVI can also be used to compute other vegetation indices such as the net primary productivity (NPP) (Alexandrov and Oikawa 1997; Rasmussen 1998), leaf-area index (LAI) (Myneni et al. 1997) and the fraction of photosynthetically-active radiation absorbed by vegetation (Asrar et al. 1984). (Bai and Dent 2006; Bai et al. 2008) integrated NDVI with rainfall data to calculate what they referred to as the rain use efficiency (RUE). These authors used RUE to reveal trends in land degradation by separating vegetation declines due to lack of rainfall from declines associated with longer term degradation (Bai and Dent 2006; Bai et al. 2008). In another study, Vlek et al., (2008) and Vlek et al., (2010) used NDVI to calculate the NPP, and later used the values to demarcate patterns of land degradation. Despite the differences in approach, the two approaches enabled mapping of land degradation patterns for the studies considered.

2.5 Land use and land cover (LULC) change and degradation

Land degradation patterns have been associated with land-use and land-cover changes. Land cover refers to the physical characteristics of the earth surface, captured in the distribution of vegetation, water, desert, ice and other physical feature of the land including those created solely by human activities such as mine exposures and settlement (FAO 1997). On the other hand, land use is a term used to describe human uses of the land, or immediate actions modifying or converting land cover (FAO 1997; de Sherbinin 2002).

Land-cover and land-use change can be classified into two broad categories: conversion or modification (Butt and Olson 2002). Conversion refers to the changes from one cover or use to another, e.g. conversion of forests to pasture or to cropland. Modification on the other hand refers to the maintenance of the broad cover or use type in the face of changes in its attributes. For example, a forest may be retained but significant alterations may be made on its structure or function. The key LULC change pathways include deforestation, desertification, wetland drainage and agricultural intensification (Butt and Olson 2002). The pathways can be envisioned as forcing functions, which have direction (forest to pasture or pasture to cropland), magnitude (amount of change), and pace (rates of change). LULC changes reflect the complex interaction of human activities and environmental processes over time and space on land. Humans play a key role in contributing to the process and are equally affected by these LULC changes.

Whereas the major reasons for such LULC changes are positive and aim to increase the local capacity to support the human enterprise, there are also unforeseen negative impacts that can reduce the ability of land to sustain the human enterprise (Houghton 1994). For example, deforestation can be beneficial through sale of forest products as well as the use of cleared land to produce food for the local community. However, deforestation can result in the loss of biodiversity and impacts on the hydrological processes, leading to localized declines in rainfall, and more rapid runoff of precipitation, causing flooding and soil erosion. Deforestation can disrupt the carbon cycle and contribute to greenhouse gases, which contribute to climate change (de Sherbinin 2002). Understanding LULC changes is therefore critical for the design of effective land management programmes.

2.5.1 Assessment of LULC change

LULC can be assessed at different scales (hierarchy theory): field to farm, the community, the landscape, and national/continental and global levels (LADA 2009). The different scales of analysis provide different types of information. Global and continental LULC assessment outputs are general in nature and hence are suitable for long-term global environmental change studies such as global climate change and biogeochemical cycles. Conversely, studies at landscape and farm levels are more detailed and provide insights on the actual causes and changes taking place at a given location; such information can aid in designing strategies for rehabilitation and restoration. Studies undertaken at national levels are often used for policy formulation and resource allocation.

The benefit of the hierarchical approach is that the findings from one scale can be used to verify the interpretation of information from other scales. It is however worth noting that data at different scales may seem to be contradictory although all are correct. Processes at different scales may be completely different, hence it may not be possible to directly ‘scale-up’ the results from a local analysis to higher levels by simple aggregation, nor to ‘down-scale’ by ascribing group attributes to individuals (Olson et al. 2004). This is because the different scales are associated with hierarchies of social order, with each level having different actors, (e.g., national government, local government, household, individual) with separate functions, activities and environmental management effects (Blaikie and Brookfield 1987). Similarly, it is important to evaluate how policies vary with scale of assessment (Turner II et al. 1995). Adopting a multi-scalar approach is therefore needed to strengthen both the interpretation and use of LULC data for designing effective sustainable land management programmes.

LULC analysis usually involves the interpretation of geographical or spatial information from aerial photographs, satellite images, ground measurements or maps. By interpreting data from different time periods, temporal changes in the landscape can be determined (Pinheiro et al. 2007). Linking the land use and other spatial data such as roads, elevation or administrative boundaries in a geographical information systems (GIS), allows enhanced interpretation of the land-use information.

Over the years, interest in LULC change studies has grown due to improved availability of remotely sensed data and facilitated analysis software. For example, the United States Geological Survey (USGS) has provided access to a wide range of satellite imagery, some free of charge, which can be used for LULC change assessments. Apart from the commercial remote sensing and GIS software applications (e.g., ArcGIS, IDRISI, ENVI, ERDAS), many open source software (e.g., ILWIS, QGIS, GRASS) with similar capabilities have been developed and made available to researchers and land managers. As a result, LULC has been mainstreamed into global environmental change research because it provides broad-scale data on aspects such as climate change, changing carbon stocks, habitats and biodiversity. It provides an entry into understanding the human dimensions of environmental change (Turner II et al. 1995; Lambin et al. 1999; de Sherbinin 2002).

By examining information across time periods or between variables, processes can be identified. Such processes may include changing size, distribution and diversity of landscapes/habitats, relationships between land tenure and land management practices, differential impact of policy on land development or use, and emerging pressures/competition on a given resource among others. With this information on spatial patterns and processes, answers to questions on where change is taking place and why it is taking place can be provided. It is more effective and sustainable to address the underlying root causes of degradation or loss than to try to address the consequences.

2.6 Land degradation assessment

A summary of previous global land degradation assessments is presented by (Kniivila 2004; Kapalanga 2008; Nkonya et al. 2011). The Global Assessment of Human Induced Soil Degradation (GLASOD) by the International Soil Reference and Information Centre (ISRIC), currently World Soil Information (www.isric.org), is the first world-wide assessment of soil degradation. Despite its significance, this assessment has been criticized for being too course and being based on expert judgment by a few individuals (Oldeman et al. 1991). The number of studies that have attempted to objectively quantify the extent of land degradation has continued to grow over the recent past. These include studies at global, continental, sub-continental and national levels (Bai et al. 2008; Hellden and Tottrup 2008; Vlek et al. 2008). Other site-specific studies have focused specific aspects of land-use change and types land degradation e.g. forests and deforestation, soil erosion and range degradation (Torrion 2002; Lufafa et al. 2003; Akotsi and Gachanja 2004; Kelebogile 2005; Muriuki et al. 2005; Akotsi et al. 2006; World Agroforestry Centre 2006; Nambiro 2007; Vrieling 2007; Schaab et al. 2009)

Most of the global, regional and national land degradation studies are of low resolution, which makes them difficult for making practical recommendations to be adopted by the land users and the policy makers at local scales (Sanchez et al. 2009). At such low resolution, it is difficult to adequately express the complexity of soils and land uses across a landscape in an easily understandable way. Such course resolution data integrate the signal from a wider surrounding area, and many symptoms of even severe degradation, such as gullies, rarely extend over such a large area and may not be discernible (Torrion 2002). King and Delpont (1993) recommended working scales of 1:10,000 to 1:25,000 for soil erosion studies and other land degradation processes.

2.7 Measurement of land degradation

The terms soil degradation and land degradation have for a long time been used interchangeably. Therefore most development of initial approaches to land degradation assessment has emphasized measurement of soil status. This is in recognition of the important role played by soil in influencing above- and below-ground biogeochemical processes. Whereas the scientific rational behind the methods remains the same, the methodologies have been refined and made more specific to the resource under investigation. Kapalanga (2008) reviewed 65 papers and identified the following as the main land degradation assessment and monitoring methods: expert opinion, land user´s opinion, modeling, field observations, productivity change estimates and remote sensing and GIS. The GLASOD assessment is based on expert opinion and though frequently cited, objectivity of the assessment and lack of verification of the land degradation estimates have remained its main weakness (Vlek et al. 2008).

2.7.1 Direct field measurements

Direct measurements and observation at individual sites are the most accurate methods of detection of land degradation (Torrion 2002). The information on the temporal and spatial distribution of long-term soil loss in drainage basins and on the rates of soil erosion generated by these techniques is used to calibrate and test various models (Loughran 1989). However, classical methodologies for soil erosion measurement are capital and labor intensive as well as time consuming. They fail to produce detailed outputs due to budget constraints and inaccessible areas and insufficient standardization and repeatability (Loughran 1989; Pickup 1989).

2.7.2 Geospatial remote sensing technique

The shortcomings of the direct measurements make geospatial remote sensing techniques handy in mapping land degradation (De Jong 1994). Remote sensing techniques have large area coverage with varying temporal, spatial and spectral resolutions making it possible to monitor temporal and spatial land degradation patterns (Vrieling 2007). Many types of satellite images and image-derived products obtained from earth-observing space missions are presently available to the general public. Satellite imagery is therefore increasingly being used for regional land degradation studies (Vrieling 2007). Despite the versatility of these techniques, care must be taken when selecting which images to use so as to maximize on the information derived from the spectral bands while at the same time ensuring that there is no compromise on the spatial and temporal resolution needed for a given study objective.

2.7.3 Radionuclides and land degradation

The potential of using natural and man-made radioisotopes to study soil erosion and sedimentation has advanced significantly over the last five decades. Key among these radionuclides are fallout cesium (^{137}Cs), natural lead (^{210}Pb) and cosmogenic beryllium (^{7}Be) (Zapata et al. 2002). Caesium-137 has emerged as a potential radionuclide for assessment of soil erosion (Zapata et al. 2002). This approach relies on the persistence and known breakdown pattern (half life), which enables dating the extent of erosion and deposition. Using ^{137}Cs approach can provide information on retrospective assessment of medium-term (30-40 years) rates of soil erosion and deposition rates and the spatial patterns of soil redistribution without the need for long-term monitoring programmes. Secondly, the resulting estimates of soil redistribution rates are integrated, medium-term, average data for all processes and are less influenced by extreme events as in the case with erosion traps. Thirdly, there are no major scale constraints apart from the number of samples to be analyzed. In addition, the results are compatible with physically based modeling and application of GIS and geostatistics to soil-erosion and sedimentation yield studies. Several models have also been developed to estimate spatial mid-term soil redistribution rates based on ^{137}Cs (Walling and He 2000; Yang et al. 2002).

2.7.4 Modeling

Models have for many years been used in land degradation studies. There are many soil erosion models as discussed by (Merritt et al. 2003). The Universal Soil Loss Equation (USLE) is perhaps the most widely used empirical and theoretical mathematical model for estimating soil erosion (Wischmeir and Smith 1978; Renard et al. 1997). The model, NUTMON (Monitoring nutrient flows and economic performance in tropical farming systems) was developed to monitor nutrient dynamics (nutrient flows, nutrient balances) at farm level (Vlaming et al. 2001). The CENTURY model is soil nutrient cycling model used to simulate carbon and nutrient dynamics for different types of ecosystems in the tropics (http://www.nrel.colostate.edu/projects/century/). Models can be used to integrate data on land processes and to validate direct measurements or assessments done using remote sensing or radionuclide techniques. However, the use of models remains low in SSA mainly because of the limited number of soil scientists and agronomists with the skills to set up and run model simulations. Secondly, the use of models is limited by the scarcity and reliability of data needed to parametize them (Kihara et al. 2012).

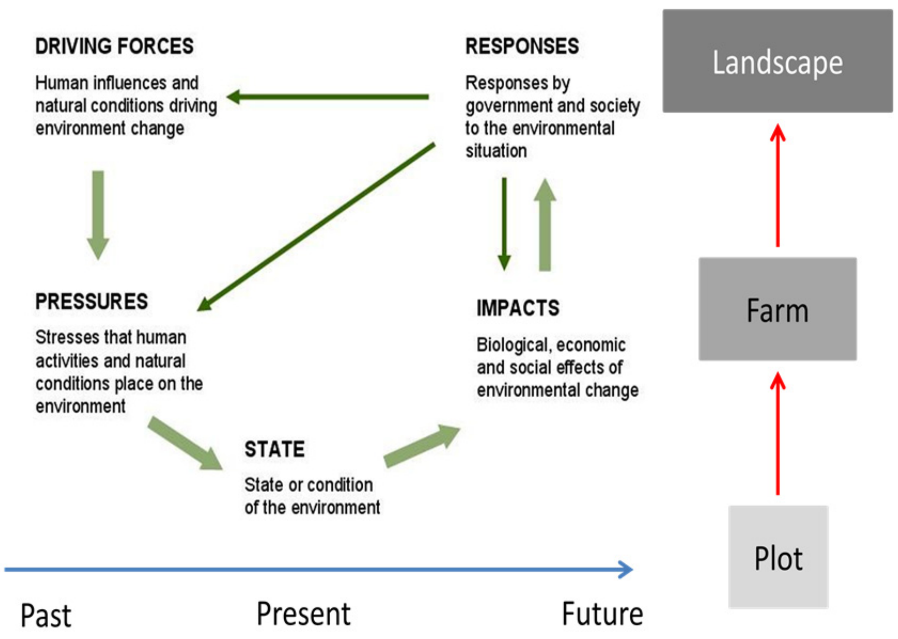
2.8 Soil testing

The combination of time-consuming methods, high cost and a shortage of scientific and technical expertise means that soil diagnostic analysis has been limited geographically and has rarely been repeated in many regions of SSA (Swift and Shepherd 2007). Often, soil sampling data lack georeferencing information making it difficult to repeat measurements and monitor changes in soil quality changes over long periods of time. Moreover, chemical and physical data from different countries or different survey campaigns are based on a wide variety of laboratory tests and analytical procedures, which are often difficult to harmonize from a diagnostic perspective (Vågen et al. 2010).

In order to capture the diversity in the soils, there is a need to use soil surveillance technologies that can guarantee rapid assessments over large areas. (Shepherd and Walsh 2002) proposed the use of infra-red spectroscopy, which is a spectral library approach whereby the variability of soil properties in a study area is thoroughly sampled and spectrally characterized. Soil properties or attributes of soil quality from georeferenced locations are measured on only a selection of soils and then calibrated to soil Vis-NIR reflectance. The soil quality indicators can then be predicted for the entire library and for new samples from the study area. Researchers have successfully been able to predict several soil fertility parameters with reasonable levels of accuracy (Shepherd and Walsh 2002; Shepherd and Walsh 2007). Spectral libraries constructed from soils sampled from georeferenced locations can also be used in conjunction with remote sensing imagery to map out soil quality and soil constraints over defined landscapes (Shepherd and Walsh 2002).

2.9 Theoretical framework of land degradation assessment

As discussed in the preceding sections, ecosystems or landscapes are in a continuous state of spatio-temporal change caused by natural as well as man-made drivers. The change has potential to create a mosaic pattern of patches of different sizes and shapes, with varying impacts on the ecosystem functioning (Rapport et al. 1985). At interfaces of change, ecosystems are likely to experience stresses, and this can reflect in some form of degradation. Like in medical practice, these stresses make the ecosystems unhealthy, unstable and unsustainable. This similarity in response of the ecosystem with human health resulting in a signal of an unhealthy environment/system was described by Rapport et al. (1985) as the Ecosystem Distress Syndrome (EDS). The authors observed that distressed systems have disrupted functions e.g., reduced productivity and biodiversity, lower decomposition and nutrient cycling, reduced aesthetic value. By identifying 'hotspot' areas within the ecosystem experiencing stresses and by identifying causes of these stresses, recommendations for restoration and conservation can be made. To do this requires the adoption of a framework that integrates all factors, i.e., biophysical, social and economic factors driving natural resource use. The DPSIR framework (Driving Force – Pressure – State – Impact – Response) was proposed by the European Environmental Agency (EEA) as an integrated approach to environmental management (EEA 2000; FAO 2011a). A summary of the DPSIR framework is presented in Figure 2.1. This framework was adopted in the Land degradation Assessment in Dryland Areas (LADA) projects it has proved versatile for land degradation assessment (LADA 2009).



Adapted from (FAO 2011a)

Figure 2.1 The DPSIR framework (Driving Force – Pressure – State – Impact – Response)

The DPSIR framework is useful in describing the origins and consequences of environmental problems. The framework provides an overview of the relation between the environment and humans (Karageorgis et al. 2005). According to this framework, social and economic developments and natural conditions (driving forces) exert pressure on the environment and, as a consequence, the state of the environment changes. This leads to impacts on human health, ecosystems and materials, which may elicit a societal or government response that feeds back on all the other elements. Results from the DPSIR framework can be applied, and the assessments on land degradation extrapolated using GIS and remote sensing techniques from local to national and even global levels. Combining the EDS and the DPSIR frameworks can help deliver an integrated or interdisciplinary assessment of land degradation not only in the proposed study site but the region as a whole.

3 STUDY AREA AND GENERAL METHODOLOGY

3.1 Kenya in perspective

Kenya is located in East Africa between latitudes 5° N and 5° S, and longitudes 34° E and 42° E. The capital of Kenya is Nairobi. The country lies along the equator and borders the Indian Ocean to its southeast. Kenya's neighbors are Somalia to the northeast, Ethiopia to the north, Sudan to the northwest, Uganda to the west and Tanzania to the south (Figure 1). The country derives its name from the unique glacier-peaked Mount Kenya located on the equator and is the second tallest mountain in Africa with the peaks rising to about 5,199 m above sea levels. Kenya has a land area of about 580,000 km^2 and a population of 38.6 million according to the 2009 census (KNBS 2010). The Kenyan population is diverse and comprises 42 different cultures. The country is divided into 8 provinces and 47 districts. However, with the enactment of the new constitution, the constellation of the administrative units is changing to a devolved government comprising of 47 counties.

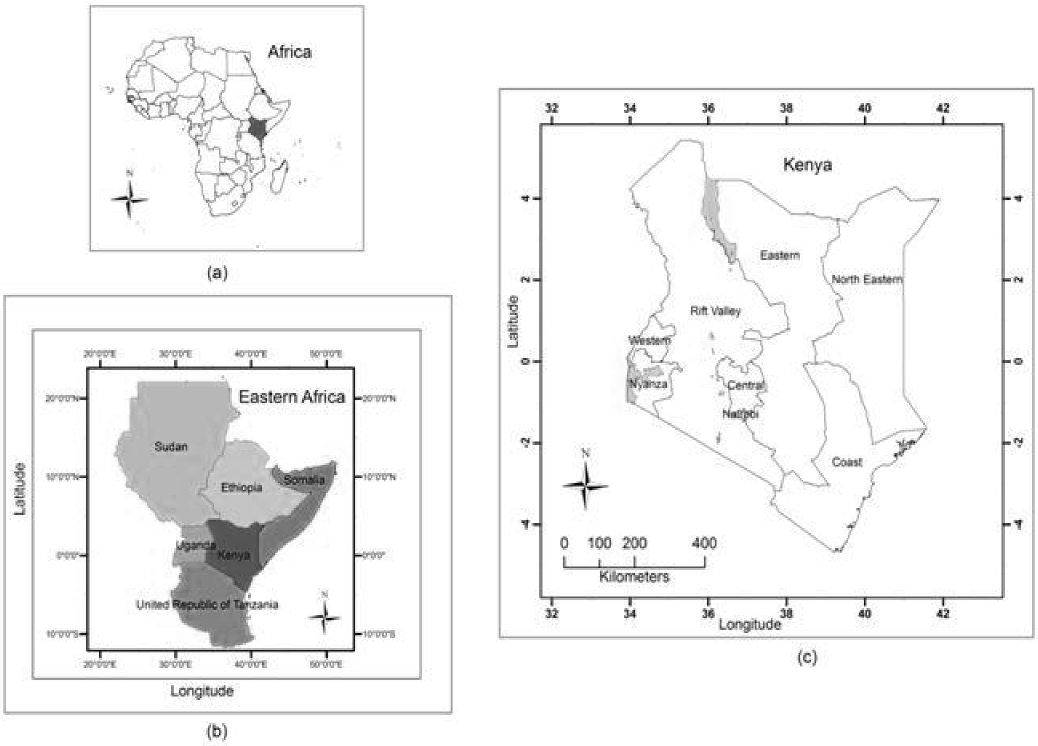


Figure 3.1 Location of Kenya on the African continent

The country has a diverse geography that ranges from the coastal climate along the Indian Ocean to savannah grasslands, and arid and semi-arid bushes in the inland. Mountains and forest areas are common in the central and western parts while the northern regions are characterized by semi-arid to arid landscapes. Rainfall is bimodal with the "long rains" season occurring from March/April to May/June while the "short rains" season is from October to November/December. Because of its proximity to the Indian Ocean, the coastal region is largely humid and wet. Higher elevation areas within the central and western region around the Lake Victoria Basin in Western Kenya receive much higher amounts of rainfall. The low plateau areas covering the north and northeastern part of the country are the driest and are classified as arid and semi-arid lands (ASALs). Settlement patterns in the country are mainly determined by the climate. The majority of the population is concentrated in the wettest areas of the country. The ASALs cover 75% of the country and support 30% of the human population, 60% of the livestock and 65% of the wildlife (Ng'ethe 1992; Jama and Zeila 2005).

Kenya is an agricultural country and agriculture is the second largest contributor to Kenya's gross domestic product (GDP) after the service industry sector. By 2005, for example, the contribution of agriculture to the GDP was about 25% and the sector accounted for 18% of wage employment and 50% of revenue from exports (Republic of Kenya 2005a). The major export crops are tea, coffee, and flowers. Other key crops include pyrethrum, maize and wheat, which are grown in the fertile highlands while coconuts, pineapples, cashew nuts, cotton, sugarcane and sisal are grown in the low altitude areas. The semi-arid savanna to the north and east part of the country are mainly used for livestock and game ranching. The agricultural sector directly and indirectly employs nearly 70% of the country's 38 million people (Republic of Kenya 2005a). Approximately, 50% of the agricultural production in Kenya is subsistent in nature. The production of major food staples such as maize is greatly influenced by the climate fluctuations, i.e., mainly by rainfall. Production downturns periodically necessitate food aid as evident in the droughts of 1984, 2004 and 2010. Pastoralism is the main activity in the arid and semi-arid parts of the country.

3.2 Study area

3.2.1 Location of the study area and rational for site selection

This study was conducted in Western Kenya covering the districts of Kakamega, Butere-Mumias and Siaya (Figure 3.2). The area is located at 34° 2' 48" - 34° 58' 45" E and 0° 4' 26" S - 0° 36' 15" N and covers an area of about 3,800 km^2. It is worth noting that following the enactment of a new constitution in 2007, the administrative constellation of the country is having a major restructuring. The administrative authority of the districts is being transformed into counties. For the purpose of this study, the names and boundaries of the districts as of 2007 are adopted.

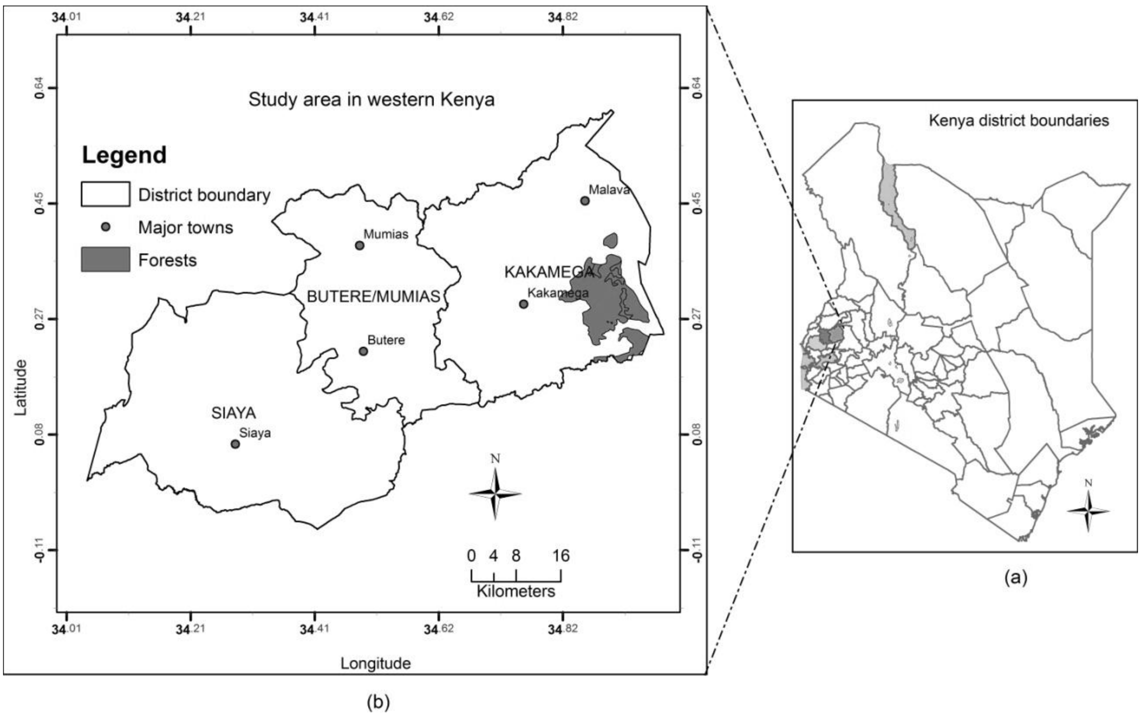


Figure 3.2 Location of the study site

Land in western Kenya region is considered to be at high risk of degradation due to the high population pressure and intensity of land use. The districts have some of the highest poverty levels in the country. The diversity in the geomorphology, land use and other demographic factors existing in these districts offer a unique opportunity to assess the impact of land-use change on land degradation and specifically soil erosion and redistribution, deforestation, declining soil fertility, overgrazing among others.

Geomorphology

The districts have varied landforms ranging from undulating hills and broad valleys, moderate lowlands and swamps (Yala). The region is drained by several rivers among them the Nzoia and Yala Rivers. These rivers drain their waters from the forests and mountains of Mount Elgon, Cherengani and Nandi Hill traversing areas of intensive cultivation in the Bungoma, Nandi, Kakamega, Butere-Mumias and Vihiga districts before draining through the plains in Siaya district and eventually discharging the water into Lake Victoria.

3.2.2 Agro ecology

The study area lies within four agro-ecological zones (AEZ): Humid (Zone I), Sub-Humid (Zone II), Semi-Humid (Zone III) and Semi-Humid to Semi Arid (Zone IV). The area is classified as moist mid-altitude zone (MM) (Lynam and Hassan 1998). The MM zone forms a belt around Lake Victoria, from its shores at an altitude of 1110 meters, up to an altitude of about 1500 meters above sea level (Jaetzold and Schmidt 1982; Lynam and Hassan 1998). The districts experience bimodal rainfall, and the distribution and amounts are greatly influenced by the relief and altitude as well as by the presence of Lake Victoria. The rain falls in two peak seasons: long rains (March to May) and short rains. Figure 3.3 shows the long-term annual rainfall distribution in selected weather stations across the study area.

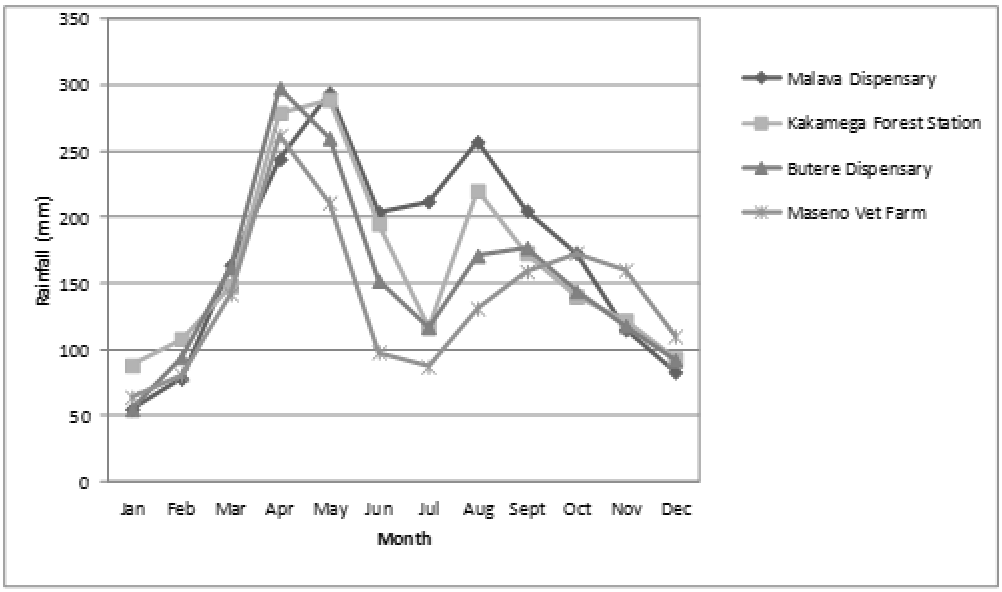


Figure 3.3 Monthly rainfall distribution in selected weather stations across the study area

3.2.3 Soils

The study area is characterized by a wide range of soil types. The dominant soils are the Ferralsols (well drained soil found mostly on level to undulating land), Acrisols (clay-rich soils, associated with humid tropical climates and supports forestry), and Nitisols (deep, well-drained, red, tropical soils found mostly in the highlands). The soils in the Kakamega and Butere-Mumias districts are mainly Ferralo-orthic Acrisols in the north of the district and Ferralo-chromic/orthic Acrisols in the southern part (Sombroek et al. 1982). Other minor soil types in the area are Nitisols, Cambosols, and Planosols. The soils are generally deficient in N, P and K (Lijzenga 1998). Siaya district is dominated by Ferralsols whose fertility ranges from moderate to low with most soils being unable to produce without the use of external inputs. Most of the areas have underlying murram with poor moisture retention.

3.2.4 Population

As of 1999, the study area had a population of about 1.5 million (Table 3.1). Kakamega and Butere-Mumias districts had the highest population densities, mainly due to the presence of large urban areas (Kakamega and Mumias towns, respectively). Dependency ratio is high (over 55%) in all the study districts.

Table 3.1 Population statistics of the study area, 1999

District	Area (km^2)	Total	Density (Persons/km^2)
Kakamega	1,395	601,511	568
Butere-Mumias	939	477,178	562
Siaya	1,521	479,424	342
Total	3,855	1,558,113	491

Source: (KNBS 2001)

3.2.5 Economy

Agricultural is the main economic activity in these districts. The food crops grown include maize, beans, and millet, while the main cash crops are tobacco, coffee, tea, sugarcane and cotton. The farmers in the districts also keep livestock, mainly the local zebu breeds on a free-range system. There is also a significant tourism industry centered on this forest is considered Kenya's last remnant of the ancient Guineo-Congolian rainforest that once spanned the continent. Including reserves, the forest covers about 230 km^2, of which about 50% is indigenous forest. Other forests in the district include Kisere (400 ha) and Malava (100 ha) to the north of Kakamega town and Bunyala forest to the west. These forests host a wide range of biodiversity including endemic trees, shrubs and animals species. As a result the forests have been the focal point for the German funded biodiversity project, BIOTA East, since 2001. The local inhabitants rely on the forests to supply most of their needs, mainly fuel wood, pasture, timber, wild fruits and medicinal herbs. Despite their protected status, these forests show evidence of degradation, mainly from encroachment by the adjacent human and livestock population. The Kenya Forest Department (KFD) and the Kenya Wildlife Service (KWS) have the mandate to protect and conserve the forests. Located in Siaya district is the Yala Swamp, which is of significant ecological and economic value to the region. The swamp serves as a natural water filter trapping sediments and nutrients before the rivers discharge into Lake Victoria. The swamp is a habitat of diverse animal and plant species. It is a source of reeds for roofing and for cottage industry as well as a fishing ground. Currently, the Dominion group of companies is reclaiming large areas of the swamp to pave way for irrigated agriculture. Figure 3.4 shows some of the characteristic of the study area.

a) Fragmented smallholder farming system

b) Subsistence farming based on maize and beans

c) Presence of isolated forest fragments

d) Livestock production

Figure 3.4 Characteristics of study area

3.3 General methodology

Land degradation assessment is a complex process. This is because multiple perspectives are needed to understand ecosystem processes and variability of ecological variables at different spatial scales. This section presents an overview of the methodologies applied to assess land degradation in the study area. Detailed descriptions of these methodologies and the results can be found in the respective chapters in this thesis. Figure 3.5 summarizes the key components of the methodologies applied in this study.

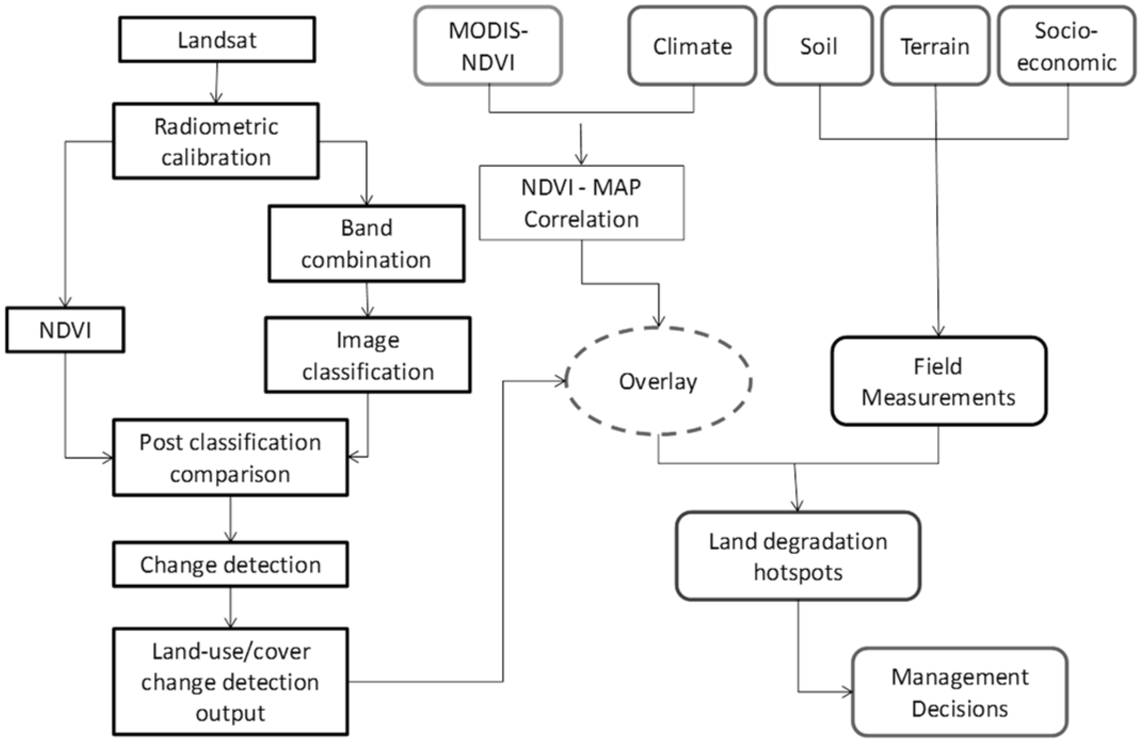


Figure 3.5 Schematic presentation of the land degradation assessment methodology

3.3.1 Description of the land degradation assessment approach

Step 1: Exploratory field surveys and reconnaissance studies

Prior to the field study, exploratory field surveys were undertaken in the selected sites to become familiarized with general condition of the sites, i.e., soils, vegetation, rivers, climate, and accessibility, among others. Reconnaissance surveys focused on characterization of the sites by collecting biophysical and socio-economic data relevant for the assessment of land degradation patterns in the study area. Collection of this information was done during the transect walks and the data was recorded in observation sheets. This general information was later complemented by the detailed characterization following the guidelines provided under the Land Degradation Sampling Framework (LDSF).

Step 2: Identification of degradation patterns

Long-term spatial and temporal patterns of land degradation were assessed using multi-scale satellite data sets (Chapter 4). The study employed the use of Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index (MODIS/NDVI) data for a 10-year period (2000-2009). A compromise between spatial and temporal resolution was made when selecting the MODIS data. MODIS data are readily available for download from the USGS, GLOVIS website. This dataset is available at a higher resolution of 250 m compared to 8 km for AVHRR. The MODIS data set is collected twice a month giving an average of 24 sets for each scene per year. The study employed the use of gridded climate CRU TS 3.1 ($0.5° \times 0.5°$) data downloaded from the CGIAR-CSI website for assessment at national level. This part of the global long-term climate dataset is available as a grid format. Complementary rain gauge data was also sourced from the Kenya Meteorological Department for the assessment at in western Kenya (See list of weather stations used). The point rainfall data was extrapolated across the study area and used to generate monthly and annual rainfall maps that ware used for correlation with the observed NDVI data.

The NDVI and the mean annual precipitation- MAP- datasets were then subjected to statistical analyses to assess variability and trends in vegetation productivity (Vlek et al. 2008; Vlek et al. 2010). This analysis enabled the pixel-by-pixel computation of the NDVI-MAP correlation coefficient and the NDVI slope (inter-annual change) which was then tested for statistical significance. In addition, NDVI differencing was done by subtracting NDVI averages across two time periods: the baseline (2001-2003) and the endline (2007-2009). Pixel by pixel subtraction of the baseline from the endline NDVI values resulted in the change in average NDVI for the study area. All computations were done in a GIS environment using ArcGIS 9.3.1.

Step 3: Land-use and land-cover change (LULC) assessment

Understanding the land use land cover (LULC) change is a key starting point for any land degradation assessment exercise since such changes have a bearing on the resultant patterns of resource degradation. The change assessment was performed using a selection of Landsat images for the years 1973, 1988 and 2003 to give a 30-year span. This period of assessment was selected to enable long-term assessment of LULC changes in the study area. A mid interval of 15 years was arbitrarily selected. The year 1973 was selected as the starting point as it coincided with the availability of the earliest Landsat images for the area. Due to the malfunctioning of the Landsat sensor in 2003 (stripping), no good-quality images were available beyond this period. Supervised and unsupervised classification supported by ground truthing and accuracy assessments were applied (Jensen 1996; Sabins 1997). The LULC classes were assigned to the appropriate class following the Land Cover Classification System (http://africover.org/LCCS.htm). To facilitate cross-site comparison and ease of communication to the land uses, broad LULC classes such as natural, secondary and plantation forests, grasslands, bare land, agricultural land and water bodies were adopted. Processing the images and classification was performed using ENVI 4.8 and ArcGIS 9.3.1. The results of this assessment are presented in Chapter 5.

Step 4: Soil characterization of the selected sites

a. Soil sampling framework

The Land Degradation Sampling Framework (LDSF) was adapted to characterize land degradation patterns at selected sites (Vågen et al. 2010). LDSF is a comprehensive framework developed by researchers at ICRAF, and currently being used under the Africa Soil Information Systems (AfSIS) Project that seeks to develop a digital map for Africa. The framework is designed to provide a biophysical baseline at landscape level, and a monitoring and evaluation framework for assessing processes of land degradation and the effectiveness of rehabilitation measures (recovery) over time. LDSF is a spatially stratified, random sampling framework built around a hierarchical field survey and sampling protocol using “Blocks” and “Clusters”. Three sampling “Blocks” measuring 100 km^2 (10 km × 10 km) were demarcated in the lower (Sidindi, Siaya), middle (Bunyala, Kakamega) and upper (Malava, Kakamega) catchment of the study area (Figure 3.6). This was done to capture the diversity in agro-ecology, geomorphology and land uses. Each block was further subdivided into 16 tiles (2.5 km

× 2.5 km) in which a “Cluster” of 10 plots was randomly allocated (Figure 3.7). Each plot consisted of 4 sub-plots that were sampled and characterized for land degradation indicators. Such a design of allocating sampling points minimizes local biases that may arise from convenience sampling.

Soil samples were collected from the plots at 0-20 cm (upper layer) and 20-30 cm (sub layer) using a 5 cm diameter and 40-cm long *Eijkelkamp* (model 04.17) undisturbed split-tube-soil sampler. The upper sampling layer was selected to coincide with the plough layer as well as the rooting zone of most annual crops. The soil samples were processed and analyzed for major soil chemical properties using standardized methodologies. The variability of the soil properties as well as the potential nutrient supply, uptake and crop productivity is discussed in Chapter 6 and 7.

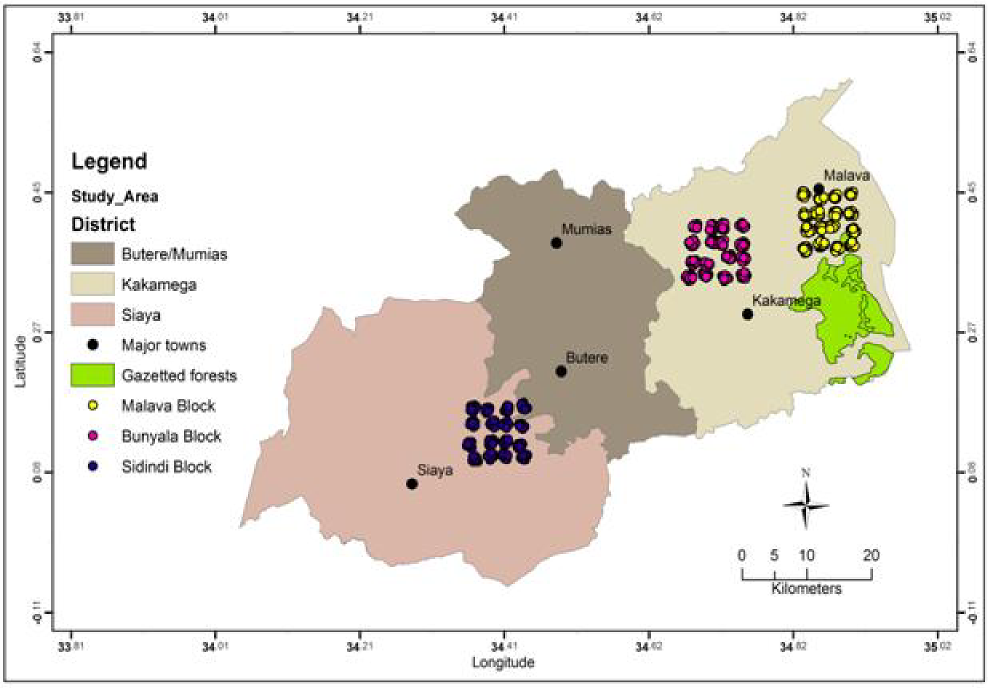


Figure 3.6 Location of the sampling blocks across the study area

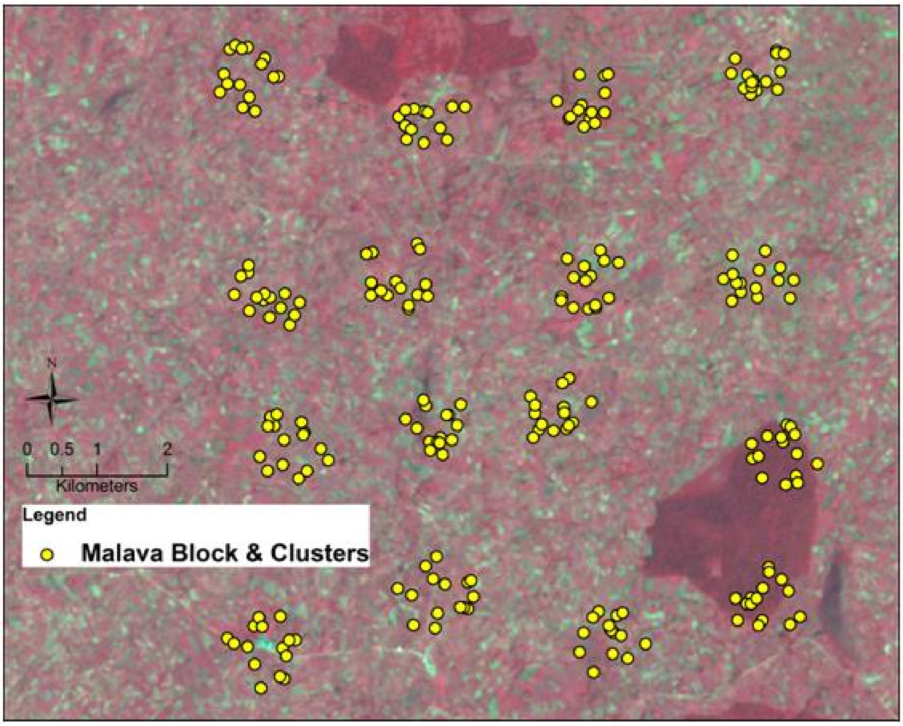


Figure 3.7 Example of the 10 km × 10 km sampling block with sampling clusters (Malava Block)

Step 5: Socio-economic surveys

Socio-economic data were collected on each farm sampled to capture additional information essential for explaining changes observed. In total 126 households were interviewed. Questionnaires and observation sheets (see appendix III and IV) were used to capture past and current land-use information and indicators essential for explaining patterns of land degradation. The socio-economic data was later coded and entered into the computer for further analysis. Detailed description and results on how this was done is presented in Chapter 8.

Additional data sets

In addition to the remote sensing imagery, the study employed numerous other secondary data sets including information on administrative base maps, soils, terrain, climate and socio-economic data such as population to interpret trends in the LULC and land degradation patterns observed.

3.3.2 Data analysis

All biophysical and socio-economic data from the study sites were organized and analyzed using Statistical Package for Social Sciences (SPSS) and STATA. LULC change analysis as well as land degradation mapping were done using remote sensing and GIS approaches (ENVI 4.8, ArcGIS 9.3.1). Spatial analysis using kriging was performed in ArcGIS to extrapolate the soil physical properties to the entire block under consideration. Pearson correlation and linear regression models were used to determine trends in the NDVI and precipitation and their interrelations for each pixel. Regression analysis and principal component analysis (PCA) of the soil properties were performed in SPSS and STATA. Detailed descriptions of the above procedures are presented in the respective chapters.

4 MAPPING LAND DEGRADATION PATTERNS USING NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI) AS A PROXY

4.1 Introduction

Meeting the food and energy demands of the world's poor from an ever degrading land resource is one of the major challenges facing humanity today. Human activity and environmental changes occurring at local to global scales have profoundly affected ecosystems so that the need to detect and predict changes in ecosystem functioning has never been greater. As a result of the above changes, there has been increased pressure on existing land resources resulting in various forms of land degradation. Land degradation results in the reduction in production potential of any given resource (Ward et al. 1998). The main direct drivers contributing to land degradation are non-sustainable agriculture, overgrazing by livestock and overexploitation of forests and woodlands. Land degradation manifests itself in various forms including soil erosion, overgrazing, agricultural mismanagement, deforestation and overexploitation of natural resources, salinization and depletion and pollution of water resources (Allen and Barnes 1985; Oldeman et al. 1991; Batjes 2001).

The magnitude of the degradation types varies. For example, in Kenya, the magnitude of soil erosion losses to the economy has been estimated at equivalent to US$ 390 million annually or 3.8 percent of gross domestic product (Cohen et al. 2006). The significance of land degradation as a global development and environmental issue has been highlighted in various international for a and conventions such as the UN Convention to Combat Desertification (UNCCD), the Convention on Biodiversity (CBD), the Kyoto Protocol on Climate Change and the resultant UNFCC and the Millennium Goals. All these initiatives advocate for the development of environmental monitoring tools to better: (a) detect land degradation and map its occurrence; (b) assess the trends of land degradation over time; and (c) understand the causes of land degradation (Li et al. 2004).

Various approaches have been used to assess land degradation. As discussed in Chapter 2 the approaches can be broadly classified as expert opinion; land user´s opinion; modeling; field observations; monitoring and measurements; productivity change estimates and remote sensing and GIS. Extensive reviews of the strengths and weaknesses of these approaches have been presented by various authors (Kapalanga 2008; Vlek et al. 2008; Nkonya et al. 2011). The outputs of each of the assessments have been useful in informing and initiating debate on patterns, extent, causes of land degradation at various spatial and temporal scales as basis for developing sustainable management practices.

Field data currently available are generally difficult to use for predicting regional or global changes because such data are traditionally collected at small spatial and temporal scales and vary in their type and reliability (Pettorelli et al. 2005). The recent past has seen increased use of satellite-derived indices as a proxy for land degradation assessment. Studies have shown that land degradation can express itself in terms of reduction in biological activity (Vlek et al. 2008) and this is reflected in the above ground net primary production (NPP) (Nemani et al. 2003; Zhao et al. 2006). Past research employing the use of NPP were based on discontinuous monitoring of individual plants or small plots of vegetation in a greenhouse or at a landscape scale, which can only provide a point value, often in a short time-scale (Zhang et al. 2009). Such patchy data are not well suited to scaling up to a regional or global level (Mooney 1991) and a long time-scale (Luo and Reynolds 1999).

Among the most commonly used indices for vegetation mapping is the Normalized Difference Vegetation Index (NDVI). This index is calculated from the near infra red and the red bands of the satellite images using the formula below:

$$NDVI = \frac{(NIR - Red)}{NIR + Red}$$

Where:

NIR is reflectance in the near infrared channel (0.725 μm to 1.1μm)
Red is the reflectance in the red band of the visible spectrum (0.58μm to 0.68 μm)

The relationship between the NDVI and vegetation productivity is well established. NDVI is highly correlated with photosynthetically active vegetation (Tucker 1979; Justice et al. 1985; Sellers 1985; Tucker et al. 1985a). NDVI is highly correlated with vegetation parameters such as green leaf biomass and green leaf area. It is also directly related to plant vigor, density, and growth conditions (Harrington and Wylie 1989; Hunt 1994), features that make it tenable as a primary tool for monitoring land degradation and land use change. NDVI multi-year mean values can be useful for monitoring both short- and long-term photosynthetic capacity variations (Dregne and Tucker 1988). When correlated with other biophysical and socioeconomic data such as rainfall, soils, population and poverty, NDVI can be used not only to point put areas that are experiencing change and degradation but also causes and patterns of such changes.

The correlation of NDVI with vegetation biomass and dynamics in various ecosystems and the relationship between NDVI and climatic variables has made this index invaluable for environmental change monitoring at varied spatial and temporal scales (Myneni et al. 1995). The NVDI has thus been used to improve predictions on the impacts of disturbances such as drought (Singh et al. 2003), fire (Maselli et al. 2003), floods (Wang et al. 2003) among other natural and man-made disturbances.

For a long time, NOAA-AVHRR (National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer) is the main source of long-term NDVI data. AVHRR NDVI data are available in a consistently processed database from 1982-present at an 8-km re-sampling grid covering the entire planet, and from 1989-present at a 1-km resolution for the United States (Tucker et al. 2005). Although AVHRR provides an extensive temporal record for comparison, the coarse spatial resolution of these data limits their effectiveness at detecting variability at localized scales. Other sources of this data have been SPOT and Landsat images with the later require processing. Since 2000, however, the Moderate Resolution Imaging Spectroradiometer (MODIS) has provided the most reliable and readily available data products for wider global vegetation assessments. These data have recently been validated and used to monitor GPP and NPP dynamics at the regional and global scale

(Nemani et al. 2003; Zhao et al. 2006). MODIS supplies various NDVI data sets including MOD13A2, MOD13A1 and MOD13Q1 with spatial resolutions of 1 km, 500 m and 250 m, respectively. The data has a temporal resolution of 16 days. Considering the continuity, the finer resolution and the relationship between GPP/NPP and NDVI, this data set has gained wide use in monitoring monthly and annual vegetation changes.

Various authors have reported using NDVI in land degradation assessment. Among the key differences in the studies is the algorithms applied to combine the datasets as well as the spatial and temporal resolution of the data used. Some studies are at global (Nkonya et al. 2011) scale while others (Olsson et al. 2005; Vlek et al. 2008; Vlek et al. 2010) are at continental and sub-continental scales. The Land Degradation Assessment in Drylands (LADA) project has used NDVI to assess land degradation at national level in various countries including Kenya, South Africa, Tunisia, Senegal, China, Argentina and Cuba (Bai and Dent 2006). Other studies have used NDVI to monitor changes at landscape and on particular vegetation resources such as forests, rangelands and croplands (Bastin et al. 1995; Geerken and Ilaiwi 2004; Wessels et al. 2004; Kinyanjui 2011).

Most of these studies have utilized course resolution NDVI data sets hence tend to over generalize observations on the ground. The studies at global and continental scales provide general and broad assessments that are mainly valuable for global environmental monitoring and assessments. There is need to undertake more high resolution studies at landscape level in order to provide practical information to land users on restoration and reclamation of degrading areas.

The objective of this study was to assess patterns of land degradation using NDVI as a proxy. Such information would serve as basis for detailed studies to identify the causes of the observed changes and to propose sustainable land management practices.

4.2 Methodology

A pixel-by-pixel analysis of the changes in NDVI over time was assessed at national level covering the whole country (Figure 4.1).

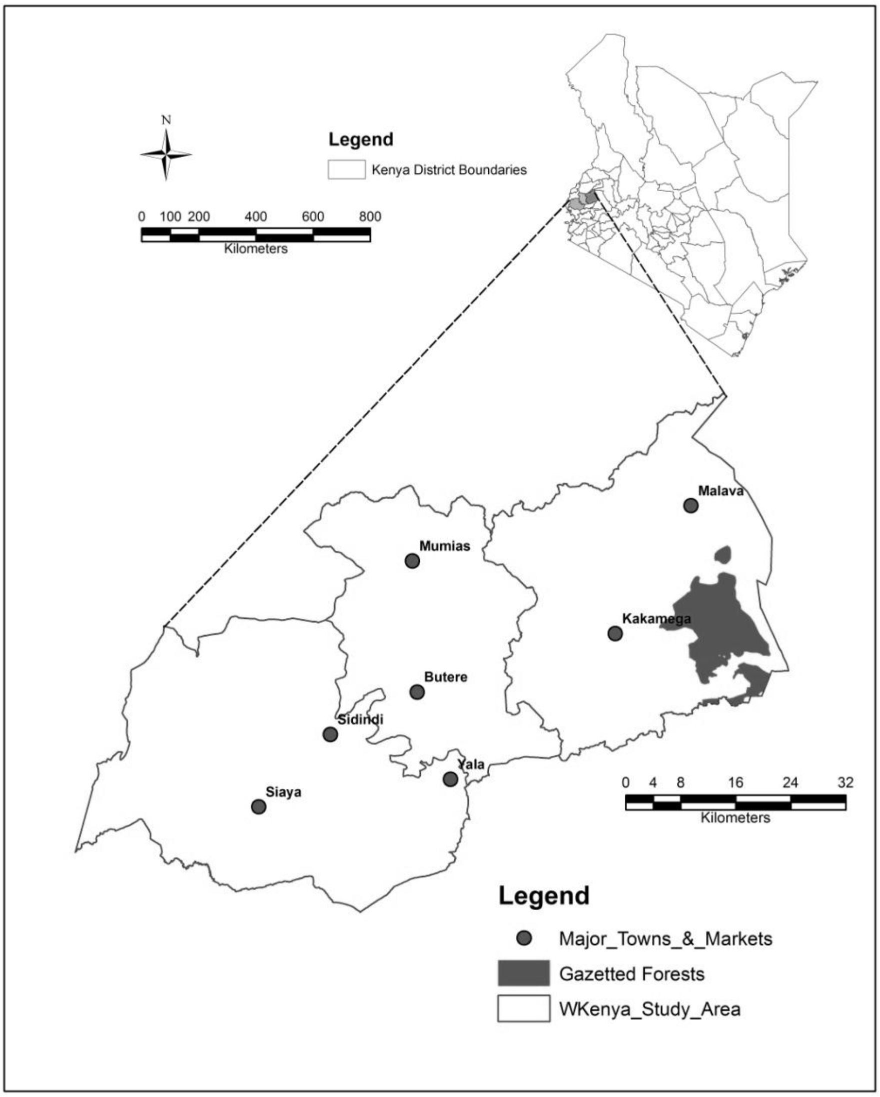


Figure 4.1 Location of the selected districts in Western, Kenya

The study employed the use of 250 m, Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index (MODIS/NDVI) data products for a ten-year period (2000-2009). The MOD13Q1 (250 m) NDVI data were downloaded from the USGS Glovis website (http://glovis.usgs.gov/). The data are available in sinusoidal projection and stored as a HDF EOS (Hierarchical Data Format – Earth Observing System) format. The original data set is bimonthly giving an average of 24 sets for each scene per year.

The MODIS tiles covering the boundary of Kenya were mosaiced and reprojected using the MODIS Reprojection Tool Web interface (MRTweb) (https://mrtweb.cr.usgs.gov/). The area of interest was then clipped against extends of administrative boundaries of the study area. For each year, the pixel values were aggregated to a monthly average. Annual NDVI values were computed as 12-month averages. An overall average NDVI value for the whole period (2000-2009) was also computed.

The study employed the use of gridded climate (CRU TS3.1) data downloaded from the CGIAR-CSI website (http://www.cgiar-csi.org/data/item/104-cru-ts-31-climate-database). The new TS (time-series) datasets released in April 2011 are month-by-month variation in climate over the last century (1901-2009). The data are presented at as high-resolution (0.5 x 0.5 degree) grids. This is a much-improved version compared to the previous version CRU TS2.1. To help facilitate the use of this database, the raw data has been converted into the ESRI ASCII raster format. Monthly data for the period 2000-2009 was downloaded and area of interest clipped. The data was then scaled and averaged to give the Mean Annual Precipitation. This MAP was correlated with the NDVI to assess changes in land productivity with rainfall over the study period.

This study utilized monthly composite NDVI data (2000- 2009) to assess the spatial and temporal patterns of land productivity. Linear regression was performed to determine the magnitude of change of the NDVI over time (inter-annual NDVI change analysis) following the methodology as described by Vlek et al. (2008) and Vlek et al. (2010) (Appendix I and II). The change in NDVI over the years (inter-annual NDVI change) was assessed by determining the slope coefficient (A) in the relationship below. The long-term persistent decline in NDVI reflects risk of land degradation.

$$NDVI = A \times Year + B$$

Where:

NDVI:	*Normalized Difference Vegetation Index*
A	*Slope coefficient*
Year	*Period of assessment (2000-2009)*
B	*Error term*

The relationship between inter-annual green biomass (NDVI) and rainfall dynamics was computed using Pearson's correlation coefficient for the period 2000-2009. The correlation between any two variable X and *Y* can be measured by the Pearson's coefficient (*Rxy).*

$$R_{xy} = \frac{\sum(X_i - \bar{\bar{X}})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}}$$

Where: *Xi is the mean annual precipitation- MAP,*

i = 2000 to 2009

Yi is mean annual NDVI,

i = 2000 to 2009

The two calculations enabled the pixel-by-pixel computation of the NDVI-MAP correlation coefficient and the NDVI slope (change over time) which were then tested for statistical significance at three confidence levels: 75%, 90% and 95% which correspond to P values of <0.25, <0.10 and <0.05 respectively.

Further analysis involved calculating the change in average NDVI over the study period. This was done by subtracting NDVI averages across two time periods: the baseline (2001-2003) and the endline (2007-2009). Pixel by pixel subtraction of the baseline from the endline NDVI values resulted in the change in average NDVI for the study area.

All computations described above were performed using ArcGIS 9.3.1. The results are presented as tables and maps showing changes in NDVI patterns.

4.3 Results

This section presents results for the inter-annual variation in NDVI assessment for Kenya for the period 2000-2009. Figure 4.2(a) shows the major agroecological zones of the country while Figure 4.2(b) shows the pixel-by-pixel mean NDVI over the 10 year period. The NDVI pattern and the AEZ map show great resemblance confirming that NDVI is directly correlated with precipitation. Over 70% of the land area in Kenya is considered very arid to semi arid lands (ASALs) with rainfall less than 600 mm per year. The ASALs form the larger part of Northern and North Eastern parts of the country. Such regions are characterized by sparse vegetation cover and as expected have low average NDVI. Only a small portion of the country, mainly in the central highlands, parts of central Rift Valley, western Kenya and coast experience humid to semi-humid climate. Such regions have diverse vegetation formations ranging from grasslands interspersed with trees to thick forests. Most of these areas are also used for crop production.

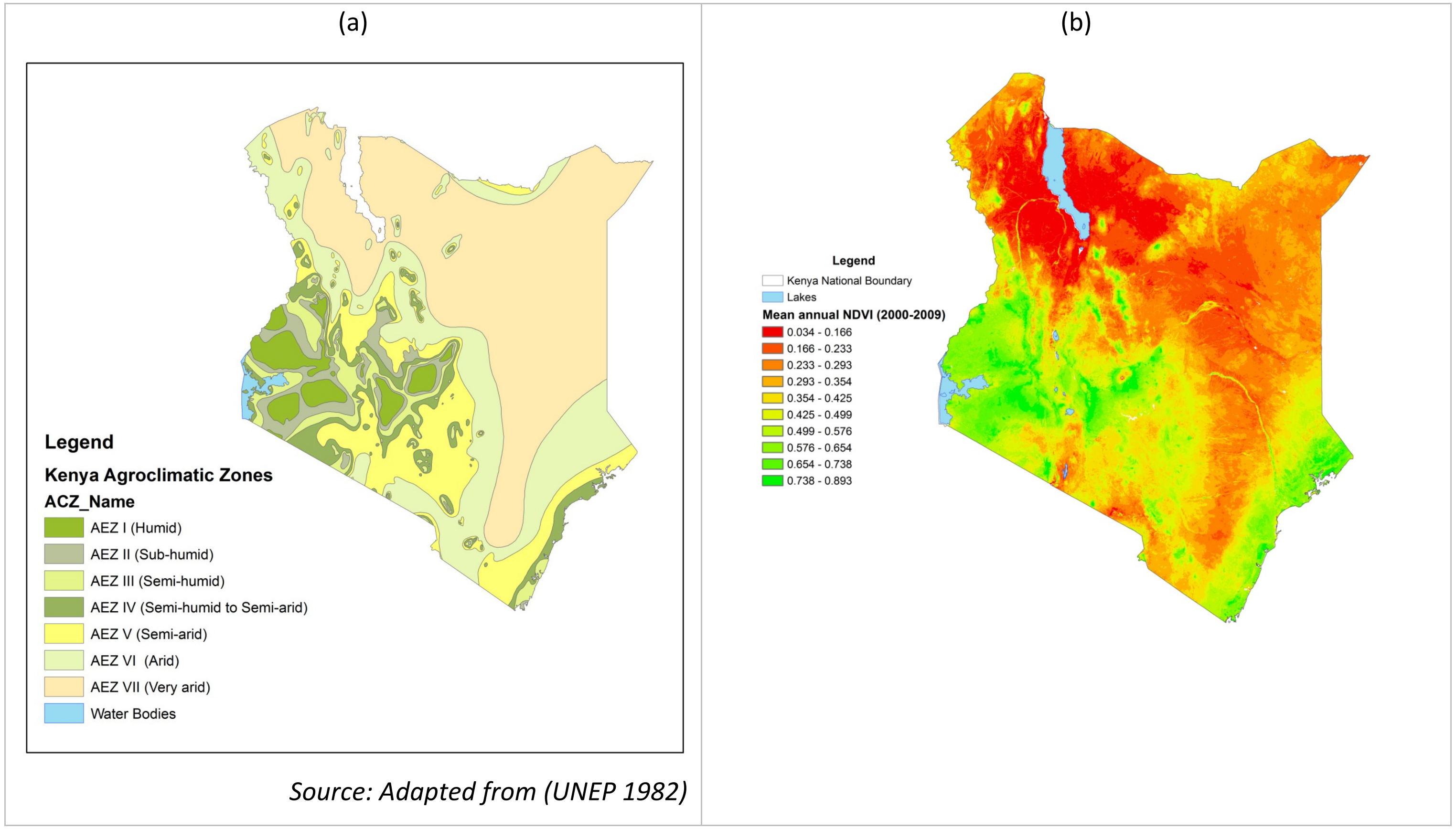


Figure 4.2 a) Agroecological zones of Kenya based on moisture availability and (b) mean annual NDVI during the period 2000-2009

Variation in precipitation and NDVI at country level

Figure 4.3 shows the variation in annual precipitation at country level. The data shows a wide range of rainfall averaging between 550 and 870 mm between the minimum and maximum precipitation. Despite the annual fluctuations, there is a general increase in mean precipitation over the period of assessment. The trends shows relatively reduced precipitation in years 2000, 2003, 2005 and 2008.

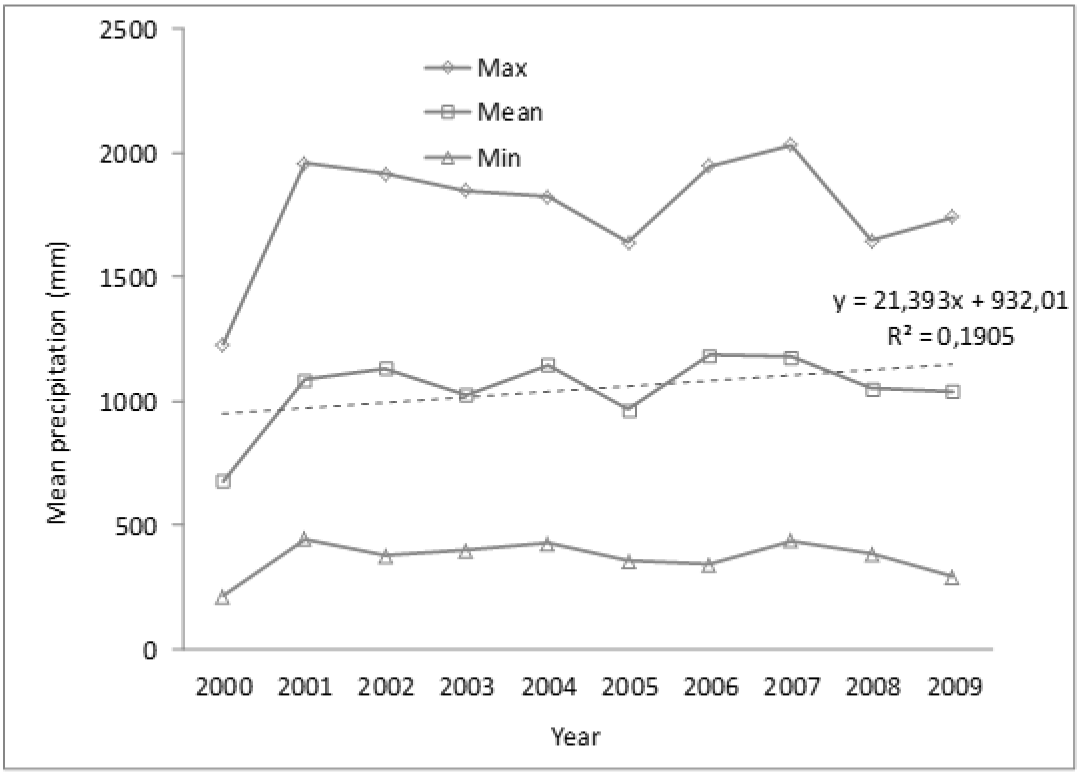


Figure 4.3 The annual variation in precipitation at country level (2000–2009)

4.3.1 Correlation between biomass (NDVI) and inter-annual rainfall

A first step of this assessment was to find out the correlation between inter-annual NDVI and precipitation and to test the significance of the coefficient of correlation. This was done on pixel basis using Pearson's correlation coefficient for the period of assessment (2000-2009). The correlation between biomass and mean rainfall was between -0.953 and +0.992 (Figure 4.4).

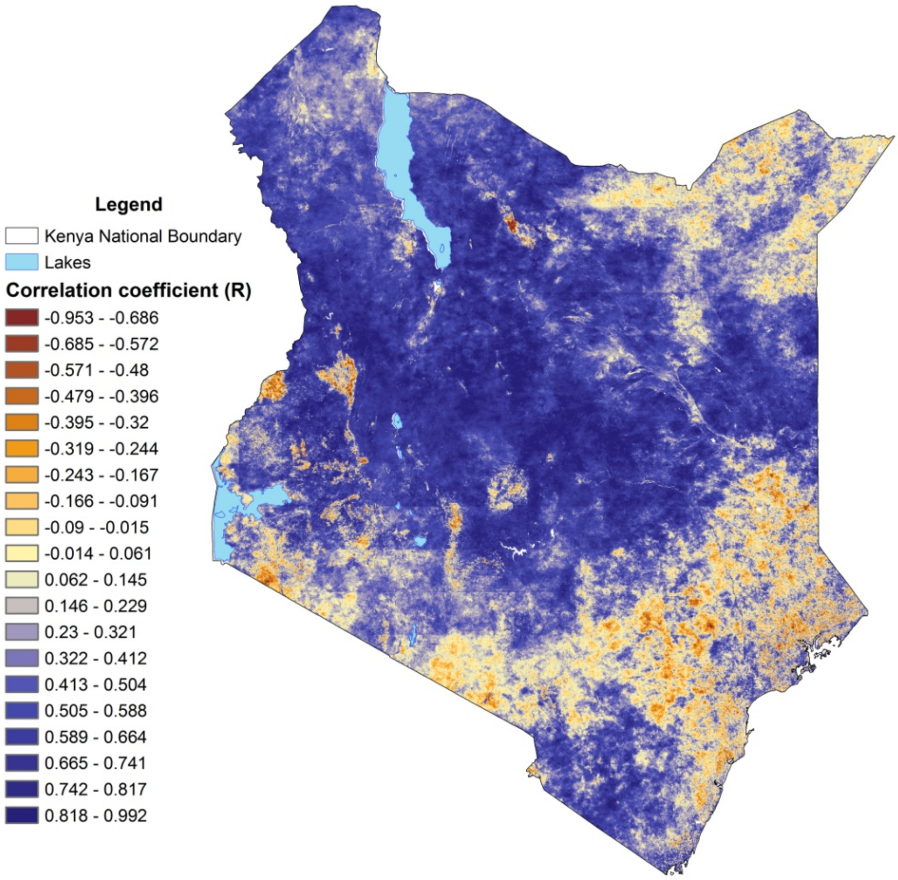


Figure 4.4 Pearson's coefficient of correlation between annual NDVI and precipitation (2000-2009)

A test of significance showed that the area with significant correlation between NDVI and MAP shifted with confidence level as indicated in the Table 4.1.

Table 4.1 Geographical extent of areas with significant correlation between NDVI and MAP (NB: total area of Kenya is 580,000 km^2)

Level of significance	Number of pixels	Area (km^2)	Proportion (%)
Significant at P < 0.25	8,148,910	434,834	75
Significant at P < 0.10	5,277,187	281,596	49
Significant at P < 0.05	3,463,058	184,792	32

Areas shaded darker blue showed that vegetation correlated positively with rainfall. Most of the areas with positive correlation encompass the dryland districts such as Baringo, Laikipia, Turkana, West Pokot, Isiolo and Samburu. Such areas also showed significant correlations between inter-annual NDVI and precipitation.

On the contrary, the brown shades show where vegetation correlated negatively with inter-annual rainfall. This may be interpreted that when rainfall increases the vegetation cover goes down (potential land degradation hotspots) or when rainfall decreases vegetation cover increases (irrigation and afforestation). The patches of exhibiting negative correlation between NDVI and rainfall span across the agroecological zones and include districts in both the arid, humid and semi-humid areas.

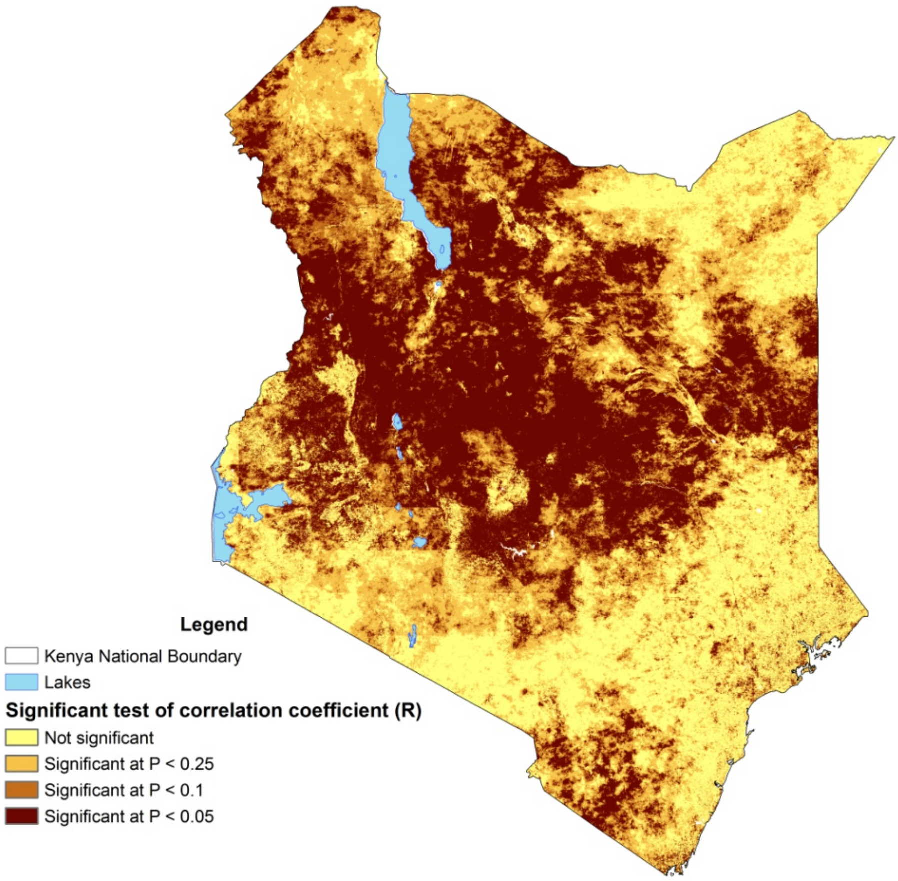


Figure 4.5 Pixel-based significant test for Pearson's coefficient between annual NDVI and precipitation (2000-2009)

4.3.2 Pixel-based linear slope of inter-annual NDVI

The long term annual change in vegetation cover depicted by the NDVI slope is presented in Figure 4.6 and shows ranges of between -0.067 and +0.068. Areas shaded blue indicate those with positive NDVI slopes over the 10 year period. Such areas can be considered as stable or improving in vegetation cover. On the other hand those shaded brown indicate areas with a negative slope of NDVI over time and could point out areas at threat of land degradation. The results show possible land degradation patterns in a wide range of districts from the regions considered high to low potential for crop production (red circles). These districts include Kitui, Kajiado and Narok in Eastern Province, Kwale, Kilifi and Tana River in Coast province, Marsabit, Turkana, Isiolo and Garrisa in North Eastern Kenya, Kakamega, Bungoma in Western, Nyandarua, Nakuru and Laikipia in Rift Valley and Kisii, Kisumu and Siaya in Nyanza Province. This widespread pattern of degradation insinuates various drivers, which can range from deforestation, overgrazing, etc. On the other hand, areas such as Wajir, Baringo and the districts around Mount Kenya (green circles) showed positive NDVI slope pointing implying that these regions are stable or improving in vegetation cover. The positive NDVI trends observed in Wajir and Baringo, in particular are very interesting considering that these are districts located in the arid and semi-arid lands (ASALs) characterized by low and irregular rainfall patterns.

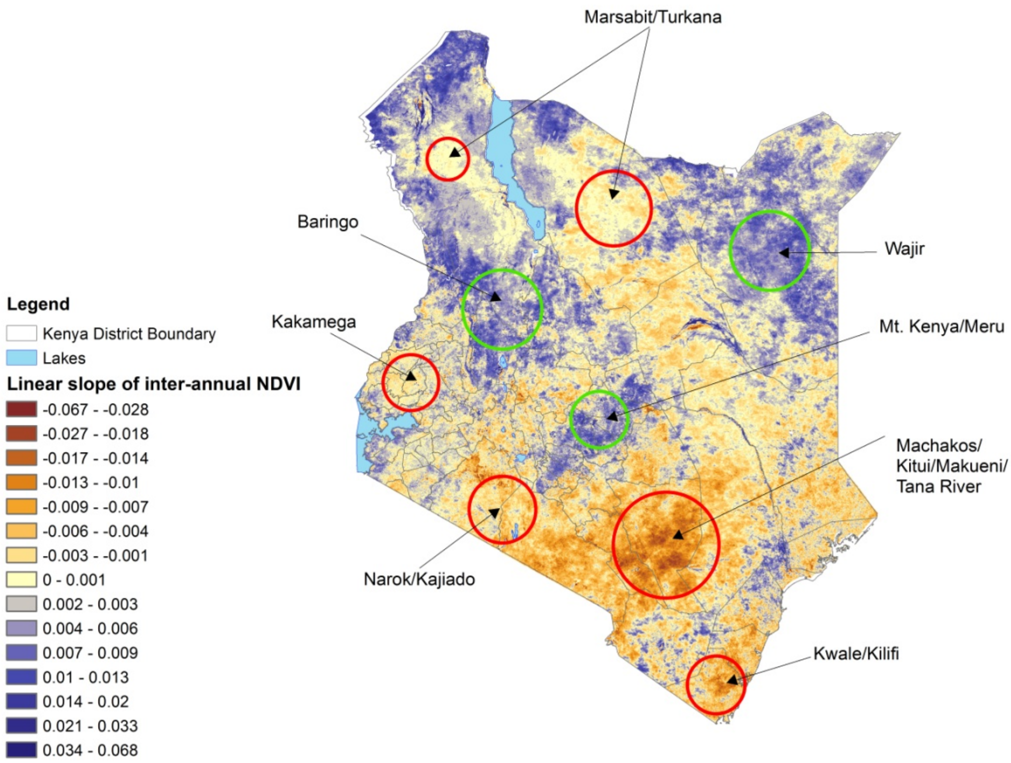


Figure 4.6 Inter-annual NDVI change for the period 2000-2009

A test of significance was performed to determine the magnitude of change in slope of NDVI over time (Figure 4.7). Table 4.2 summarizes the results irrespective of whether this change was positive or negative. At 95% confidence level, there was significant change in NDVI in 11% of the study area.

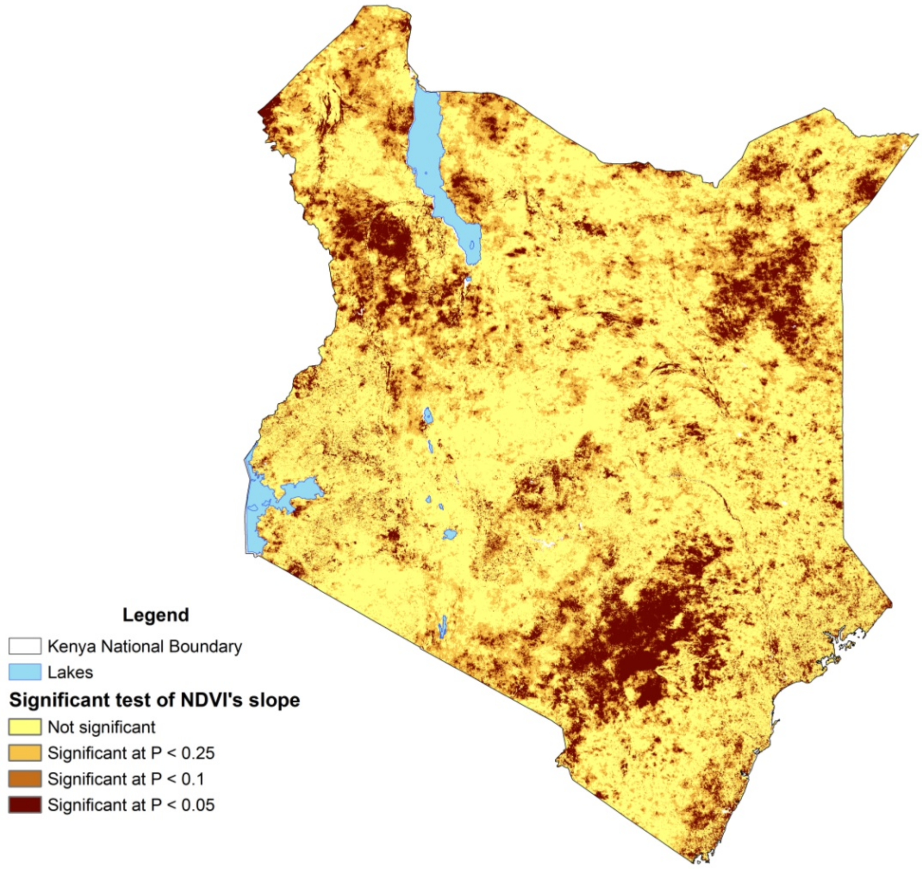


Figure 4.7 Pixel-based significance of inter-annual NDVI change over the period 2000-2009

Table 4.2 Geographical extent of areas with significant inter-annual change in NDVI (NB: total area of Kenya is 580,000 km^2)

Level of significance	Number of pixels	Area (km^2)	Percentage (%)
Significant at P < 0.25	5,603,987	299,034	52
Significant at P < 0.10	2,354,815	125,655	22
Significant at P < 0.05	1,204,510	64,274	11

Vegetation changes based on NDVI differencing

Figure 4.8 shows the absolute and relative NDVI changes across the country between the baseline (2001-2003) and the endline (2007-2009). The absolute change in NDVI ranged from -0.42 to +0.48. Presenting the change in relative terms was able to highlight the magnitude of change in NDVI across the country. Areas exhibiting improving NDVI recorded relative change values of up to 238% while those exhibiting declining vegetation recorded negative NDVI change values of up to -74% relative to the initial time line.

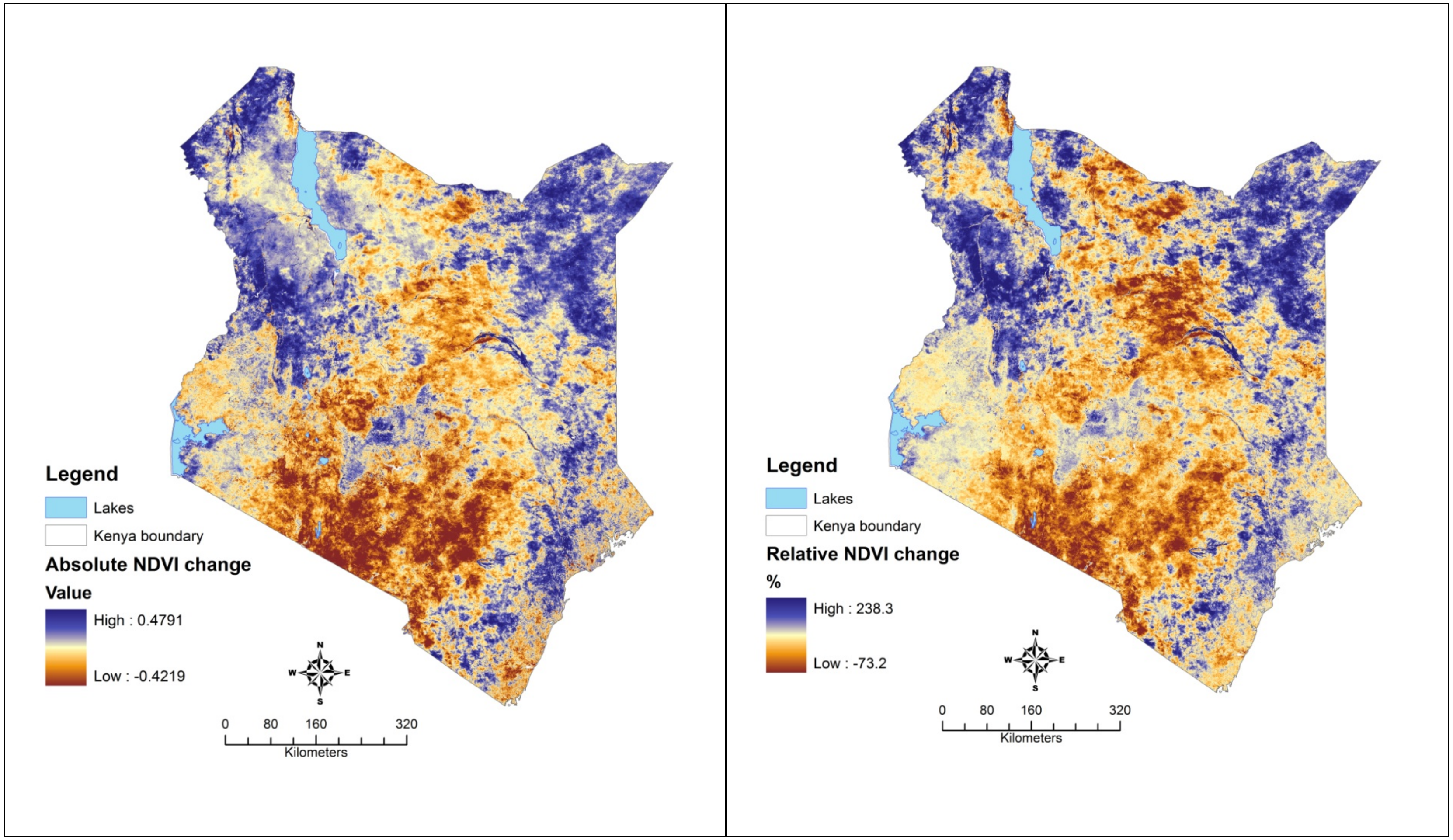


Figure 4.8 Absolute (a) and relative (b) change in biomass based on NDVI differencing

Figure 4.9 and Table 4.3 show the proportion of land that experienced at least 10% change in relative NDVI between the two time periods of consideration. About 20% (119,598 km^2) of the country was characterized by declining relative NDVI while 12% showed areas with improving relative NDVI greater than 10%.

Table 4.3 Proportion of land experiencing at least 10% change in relative NDVI

Biomass trend	Number of pixels	Area (km^2)	Percentage (%)
Declining relative NDVI	2,260,836	120,640	21
Neutral	7,266,198	384,732	67
Improving relative NDVI	1,292,222	68,954	12
Total	10,819,256	577,326	100

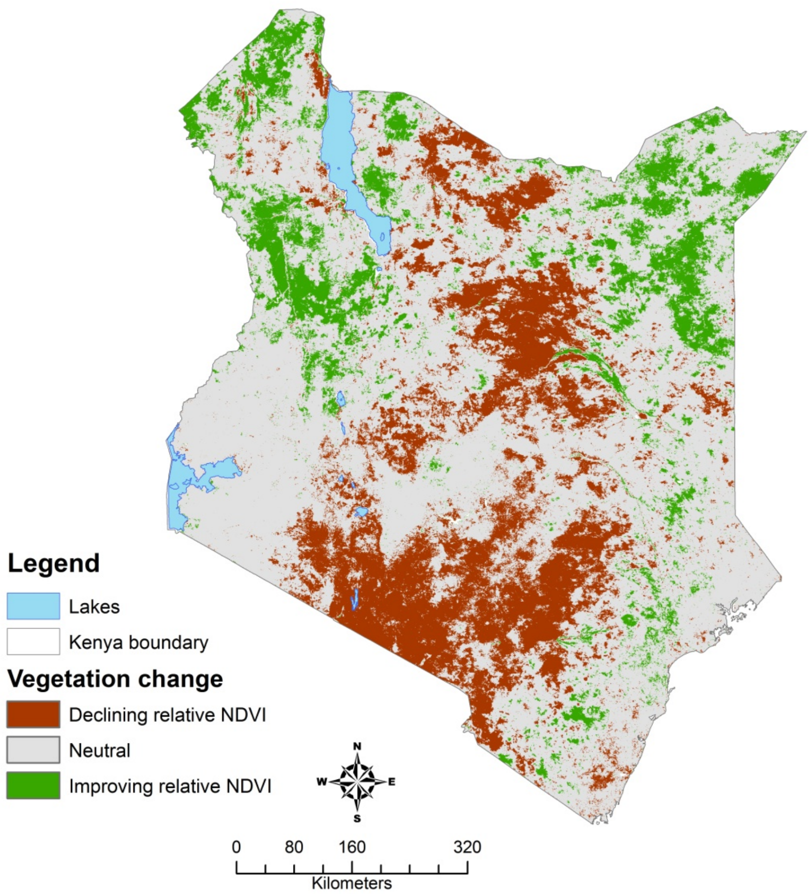


Figure 4.9 Areas of land experiencing at least 10% change in relative NDVI

NDVI patterns for selected districts in western Kenya

4.3.3 Land degradation patterns in Western Kenya

A similar procedure for monitoring changes in vegetation was applied for the target districts in western Kenya but this time with measured rainfall data from weather stations located in the study area. Figure 4.10 shows the agroecological zones of the study area and the location of rain gauges.

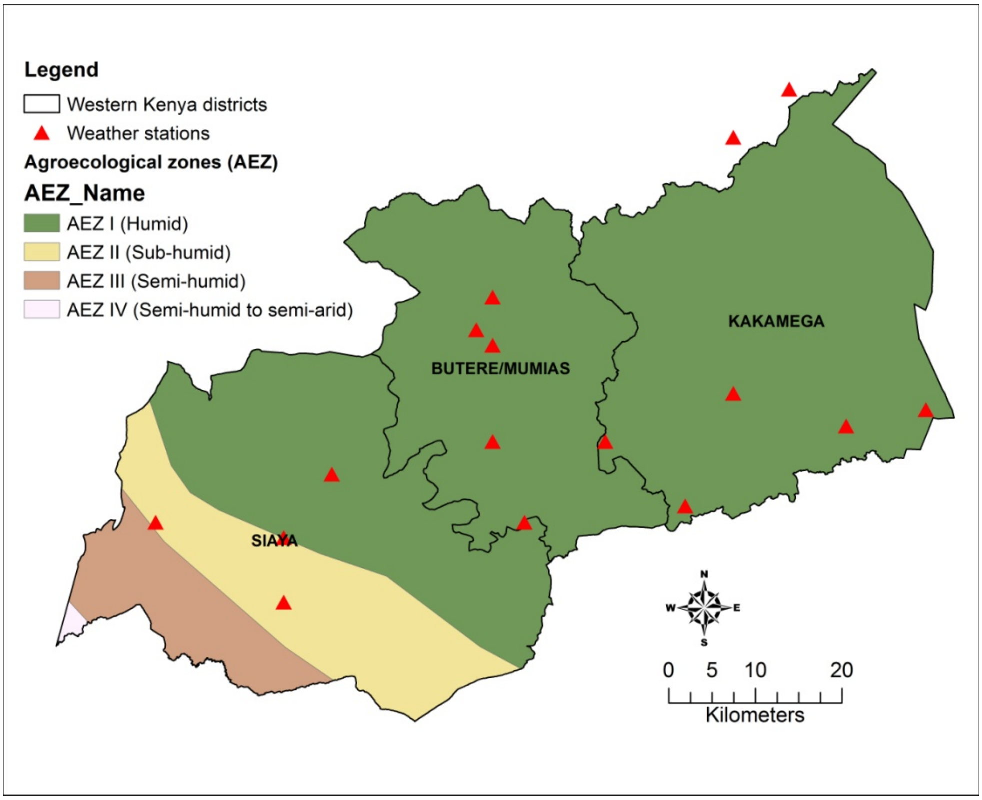


Figure 4.10 Agroecological zones and weather stations in the study area of western Kenya

Figure 4.11 shows the correlation between mean annual precipitation and NDVI for the districts in Western Kenya. The correlation coefficient was between -0.855 and + 0.821. The geographical area with significant correlation between rainfall and NDVI was 3%, 12% and 41% when considered at 95%, 90% and 75% confidence levels, respectively (Table 4.4; Figure 4.12).

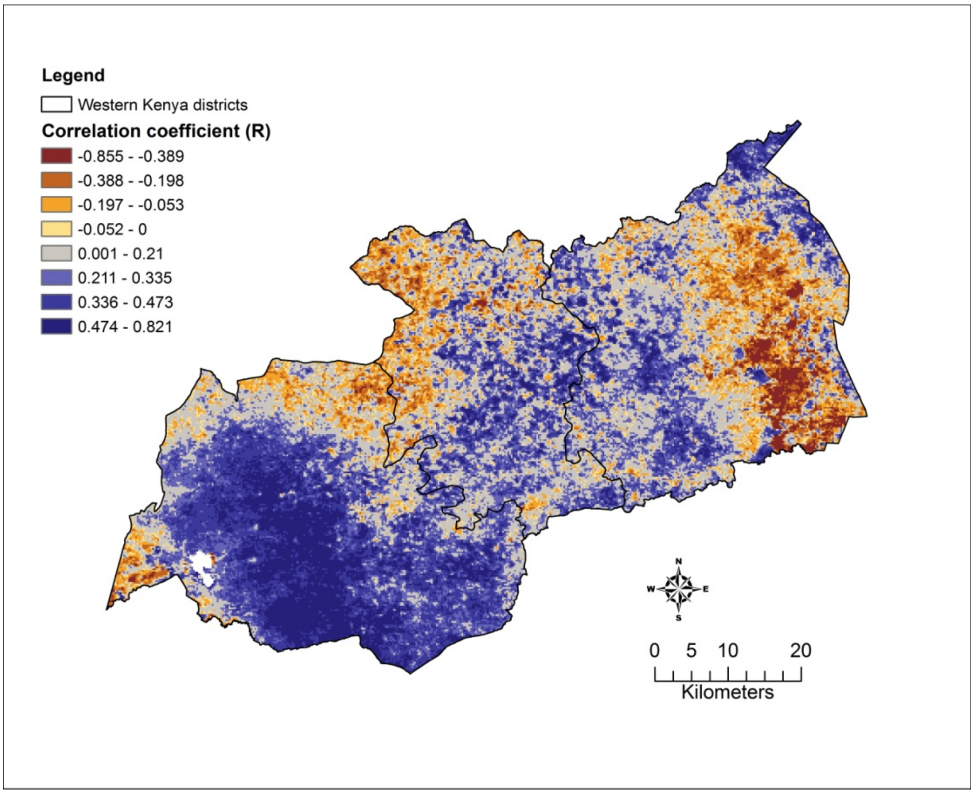


Figure 4.11 Pearson's coefficient of correlation between annual NDVI and precipitation for the districts in western Kenya (2000-2009)

Table 4.4 Geographical extent of areas with significant correlation between NDVI and rainfall for the districts in western Kenya (NB: total area of study area 3,800 km^2)

Level of significance	Number of pixels	Area (km^2)	Percentage (%)
Significant at P < 0.25	34,487	1,840	41.0
Significant at P < 0.10	10,024	535	11.9
Significant at P < 0.05	2,371	127	2.8

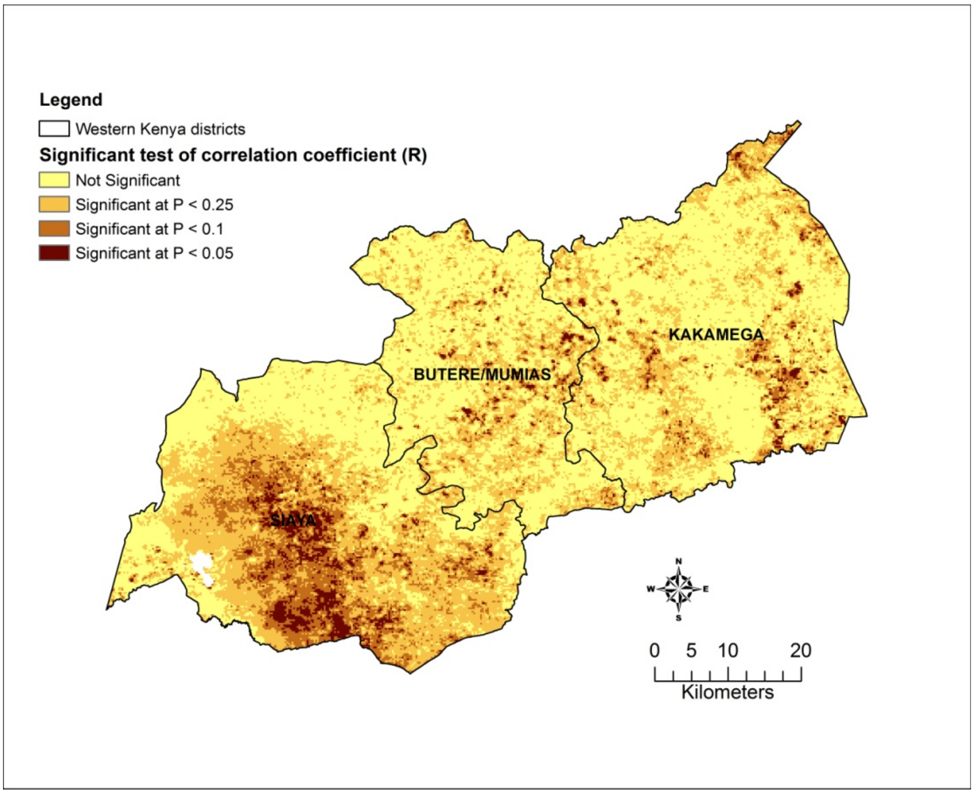


Figure 4.12 Pixel-based significant test of NDVI linear slope over the period 2000-2009

The inter-annual NDVI change showed that most of the region experienced a general decline in net primary productivity over the period of assessment (Figure 4.13). The expanse of region having negative NDVI trends is predominantly under intensive smallholder crop cultivation. Notable however are the positive NDVI values in Siaya District. This region is located in lowland could be benefiting from longer residual moisture and frequent flooding that benefits vegetation even in times of declining rainfall. The region is considered semi arid area climate and hence slight changes in NDVI could result in very significant changes being observed.

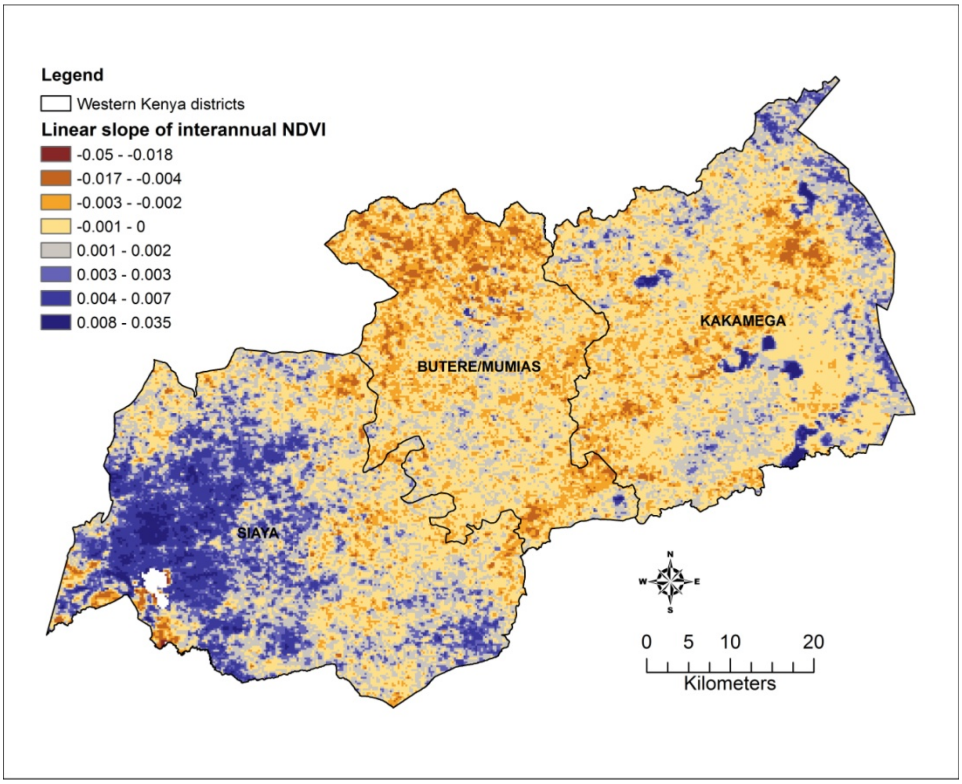


Figure 4.13 Linear slope of inter-annual NDVI for the period 2000-2009 for Western Kenya

The above patterns are confirmed by a test of significance of the NDVI slope, which showed significant changes in NDVI around Kakamega Forest, Yala Swamp, North Bunyala and Malava/Kabras (Figure 4.14). At 95% confidence level, 5% of the area was experiencing declining vegetation over the years (Table 4.5).

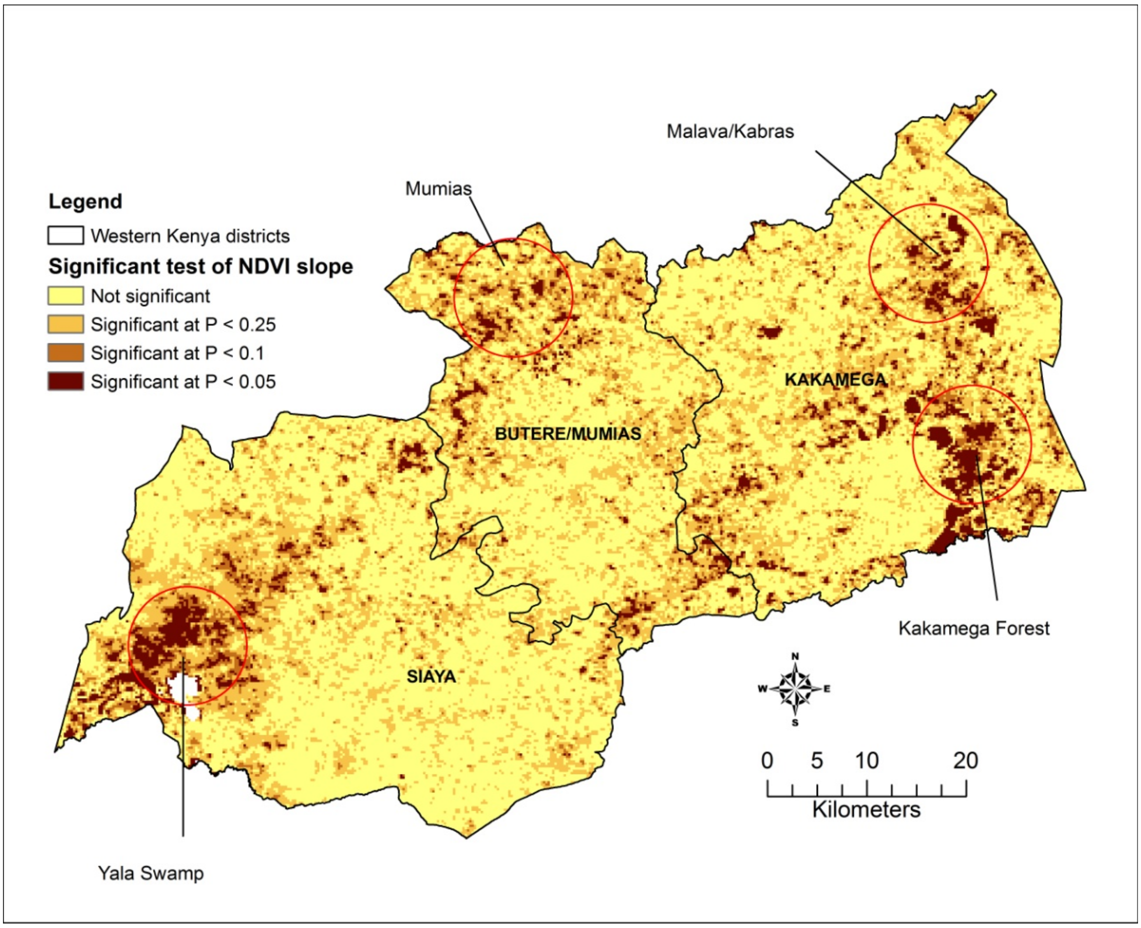


Figure 4.14 Pixel-based significance of inter-annual NDVI change over the period 2000-2009 for Western Kenya

Table 4.5 Geographical extent of areas with significant inter-annual change in NDVI for the districts in western Kenya (NB: total area of Kenya is 580,000 km^2)

Level of significance	Number of pixels	Area (km^2)	Percentage (%)
Significant at P < 0.25	31,157	1,663	36.6
Significant at P < 0.10	9,560	510	11.2
Significant at P < 0.05	3,996	213	4.7

4.4 Discussion

There is a strong correlation between rainfall and NDVI as shown by the similarity in patterns between the agroecological zones and the average NDVI patterns across the study area. Numerous studies have used this relationship to study changes in vegetation patterns and by extension to understand patterns of land degradation or improvement (Anyamba and Tucker 2005; Olsson et al. 2005; Vlek et al. 2008; Vlek et al. 2010; Fensholt et al. 2012). Beyond rainfall, patterns of vegetation could also be influenced by inherent soil fertility status as well as the land use and land cover changes taking place either due to natural or human activities.

In general, the vegetation patterns were clearer in the arid and semi-arid land (ASAL) districts compared to the humid and semi-humid zones. This observation could be attributed to the observation that NDVI tends to saturate (level off) for high biomass values/ leaf area index (Hobbs 1995) and such behavior leads to a non-linear relationship (e.g., quadratic, log-linear) between NDVI and biomass data (Hobbs 1995; Santin-Janin et al. 2009). Nicholson et al., (1990) in a comparative study between the Sahel and East Africa region observed that there is little change of NDVI with rainfall when the latter exceeds 1,000-1,200 mm/year. The authors concluded that NDVI might therefore be a sensitive indicator of rainfall in drier regions but not humid ones and might potentially serve as an indicator of abnormally dry conditions but not wet ones. This observation is confirmed by the high relative change in NDVI in dryland areas compared to the humid areas (Figure 4.8). Despite this limitation, using NDVI provided indicative patterns of vegetation changes taking place in the study area to warrant further monitoring and assessment.

The patterns of productivity reported in this study corroborate with previous assessments (Bai and Dent 2006) which concluded that areas around Lake Turkana and the various districts of Eastern province (Machakos, Kitui, Makueni) showed greatest risk of degradation as evident from the large extents of areas with long term decline in vegetation productivity. The history of soil erosion and conservation in the districts of Eastern Kenya, especially Machakos, Kitui and Makueni has been documented by in the book 'More people le*ss erosion*' (Tiffen et al. 1994). As a result of low rainfall, vegetation cover is sparse leaving the land exposed to agents of soil erosion, mainly, water and wind.

This study relied on documented literature to postulate possible reasons for the changes in vegetation observed across the country. Overgrazing is singled out as one of the main catalysts of land degradation in these dryland areas that are inhabited by nomadic pastoral communities who keep a wide array of livestock (O' Leary 1985).

Since the 1960s, the grazing range of the pastoral communities has continued to decline due to the establishment of wildlife protected areas and land fragmentation (Kioko and Okello 2010). However, the livestock numbers have remained high. This has led to overstocking and decline in the general health of the rangelands and the land's ability to recover from stochastic events such as droughts (Milton et al. 1994). In addition to overgrazing, loss of above ground biomass in the arid and semi-arid areas have resulted from increased cutting of trees for use as fuel wood, fencing, charcoal and construction.

Patterns of declining vegetation in the humid and sub humid areas could be attributed the expansion of land under cultivation. Rapid human population growth has led to increased demand for land for crop production and settlement. This has led to increased land fragmentation and encroachment of natural areas such as open grasslands and forests. For example, forests have been subjected to increased destruction due to clear cutting, burning and slashing. Since the 1990s, the Mau Forest Complex lost over 107,000 hectares representing approx. 25% of its forest cover due to encroachment, ill-planned and irregular settlements, as well as illegal forest resources extraction (MTF 2009). Between 1955 and 2004, the indigenous forest areas in the Taita Hills decreased by 50% (Pellikka et al. 2009; Maeda et al. 2010). Similar forest decimations have been reported for other areas such as Nandi and Kakamega (Mitchell and Schaab 2006), Mt. Kenya and the Arberdares (NEMA 2011). The patterns of forest destruction are reflected in the overall decline in the national forest cover from 10% in 1963 to 1.7% in 2006 (Masinde and Karanja 2011). This proportion of forests is way below the government's goal of having Kenya's forest cover at 10% by 2015 (MTF 2009).

Continuous cultivation without adequate replenishment of nutrients has been blamed for the declining soil fertility in most of the smallholder farming systems of central and western Kenya (Smaling et al. 1993; Sanchez et al. 1997). The scarcity of land has resulted in the reduction or complete elimination of fallow periods previously used to regenerate the lost fertility. Accompanying declining soil fertility is the problem of soil erosion. Soil losses of up to 90 ton/ha/year have been reported in

Kenya's semi-arid areas (Thomas et al. 1981). Elsewhere, (Gachene 1995) reported soil loss of 247 tons/ha/year on steep slopes of the high-potential areas in Central Highlands. Waswa et al. (2002) reported that approximately 17% and 50% of agricultural land in Ndome and Ghazi, Taita Taveta District respectively had been permanently lost due to the combined effect of rill, inter-rill, and gully erosion, and sand deposition between 1961 and 1998. It is estimated that smallholder farming systems in the highlands of Kenya loose an equivalent of 112 kg N, 2.5 kg P and 70 kg K due to nutrient removals in form of crop harvest, leaching and soil erosion (Smaling et al. 1993). Poor soils result in reduced above ground productivity.

Conversely, positive and significant changes in the NDVI slope were reported for some selected locations across the country. Of great interest are areas such as Wajir and Baringo that are located in the dryland areas often perceived as under threat of desertification. A similar trend of 'greening' of drylands has been documented by (Olsson et al. 2005; Vlek et al. 2008; Vlek et al. 2010; Fensholt et al. 2012). Some authors stated that the greening observed in the arid lands is due to a gradual improvement in precipitation (Hulme 2001; Vlek et al. 2008). Other studies have attributed this increase in vegetation to atmospheric carbon dioxide (Billings et al. 2003) and nitrous oxide (Dentener 2006) fertilization. Olsson et al. (2005) in a study on the greening of the Sahel identified change in land use patterns, rural-to-urban migration, political unrest and armed conflicts and the general ecosystem resilience as other potential causes of the 'greening' of the drylands.

The positive trends in NDVI in districts located in the dryland parts of Kenya could also be attributed to the resilient tree and bush species (e.g., Acacia species) growing in these regions. Such species can withstand harsh climatic conditions and grazing and recover rapidly when conditions become favorable. Kiage et al. (2007) observed that the network of Acacia bushes in Baringo remained largely unchanged over the 14-year period and so were the NDVI values that remained largely unchanged between 0.2 and 0.4.

Localized greening effects of the drylands could be attributed to the expansion of agriculture and especially irrigation activities. The recent past has seen an in increase in irrigation activities in the dryland areas, especially along the Tana River, near Garissa, Baringo and Machakos districts. However, the irrigation schemes are small to cause the magnitude of vegetation change observed.

Impacts of land use change resulting in localized greening effects have also been observed in Kajiado district located to the south of Nairobi City (NEMA 2011). This is an area that has in the recent past seen expansion of peri-urban settlements. Subdivision and eventual change of ownership of this land previously under communal nomadic grazing has resulted in a change in the vegetation characteristics as the new landowners aggressively engage in Eucalyptus tree farming as a commercial activity or grow other trees to transform and improve the microclimate of this semi-arid landscape for settlement.

The greening effect observed in the drylands could also be attributed to the Government's and other development partners' initiative to promote soil and water conservation practices. For example extensive afforestation programs have in the past been initiated by the Green Belt Movement, Vi Agroforestry Programme and the World Agroforesty Centre. The Green Belt Movement initiative, for example, has been successful in promoting maintenance of tree cover at farm level in Central Kenya despite this region having one of the highest population densities and agricultural intensification. One notable Government-led initiative on soil and water conservation is the Fuel wood Afforestation Extension Project implemented in the 1970s and 1980s. This initiative aimed to control soil erosion, improve biomass cover, rehabilitate arid and semi arid land and rehabilitate disused quarries (Lenacuru 2003; Choge and Chikamai 2004; Mwangi and Swallow 2005). Among other strategies such as promotion of gully control and terracing, this project promoted the growing of *Prosopis juliflora*, an introduced tree species from South and Central America (Choge et al. 2007).

In the initial stage *P. juliflora* was appreciated due to its ability to grow on degraded areas where nothing else seemed able to grow (Mwangi and Swallow 2005). The tree was easy to plant, it prevented soil erosion and sandstorms, provided shade and the pods used as feed for livestock (Lenacuru 2003). In the late 1990s, however, the shrub started to spread rapidly and its suckering ability after cutting made it difficult to control. Today the shrub has colonized a large proportion of Kenya's arid lands, such as the Taita Taveta, Wajir, Mwingi, Marsabit, Isiolo, Mandera, Baringo and Turkana Districts (Sirmah et al. 2008). Expansive areas of Baringo are now covered by impenetrable thickets that prevent other plants, especially grass from growing (Andersson 2005). Goats feeding on the pods of the shrub have been reported to develop bad teeth. Other complaints about *P. juliflora* are that its thorns cause injuries on people and livestock and punctures on vehicles (Lenacuru 2003). *P. juliflora* has been reported as gradually diverting the Tana river from its course, thus affecting the Bura Irrigation Scheme as well as overgrowing a large proportion of the road network in the Kerio Delta (Sirmah et al. 2008).

The invasiveness of *P. juliflora* has been document for other parts of Africa drylands (Pasiecznik et al. 2001) and raises a question on whether the 'greening' observed in the these areas is as a result of this invasion and how desirable this is. Whereas the spread contributes to the greening of the drylands, the tree and the associated impacts can be considered as biological degradation with potential harmful effect on the integrity of the dryland ecosystems. Currently, *P. juliflora* is listed among the world's top 100 worst invasive alien species by the Invasive Species Specialist Group of the IUCN.

4.5 Conclusion

Using NDVI as a proxy can facilitate reasonable mapping of the patterns of land degradation and improvement across the landscape. This study estimated that 21% of the land was experiencing significant negative changes in vegetation cover, 12% was experiencing increasing vegetation cover while the remaining 67% was stable. These patterns are spread across the different agroecological zones (humid to arid) and suggesting that there could be different drivers of change in these areas. The assessment, both at national and regional level, provided an indication of areas at risk of degradation as well as those showing improvement. Whereas rainfall is the main driver of the vegetation changes, other land use land cover changes either natural or man-made could also influence the patterns of above ground biomass observed. Overgrazing, deforestation, soil erosion, nutrient decline were identified as possible reasons for the decline in vegetation cover while irrigation and afforestation were identified as possible causes of vegetation decline in the study area.

While using NDVI as a proxy for land degradation it is important to be aware that the vegetation patterns can be influenced by the shifts in climatic conditions. In a study on the expansion and contraction of the Sahara Desert, Tucker et al. (1991), observed that the variability in the inter-annual rainfall patterns had implications for detecting desertification. These authors further observed that as a result of such inter-annual variations, it would require a decades-long study to determine whether long-term expansion or contraction of the Sahara is occurring. This means that studies using NDVI as a proxy should consider extended periods of assessment to capture all variability to arrive at reliable conclusions.

The use of NDVI only looks into changes in total undifferentiated green biomass hence it is difficult to tell which type of vegetation (forest, woodlands, bushlands, grasslands) have changed. Further, certain stages of degradation e.g. loss of biodiversity, replacement of desired species, or invasion of new species, which are components of biological degradation are not detected by this method (Evans and Geerken 2004).

Loss of above ground biomass is not necessarily synonymous with land degradation nor is increase in above ground biomass necessarily land improvement. The tree canopy can mask incidences of sheet, rill and gulley soil erosion. Some positive biomass trends may indicate a harmful development for example, bush encroachment or expansion of cultivation into fragile ecosystems such as the drylands. The case of *P. juliflora* is an excellent example of how a land management initiative can turn out to be an environmental disaster with serious socio-economic impact on the residents (Pasiecznik 1999; Pasiecznik et al. 2001). Land cover changes from forests or grasslands to croplands may result in lesser biological productivity but may not be accompanied by soil erosion or other forms of degradation such as compaction and nutrient depletion (Bai et al. 2010). This means that the actual causes of degrading or improving vegetation as mapped using NDVI as a proxy have to be ascertained by conducting direct field observations and measurements at selected areas of interest using standardized methodologies and frameworks.

5 LAND USE LAND COVER (LULC) CHANGE AND IMPLICATIONS FOR LAND DEGRADATION

5.1 Introduction

Understanding land use and land cover (LULC) changes is critical for the design of effective land management programmes as well as an essential element for modeling and understanding the earth feature system. Land cover (LC) refers to the physical characteristics of the earth surface, captured in the distribution of vegetation, water, desert, ice and other physical feature of the land including those created solely by human activities such as mine exposures and settlement (Lillesand and Kiefer 2000). On the other hand, land use (LU) is any human activity or economical related function associated with a specific piece of land (Lillesand and Kiefer 2000). For example, a forest, a land cover may be used for selective logging, recreation or for tourism. Land cover and land use change may be classified into two broad categories: conversion or modification (Butt and Olson 2002). Conversion refers to the changes from one cover or use to another, e.g. conversion of forests to pasture or to cropland. Modification on the other hand refers to the maintenance of the broad cover or use type in the face of changes in its attributes. For example, a forest may be retained but significant alterations may be made on its structure or function.

Over the years, interest in LULC change studies has grown due to improved availability of remotely sensed data and facilitated interpretation using GIS software. LULC assessment has now been mainstreamed into global environmental change research because it provides broad scale data on aspects such as climate change, changing carbon stocks, habitats and biodiversity and also it provides an entry into understanding the human dimensions of environmental change (Turner II et al. 1995; Lambin et al. 1999; de Sherbinin 2002).

LULC changes can be assessed at different scales (hierarchy theory): field to farm, the community, the landscape, and national/continental and global levels (Olson et al. 2004). The different scales of analysis provide different types of information. This means that a multi-scale approach is necessary to fully understand trends and their causes. Global and continental LULC assessment outputs are general in nature and hence are suitable for long term global environmental change studies such as global climate change and biogeochemical cycles (Vitousek 1994). Studies undertaken at national levels are often used for policy formulation and resource allocation. On the other hand, studies at landscape and farm levels are more detailed and provide insights on the actual causes and changes taking place at a given location and such information can aid in designing strategies for rehabilitation and restoration.

Patterns of LULC change, and land management are shaped by the interaction of economic, environmental, social, political, and technological forces on local to global scales. The key LULC change pathways include deforestation, desertification, wetland drainage and agricultural intensification (Butt and Olson 2002). As observed by de Sherbinin (2002), the great interest in LULC changes results from their direct relationship to many of the earth's fundamental characteristics and processes, such as land productivity, diversity of plant and animal species, and the biochemical and hydrological cycles. LULC changes are linked to climate and weather in complex ways. LULC affects exchange of greenhouse gases between the land surface and the atmosphere, the radiation balance of the land surface, the exchange of sensible heat between the land surface and the atmosphere, and the roughness of the land surface and its uptake of momentum from the atmosphere (NRC 2001). Changes in LULC can be important contributors to climate change and variability. LULC changes therefore affect ecosystems and the many important goods and services that they provide to society. Understanding these interactions is essential in providing explanations and predictions of current and new land use changes in light of changing environmental conditions.

The objective of the LULC change assessment was therefore to ascertain the long-term trends in LU and LC changes in the study area as basis for understanding the state and patterns of land degradation.

5.2 Study area and description

The LULC assessment was conducted for the area covering three districts: Kakamega, Butere-Mumias and Siaya located in Western Kenya (Fig 5.1). The study is located is located at 34° 2' 48" - 34° 58' 45" E and 0° 4' 26" S - 0° 36' 15" N and covers about 3,800 km^2. The altitude ranges from 1200 to 1500 m.a.s.l. The rainfall distribution follows an altitude gradient with the regions in the north east (higher altitude) receive higher rainfall (1800 mm/yr) while those in the southwest (lower) altitude receive lower amounts (800 mm/yr) of rainfall.

Western Kenya is considered a 'bread basket' area of Kenya due to its great potential to produce food to feed the growing human population. However, the rapidly growing human population has led to intense fragmentation of the existing land. The region has one of the highest population densities (300-1,300 persons per sq km) with average farm sizes ranging between 0.5 and 2.0 ha per household of 6-8 members (Tittonell et al. 2008). Despite the region being classified as of high potential, production of the major cereal (maize) is very low and declining, averaging 1 t/ha of grain compared to the potential yields of 8 t/ha. The low productivity is attributed to poor land management practices e.g. low use of external nutrient sources, soil erosion among others (Ojiem and Odendo 1996; Sanchez et al. 1997; Woomer et al. 1998).

The land scarcity and increasing need for food production has put immense pressure on the natural resource base thus leading to widespread land degradation in form of deforestation, soil erosion, overgrazing, and wetland draining among other. Like many other parts of the country, the region has in the past suffered from periodic fluctuations in rainfall resulting in poor yields. Continued sustenance of the system will depend on how the LULC changes are in harmony with the ability of the ecosystem to provide environmental services.

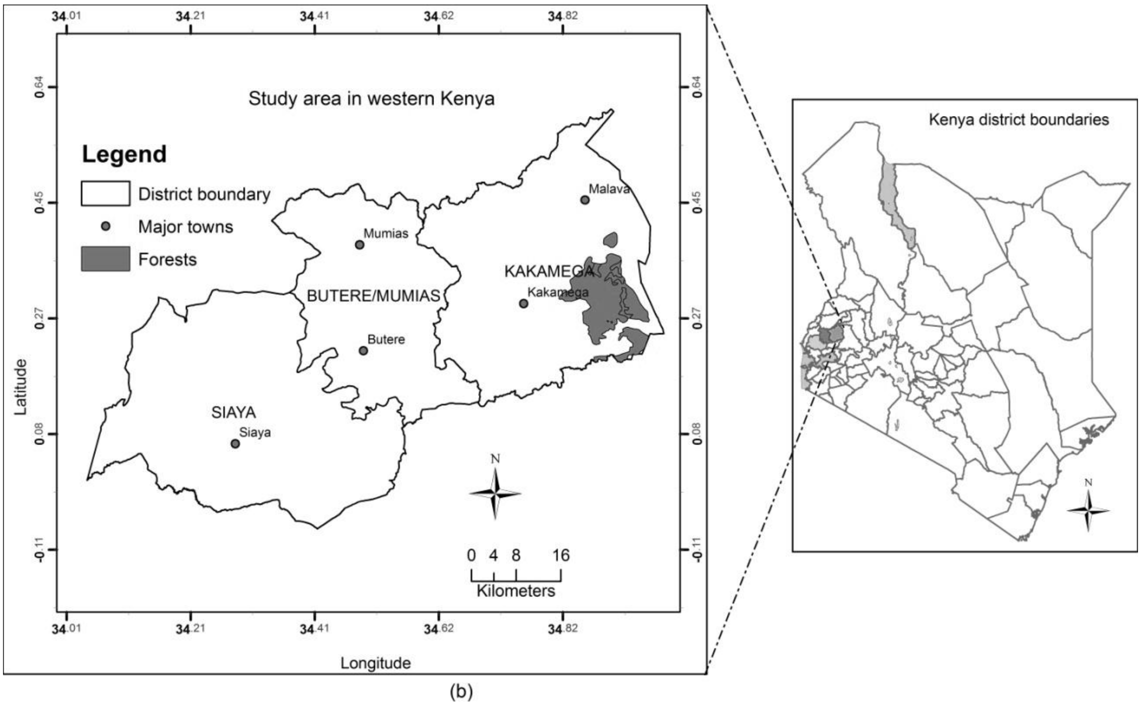


Figure 5.1 Location of the study site

5.3 Materials and methods

The land use/cover change assessment of the study area was conducted using three scenes of Landsat imagery for the years 1973, 1988 and 2003 to cover a period of 30 years. Landsat imagery was selected because Landsat has the longest running imagery acquisition dating back to 1972 hence can provide long-term mapping of changes. The images were obtained from the USGS Glovis website (http://glovis.usgs.gov/). Figure 5.2 shows the Landsat imagery scene with the boundary of the study area.

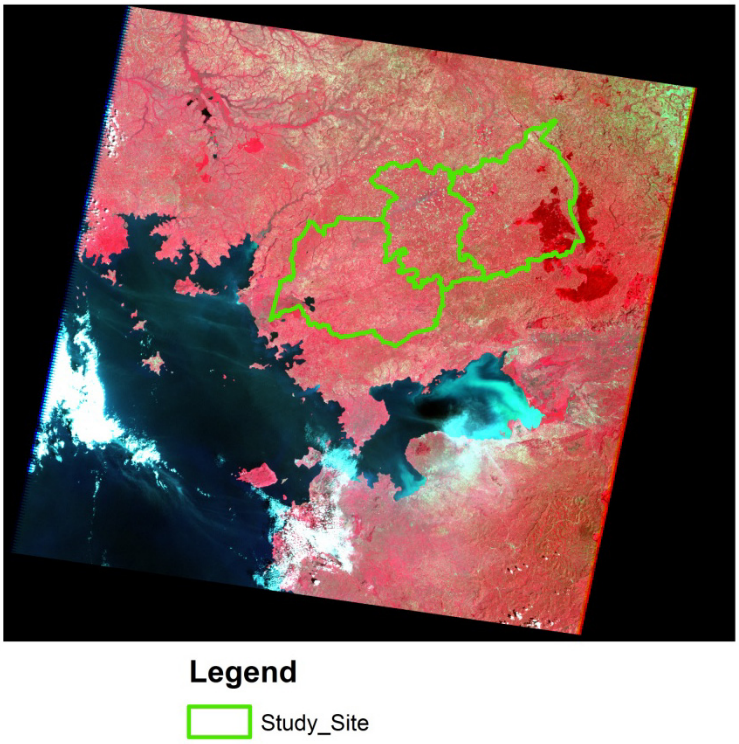


Figure 5.2 Landsat false color composite (Bands 4,3,2) with the study site boundary

The data sets comprised of Landsat Multi Spectral Scanner (MSS) for 1973, Thematic Mapper (TM) for 1988 and Enhanced Thematic Mapper (ETM+) for 2003. Table 5.1 shows the characteristics of the three data sets. For consistency in vegetation and land use change comparison, selection of the images was done to ensure that the period of assessment was the same (dry season between January and March). Selection of images during the dry period was to minimize on interference due to cloud cover. The images selected were relatively cloud free and fitted very well to the study site since they were already georeferenced.

Table 5.1 General attributes of the Landsat images

Year	Scene (Path/Row)	Date of Acquisition (yy/mm/dd)	Sensor	Spectral Range (m)	Bands	Pixel Resolution (m)
1973	182/060	1973-02-01	MSS multi-spectral	0.5-1.1	1, 2, 3, 4	60
1988	170/060	1988-02-18	TM multi-spectral	0.45-2.35	1, 2, 3, 4, 5, 7	30
			TM thermal	10.40-12.50	6	120
2003	170/060	2003-01-10	ETM+ multi-spectral	0.45- 2.35	1, 2, 3, 4, 5, 7	30
			ETM+ thermal	10.40-12.50	6.1, 6.2	60
			Panchromatic	0.52-0.90	8	15

Image processing and land use/cover change assessment was performed using the software Environment for Visualizing Images (ENVI, 4.8 Student Edition) and ArcGIS 9.3.1.

5.3.1 Image pre-processing

Upon downloading, the images the datum was projected to WGS 1984 and referenced to the Universal Transverse Mercator (UTM) Zone 36 North. Satellite images captured at different times contain noise due to changes in sensor calibration over time, differences in illumination and observation angles, and variation in atmospheric effects (Eckhardt et al. 1990). To facilitate effective mapping of vegetation and environmental changes, it is helpful to remove these exogenous effects and standardize the images (Richter 1990; Githui 2008). This can be done by radiometric preprocessing (Teillet et al. 2001; Kiage et al. 2007). There are two types of radiometric preprocessing techniques for change detection: relative and absolute correction (Olsson 1995). This study adopted the absolute correction technique where the brightness values (represented by the digital numbers -DN- 0-255) were converted into surface reflectance using a number of atmospheric correction and calibration equations (Lillesand and Kiefer 2004). The image bands for the three periods were calibrated to reflectance values - the ratio of exitance to irradiance. Reflectance is unit less and is measured on a scale from 0 to 1 (or 0-100%). This process was done in ArcGIS and ENVI using reliable and accurate conversion factors already developed for Landsat satellite sensors (Masek et al. 2001; Chander et al. 2009). The procedure of converting Landsat images from brightness values to reflectance and calculating vegetation indices is summarized in the article (Firl and Carter 2011). The calibrated image scenes were then clipped against the administrative boundaries of the study area for subsequent processing and analysis.

5.3.2 Computation of NDVI

Simple NDVI classification was incorporated in this study to assess trends in vegetation. NDVI was computed from the calibrated bands using the following equation:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

Where:

NIR is the reflectance in the near-infrared waveband (0.7 to 1.1 μm) and RED is the reflectance radiated in the visible red (0.4 to 0.7 μm) regions of the electromagnetic spectrum (Tucker 1979).

NDVI values range between -1 and +1, with values near zero and decreasing negative values indicate non-vegetated features such as barren surfaces (rock and soil) and water, snow, ice, and clouds. Increasing positive NDVI values indicate increasing amounts of green vegetation.

Different vegetation phytomes can be demarcated using different NDVI ranges (Davenport and Nicholson 1993; Weier and Herring 1999). Classifying the NDVI images using these ranges can be used to generate land cover classes, which can be used to monitor vegetation changes. The NDVI values were therefore reclassified with those below 0 representing water, 0 - 0.1 representing bareland or areas with very sparse vegetation, 0.2-0.3 representing pastures or grasslands, 0.4-0.5 representing bushlands/woodlands while values above 0.6 indicating dense vegetation such as forests. As a precaution, it is worth mentioning that NDVI is an indicator of the condition of the overall vegetation in an area, and so the value at any given point is the sum of the radiation from all land cover types within the area covered by that pixel, irrespective of whether this is natural vegetation or agricultural areas. As a result, land cover classification using NDVI can result in overgeneralization of the land cover classes. Despite this limitation, using this approach provided a rapid assessment of the land cover changes in the study area over the period of interest.

5.3.3 Image classification

Imagery classification is the most commonly used approach for monitoring landscape changes. Different color composites were generated by compositing individual bands in a Red, Green, Blue (RGB) combination. True color composites were made by combining bands 3-2-1 in a Red, Green, Blue (RGB) combination for the Landsat TM and ETM+. The standard false color composite (FCC) were derived by combining bands 4-3-2. Other band combinations used included 4-5-3 to visualize different vegetation types and 5-4-1 to help visualize agricultural vegetation. Imagery classification was done on the pre-processed images using unsupervised and supervised methods. The procedure involved starting with the most recent scene (ETM2003) and proceeding to the oldest (MSS1973) imagery.

Supervised classification

Supervised classification methods are used to cluster pixels in a data set into classes corresponding to user defined regions of interest (ROIs) or training classes (Eastman 1995). These ROIs are usually prior selected as representative areas to be mapped in the output. This study adopted the use of Maximum Likelihood method- a statistical decision criterion that assigns pixels to the class of highest probability. Training classes were defined prior to performing supervised classification by defining regions of interest (ROIs). Demarcation of the ROIs was based on personal knowledge of the study area coupled with reference to high-resolution images, Google Earth maps, topographic maps as well as based on previously classified images of the study area. The results from this process were used to ascertain those obtained using the unsupervised classification approach.

Unsupervised classification

Unsupervised classification is a method, which examines a large number of unknown pixels and divides into a number of classed based on natural groupings present in the image values (Lillesand and Kiefer 2000). The basic premise is that values within a given cover type should be close together in the measurement space, whereas data in different classes should be comparatively well separated. The identity of the spectral class is initially unknown and it is only after comparing the classified data to some form of reference data (such as larger scale imagery, maps, or site visits) that one can determine the identity and informational values of the spectral classes. This approach allows natural spectral classes to be defined with high degree of objectivity.

Unsupervised image classification was first done on each scene using the K-means approach. This produced a map with 50 spectral classes. Starting with a large number of classes ensured complete disaggregation of the spectral classes. The spectral classes were then assigned to a specific LULC category following visual interpretation based on personal knowledge of the study area as well as comparing the classes with high resolution Google Earth images and topographic maps. Visual interpretation was based on the relationships between ground features and image elements like texture, tone, geometry, location and pattern. Similar LULC classes were merged in instances where they were assigned to different spectral classes. The following 8 classes were derived (Table 5.2). These LULC classes build on the broader land cover (LC) classes derived using NDVI data. Secondly, the classes are easily recognizable and can easily be related to land degradation patterns in study area.

Table 5.2 Description of the land use/cover classes

Land use/cover class	Description
1. Plantation forest	Areas covered with exotic stands of trees mainly *Pinus patula*, *Bischoffia javanica, Cypress spp. among others*
2. Natural forest	Areas covered with old, natural or near natural tree stands with lowest disturbance. Believed to be remnants of the Congo Tropical Forest
3. Secondary forest (especially around main natural forest)	Areas covered with a mixture of trees regenerating especially after clearing or reforestation programs, e.g. *Maesopsis eminii*
4. Bushland	A mixture of trees and shrubs especially *Psidium guajava* and *Lantana camara*
5. Wooded grassland	Open areas with grasses interspersed with trees often used for grazing and grass used for roof thatching. This category also encompassed wetland vegetation (Papyrus species and associations)
6. Agricultural land	Cultivated areas of diverse characteristics with field crops both food and cash crops such as maize, sugarcane, tea among other.
7. Bareland	Areas with sparse or no vegetation cover due to prolonged drought or degradation (This class also encompassed roads and build up areas)
8. Water bodies	Areas permanently covered with standing or moving water, e.g. wetland lake, rivers, water ponds

5.3.4 Image post-classification

Classified images often suffer from a lack of spatial coherency (speckle or holes in classified areas (Lillesand and Kiefer 2000). Post classification operations are therefore needed to "smooth' the classified output to show only dominant classification. Class merging, sieving and clumping were done to achieve class spatial coherency.

Classification accuracy assessment or confusion matrix is normally performed after classification to give an overview of the preciseness of the classification (Congalton and Green 1998). Classification accuracy assessment compares the classification to geographical data that are assumed true to determine the accuracy of the classification process. The resultant matrix displays producer and user accuracies for each class as well as the overall accuracy of the classification (Campbell 1996). The producer accuracy is calculated by dividing the number of pixels that are correctly classified in one class by the number of ground truth pixels used for the associated class. The user accuracy is the result of dividing the number of pixels that are correctly classified in one class by the total number of pixels within this class. To calculate the overall accuracy the sum of correctly classified pixels is divided by the total number of ground truth pixels (Lillesand and Kiefer 2000). The accuracies can be expressed either in absolute numbers or in percent of pixels (Campbell 1996; Lillesand and Kiefer 2000).

For this study, accuracy of the classification was assessed using the Confusion Matrix but only on the ETM2003 scene because comparative data on past LULC classes was available. Accuracy assessment of for the classification of the earlier periods (MSS1973 and TM1988) was limited by lack of reasonable reference data since it is impossible to go back in time to collect historical ground reference (Jensen 1996). This study relied on information closest to the historical date such as topographic maps, Google Earth images, previous classification by other studies and familiarity with the study area to assess the accuracy.

Table 5.3 & 5.4 show the total number and percentage of pixels for each LULC class used for the accuracy assessment while Table 5.5 shows the overall accuracy, producer and user accuracies, and kappa coefficient. The results show a good overall classification accuracy of 90.85% and a Kappa coefficient of 0.89. The highest accuracy was with water bodies followed by bareland. Errors in classification came from misclassification of the forest classes (natural, secondary and plantation with bushland and wooded grasslands as well as misclassification of agricultural land with wooded grasslands and bareland. Despite these errors, the good overall justified the use of the classification to assess LULC changes in the study area.

The classified raster map thus, prepared was then converted to feature data and exported to ArcGIS for area calculation and preparation of the thematic maps.

Table 5.3 Confusion Matrix (ETM2003)

LULC Class	Plantation forest	Natural forest	Water bodies	Secondary forest	Bushland	Wooded grassland	Agricultural land	Bareland	Total
Plantation Forest	408	483	18	0	0	0	0	0	909
Natural forest	52	2602	0	59	1	1	0	0	2715
Water bodies	75	9	1739	0	0	0	0	0	1823
Secondary forest	0	12	0	1258	30	0	0	0	1300
Bushland	0	1	0	34	876	1	4	0	916
Wooded grassland	0	0	0	0	8	432	3	0	443
Agricultural land	0	0	0	0	20	35	915	4	974
Bareland	0	0	0	0	0	0	5	259	264
Total	535	3107	1757	1351	935	469	927	263	9344

NB: The diagonals shown in bold represent the number of pixels classified correctly)

Table 5.4 Confusion Matrix (ETM2003)

LULC Class	Plantation Forest	Natural Forest	Water Bodies	Secondary Forest	Bushlands	Wooded Grassland	Agricultural Land	Bareland
Plantation forest	76.4	15.6	1.0	0	0	0	0	0
Natural forest	9.7	83.9	0	4.4	0.1	0.2	0	0
Water bodies	14.0	0.3	99.	0	0	0	0	0
Secondary forest	0	0.4	0	93.1	3.2	0	0	0
Bushlands	0	0.3	0	2.5	93.7	0.2	0.4	0
Wooded grassland	0	0	0	0	0.9	92.1	0.3	0
Agricultural land	0	0	0	0	2.1	7.5	98.7	1.5
Bareland	0	0	0	0	0	0	0.5	98.5
Total	100	100	100	100	100	100	100	100

NB: The diagonals shown in bold represent the percentage of pixels classified correctly

Table 5.5 Producer and user accuracy assessment of classification (ETM 2003)

LULC Class	Number of Pixels	+Producer Accuracy (%)	*User Accuracy (%)
Plantation forest	909	76.26	44.88
Natural forest	2715	83.75	95.84
Water bodies	1823	98.98	95.39
Secondary forest	1300	93.12	96.77
Bushland	916	93.69	96.77
Wooded grassland	443	92.11	97.52
Agricultural land	974	98.71	93.94
Bareland	264	98.48	98.11
Total	9344		
Overall Accuracy		(8489/9344) 90.85%	
Kappa Coefficient		0.89	

*NB: +Producer's accuracy indicates the probability of a reference pixel being correctly classified and is a measure of omission error. *User's accuracy is indicative of the probability that a pixel classified on the map actually represents that category on the ground*

5.4 Results

5.4.1 Land cover change classification based NDVI values

The results of the change detection procedure based on NDVI values for the period 1973, 1988 and 2003 are presented in Figure 5.3 and Table 5.6. Vegetation changes are evident across the different NDVI range classes over the three periods of assessment. Areas with NDVI values 0 – 0.1 increased from less than 1% in 1973 to 1.4% in 2003. Areas with NDVI values >0.6 increased from 23% in 1973 to 42% in 1988 but declined to 10% in 2003. Areas with NDVI 0.4 - 0.5 was 72% in 1973 but declined to 50% in 1988 before increasing to 76% in 2003. Generally, the areas northeast are characterized by dense vegetation- forests- compared to the southwest regions which are dominated by grasslands and scattered trees. This distinct pattern of vegetation is attributed to the rainfall pattern as well as altitude variations. The areas in the northeast are at relatively higher altitude and experience higher rainfall compared to those in the lowland areas of the southwest. The areas southwest of the study area also have large areas of bare or exposed mainly due to sparse vegetation and possibly overgrazing. Such exposed areas are prone to soil erosion.

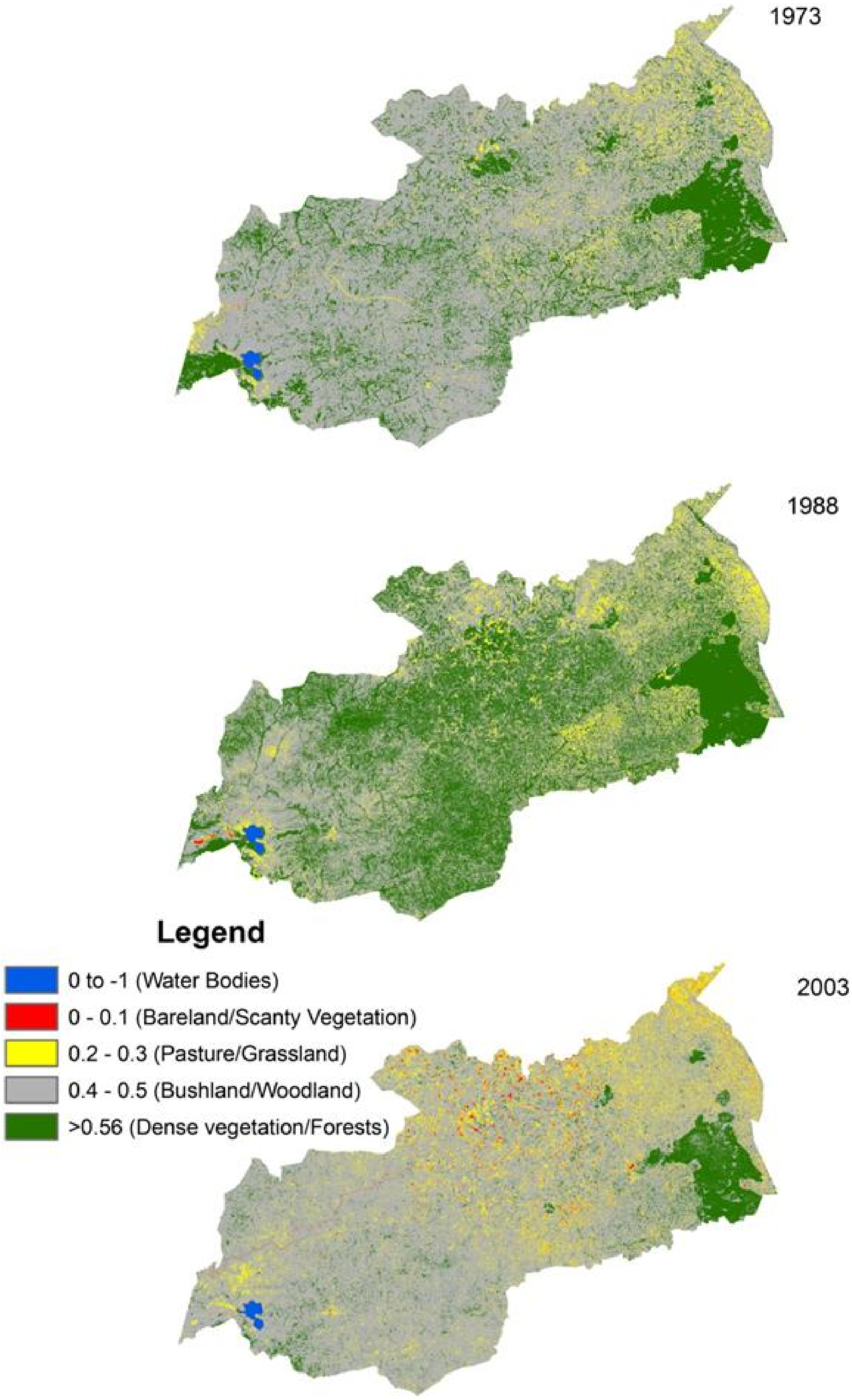


Figure 5.3 Land cover change classification based on NDVI values for 1973, 1988 and 2003

Table 5.6 Land cover change assessment based on NDVI values for 1973, 1988 and 2003

Land cover	1973		1988		2003	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Water (<1)	9.5	0.2	10.6	0.3	11.4	0.3
Bareland (0-0.1)	2.9	0.1	3.7	0.1	54.5	1.4
Pasture/Grassland (0.2-0.3)	190.0	5.0	294.2	7.7	471.6	12.3
Bushland/Woodland (0.4-0.5)	2,761.8	72.0	1,909.5	49.8	2,919.1	76.1
Dense vegetation (>0.56)	873.1	22.8	1,619.3	42.2	380.7	9.9
Total	3,837.3	100.0	3,837.3	100.0	3,837.3	100.0

5.4.2 Land use land cover change classification based supervised and unsupervised classification

The results for the supervised and unsupervised classification are presented in Figure 5.4. The summary of the LULC changes is presented in Table 5.7.

Table 5.7 Land use/cover evolution (%) between 1973 and 2003

Class	1973	1988	2003
Unclassified	2.6	2.1	2.0
Plantation forest	0.2	0.1	0.3
Natural forest	3.9	3.8	3.4
Secondary forest	0.3	1.2	0.5
Bushland	1.7	3.1	5.7
Wooded grassland	51.3	30.2	11.8
Agricultural land	27.9	50.5	70.4
Bareland	12.3	8.9	7.4
Water bodies	2.3	1.1	0.5
Total	100.0	100.0	100.0

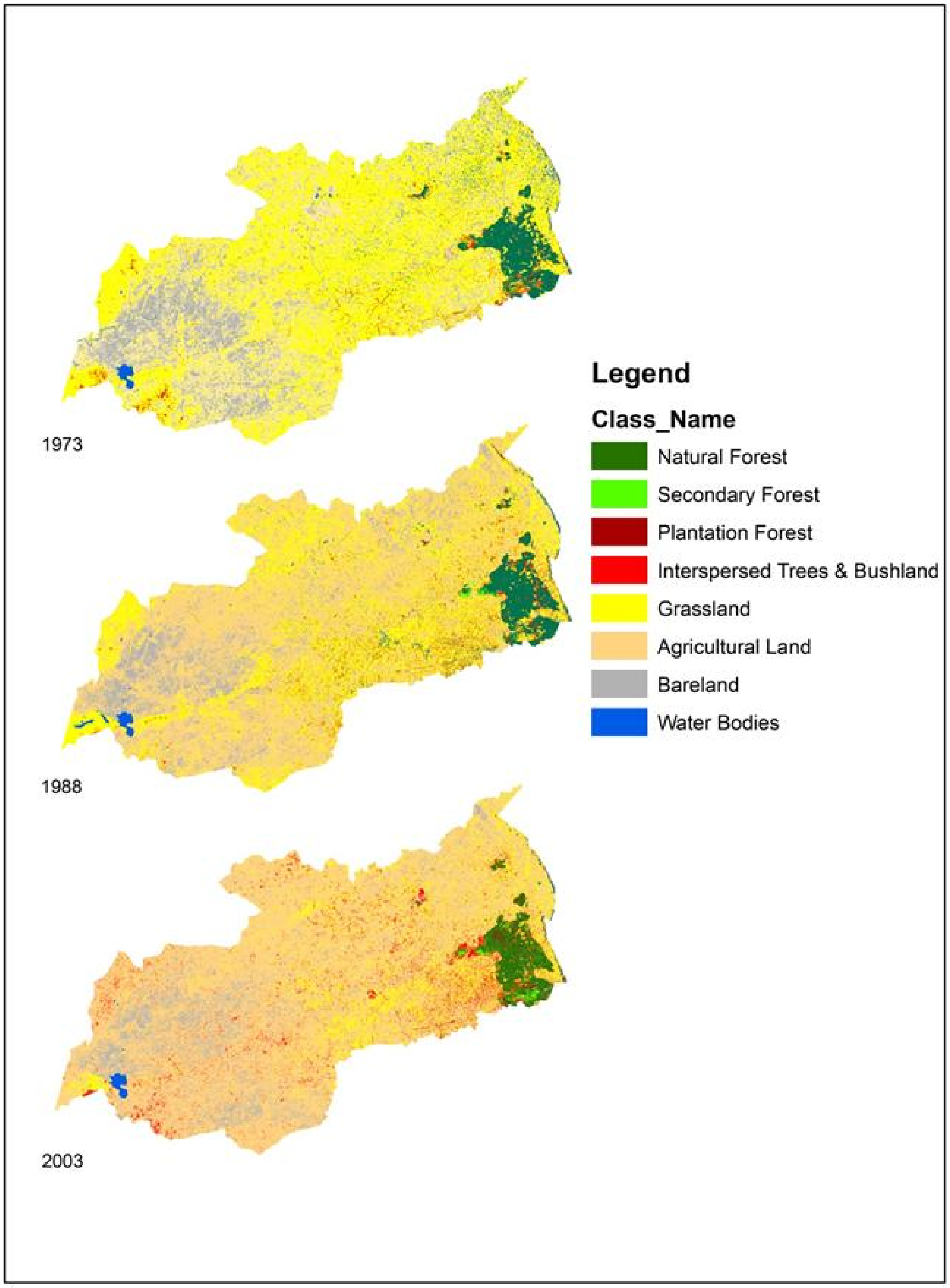


Figure 5.4 Classified images of Landsat 1973, 1988 and 2003

Results show that the natural forest cover decreased from 3.9% in 1973 to 3.4% in 2003. In addition to the forest excisions around the larger Kakamega forest, the smaller forests in the study area such as Bunyala and Malava face even more severe deforestation and have nearly been cleared to pave way for agriculture.

Notable also is the decrease in area under wooded grassland from 51.3% in 1973 to 11.8% in 2003. Note however that this study did not differentiate the wetland vegetation around the Yala Swamp, which could have contributed to the proportion of this class. Conversely, the area under agricultural activities increased from 27.9% in 1973 to 50.5% in 1988 then to 70.4% in 2003. This increase in agricultural areas can partly be due to conversion of forest and wooded grasslands to farmlands (Figure 5.5). Field visits also indicated extensive conversion of wetlands e.g. the Yala Swamp and other inland wetlands to agriculture.

(a) (b)

Figure 5.5 Cultivation and grazing in Bunyala forest areas

Another notable change is the increase in the area under secondary forest from less than 1% in 1973 to about 1.2% in 1988. This can be attributed to the thinning of the population density of the natural forest through deforestation or the regeneration of areas previously deforested as well as the reforestation of the previously degraded areas and afforestation at farm level. Though covering a very small proportion, there was a fluctuation in area under planted forests in the study area, could be due to the cycles of tree establishment and harvesting.

5.5 Discussion

5.5.1 Classification based on NDVI

The land cover classification based on NDVI revealed that there were changes in the overall vegetation cover in the study area. Notable was the general decrease in areas with dense vegetation cover (NDVI > 0.56) and an increase in the areas with sparse vegetation cover (NDVI = 0 - 0.1), hereby referred to as bareland. Soil erosion is increased if the soil has no or very little vegetation cover (Thomes 1990). Plant cover protects the soil from direct impact of raindrops and also slows down surface runoff and allows excess surface water to infiltrate into the soil. The effectiveness of vegetation to reduce soil erosion depends on the type, extent and quantity of cover over a given surface. This assessment was done for periods between January and February which represent the dry season in the area. With the onset of the main rainy season April, there is a high risk of the areas classified as bare to experience severe soil erosion.

There were inconsistencies in classification observed across the classes and the years despite the images having been taken around the same dry season period (January – February). The areas with NDVI values between 0 and 0.1 were classified as bareland and this encompassed areas that were either entirely or nearly bare but also recently cultivated, roads and urban areas. Large areas with NDVI values 0.3-0.4 are considered as bushland/woodland. Most of these areas especially for the 1988 and 2003 periods are croplands or areas with dense grasslands. A similar misclassification was observed for NDVI value >0.56 which is considered dense vegetation such as forests. Dense cropland areas especially in areas under sugarcane production were classified together with forests. (Hesketh and Moss 1963) reported that photosynthesis by leaves of maize, sugarcane and related tropical grasses could reach much higher rates, with less marked light saturation, than leaves of other plants.

Comparing across the years reveals that the 1988 results exhibited significantly high proportions of pixels with NDVI values >0.56 synonymous with dense vegetation. A review of long-term weather data showed that the years 1987 to 1990 were relatively wet years due to the El-Niño phenomenon experienced since 1987/88. This could have resulted in increased above ground biomass during this period when the imagery was acquired. These results show how extreme climatic events can affect the overall classification results especially when one-time assessments are relied upon. This highlights the importance of ensuring similarity in phenological cycles, inter-annual climatic variability and human activities when conducting change detection (Bhandari et al. 2012). Time series analysis and use of data with high temporal resolution is therefore important to capture seasonal variability that may influence LULC classifications (Gonzalez-Sanpedro et al. 2008).

5.5.2 Classification based on Landsat image band combination

The second procedure of classification was based supervised and unsupervised classification after Landsat band composition. This classification disaggregated the land cover into key land uses such as agriculture, grasslands and the different types of forests. Like many other regions in SSA, study area continues to experience changes in LULC. The results indicate a general decrease in areas under natural vegetation formations (forest, bushland and grassland) and an increase in areas under agricultural land. These results are in conformity with the results reported by Githui et al., (2009) in Nzoia Basin of Western Kenya who observed that the area under agricultural land increased from 39.6% in 1973 to 46.6% in 1986/1988 and to 64.3% in 2000/2001. Similar patterns of LULC change were also reported by Nambiro (2007). This increase in area under cultivation is in response to the increased demand for land to produce more food for the increasing human population. For example, the population of Western Kenya province increased from 1.3 million in 1969 to 4.3 million in 2009 (Republic of Kenya 2005b; Kahl 2006; Republic of Kenya 2010). Further, the smallholder agriculture that is predominant in the region is much less productive in terms of yield per unit of land. This has forced communities to seek extra land (extensification) as opposed to increasing production on existing areas (intensification).

Despite the seemingly modest change in area under forest cover, the decrease contributes to an alarming rate of deforestation in the region. Mitchell (2004) concluded that the forest formations covering Kakamega, North Nandi and South Nandi Forests totaled 74,718 ha in 1913 but had decreased by 34.4% to 25,727 by 2001. Specially, the area of Kakamega forest decreased from 18,388 ha in 1965/67 to 13,335 ha in 2001. The changes in forest cover have mainly been attributed to forest excision to pave way for agricultural land expansion, charcoal burning, pit sawing, grazing and collection of fuel wood (Mitchell 2004). Whereas some of the forest excisions have been legal, the forests in the region continue to suffer from illegal harvesting by timber traders and illegal felling by local communities. Implications of deforestation are numerous ranging from scarcity of basic products mainly fuel wood, timber, medicine and fruits; destruction of carbon sinks; accelerated runoff and soil erosion; disruption of water cycle- mainly ground water recharge and discharge and habitat destruction.

5.6 Conclusion

Land use land cover change assessments form a good starting point for assessing land degradation patterns in any ecosystem. The results show that there have been significant changes on the LULC in the study area over the period of assessment. LULC changes are part of humanities strive to meet basic needs of food, feed and energy hence are essential for human survival. However, there is potential for soil, vegetation and water degradation to occur where such LULC changes have taken place followed by unsustainable land management practices. On the other hand LULC changes do not necessarily translate in land degradation, as the resultant new use could be more economically useful and environmentally sustainable. Land users may experience some impacts (positive or negative) of LULC change in the short term, but other impacts take long to manifest and have far reaching implications on the entire ecosystem health. The key message from these assessments is therefore to understand the state of the resources under consideration, the pressures being experienced and the implication of the two (state and pressure) on the sustainability of the systems under consideration.

Equipped with such information, decisions can be made to where to intervene to stop further land degradation.

Apart from the changes in the LULC classes, the approaches used in this study were not able to capture the actual indicators of land degradation at the areas where changes were taking place. Often, such indicators are masked due to the complexity of topography, vegetation and spatial extent of the imagery. This therefore requires further detailed assessments at selected areas to ascertain the types and extent of degradation present. This formed the basis for the next chapter on indicators of land degradation.

6 EVALUATING INDICATORS OF LAND DEGRADATION IN SMALLHOLDER FARMING SYSTEMS OF WESTERN KENYA

6.1 Introduction

Direct measures of site integrity and status of ecological processes are difficult or expensive to measure due to the complexity of the processes and their interrelationships (Pellant et al. 2005). Spatial variability in landscapes arises from a combination of intrinsic and extrinsic factors (Rao and Wagenet 1985). In the case of soils, intrinsic spatial variability refers to natural variations in soil characteristics, often as a result of soil formation processes such as weathering, erosion, or deposition processes, and variability in organic matter content due to the architecture of native plant communities (Zacharias 1998). Extrinsic spatial variability refers to the variations caused by lack of uniformity in management practices such as chemical application, tillage, and irrigation (Zacharias 1998; Vieira et al. 2002). These two causes of ecosystems variability ultimately impact on overall aboveground productivity, which is an indicator of ecosystem health. Further, understanding the variability can help in the design of integrated approaches to land management that take into consideration the farmers resource endowment (Adhikari et al. 2011; Bai and Wang 2011).

Scientific awareness and interest in the spatial variation of field soils dates back to the early 1900’s (Pendleton 1919; Smith 1938), but it is only in the 1960’s and 1970’s that field scientists began to study soil variability in a systematic way (Beckett and Webster 1971; Webster 1994). To determine whether the land is degraded or not, direct assessment can be done by defining and using attributes and indicators that may take a qualitative or quantitative form. The criteria or attributes for assessment may consider factors such as soil stability, vegetation, nutrient cycling and many others aspects (NRC 1994). Indicators are components of a system whose characteristics (e.g., presence or absence, quantity, distribution) are used as an index of an attribute (e.g., hydrologic function, soil stability) that is too difficult, inconvenient, or expensive to measure (Pellant et al. 2005). The use of qualitative and quantitative measurements involves classifying or rating the attribute indicators along ordinal or categorical scales to capture the significance of degradation. Attribute ratings reflect the degree of departure from expected levels for each indicator. Complementing the qualitative and quantitative measures can help to achieve a better certainty of the results of assessment. Using such indicators, it is possible to determine the types and magnitude of land degradation taking place on a given land and the impact of the same on the overall integrity of the ecosystem.

Over the years, various authors have used attributes and indicators to assess land degradation. For example, Pyke et al. (2002) identified 17 indicator attributes, among them types of erosion, plant community composition, litter amount, annual production, invasive plants, to assess rangeland degradation patterns in the USA. Other studies such as the Landscape Function Analysis (LFA) based the assessments on processes involved in surface hydrology, i.e., rainfall, infiltration, runoff, erosion, plant growth and nutrient cycling (Tongway and Hindley 2004; Tongway 2010). Manske (2001) used four condition categories: excellent, good, fair and poor to define the levels of ecosystem health in a grassland ecosystem. These categories helped to define the range of degradation from an extremely healthy to an extremely unhealthy condition. The use of such qualitative categories simplifies the methodologies and makes it easy for any assessor or resource manager to understand and thus to adopt the assessment methods quickly.

A review of literature shows that soil quality indicators can be identified using a wide range of statistical techniques, which include rating factors based on soil-related constraints to crop production (Lal 1994a), standardized scoring functions based on threshold functions (Karlen and Stott 1994), linear or multiple regression analysis (Doran and Parkin 1994; Li and Lindstrom 2001), and principal component analysis (PCA) (Oluwole 1985; Kosaki and Juo 1989; Adhikari et al. 2011; Titilope et al. 2011). Soil variability can be assessed as the relative magnitude of the sources of variability on a soil property as well as the combined effect of variability of some of these properties (van Es et al. 1999). Coefficient of variation (CV) is the most commonly used measure of soil variability (Oluwole 1985; Wilding 1985). Using this measure, soil properties can be expressed by dividing the coefficient of variation into different ranges, e.g., least (<15%), moderate (15%-35%), and most (>35%) (Wilding, 1985). The use of PCA has increased over time due to its ability to reduce the dimensions of data without significant loss of information (Garten et al. 2007). Using this technique, it is possible to group the often numerous soil physical and chemical parameters into functional groups, thus easing interpretation and targeting of land management interventions.

Repeatability when using or interpreting the indicators for land degradation can be a challenge if there is no standardized protocol to guide assessors. The selection of which indicator to use must take into consideration the objective of assessment, time, expertise and resources available. Several protocols for land degradation assessment have been developed to educate assessors on using observable indicators in order to interpret and assess ecosystem health. Examples of such protocols or frameworks include the Landscape Function Analysis (LFA) (Tongway and Hindley 2004; Tongway 2010), the Visual Soil-Field Assessment Tool (VS-Fast) designed to support and enhance the LADA program of the FAO (McGarry 2004), and the Land Degradation Sampling Framework (LDSF) (Vågen et al. 2010) designed to support the African Soil Information Service (AfSIS) project. The above frameworks are based on standard scientific principles. Attempts have been made to make these frameworks farmer-usable and based on visual assessment of soil condition and health, with particular emphasis on simple, repeatable methods using every-day, low-cost apparatus (Kapalanga 2008). Where applied, some of these methods have proven to be simple yet robust, ensuring immediate data availability, farmer acceptance and rapid update of the descriptive and measurement tools, leading to rapid assessment of the current condition with a potential for longer-term monitoring (McGarry 2004).

The objective of this study was to evaluate indicators of land degradation in the smallholder cropping systems of western Kenya as a basis for understanding the patterns of land degradation.

6.2 Methodology

6.2.1 Study area and sampling framework

The study was conducted in in the Kakamega and Siaya districts, of western Kenya. A detailed description of the study is presented in Chapter 3. The Land Degradation Sampling Framework (LDSF) was adopted to characterize land degradation patterns (Vågen et al. 2010). The LDSF is a spatially stratified, random sampling design built around a hierarchical field survey and sampling protocol using “Blocks” and “Clusters”. Three sampling blocks measuring 100 km^2 (10 km × 10 km) were demarcated in the lower (Sidindi, Siaya), middle (Bunyala, Kakamega) and upper (Malava, Kakamega) catchment of the study area (Figure 6.1). The allocation of these blocks was guided by the previous assessment on vegetation changes (Chapter 4) as well as the researcher’s knowledge of the land degradation problem in the study area. This was also done so as to capture the diversity in agro-ecology, geomorphology and land uses across the study area. Each block was further subdivided into 16 tiles (2.5 km × 2.5 km) in which a cluster of 10 plots was randomly allocated in each tile for detailed sampling and coordinates assigned (Figure 6.2).

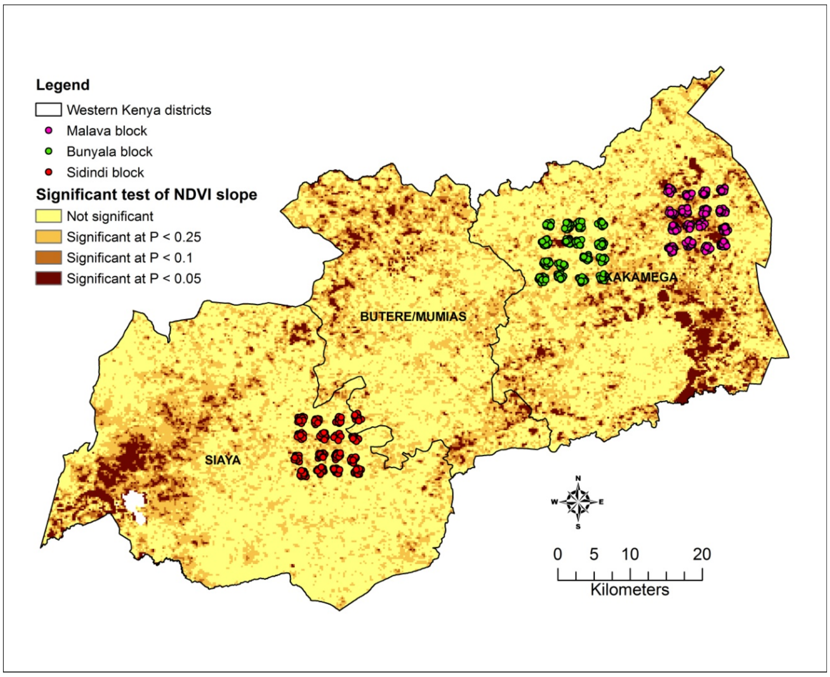


Figure 6.1 Position of the sampling blocks across the study area

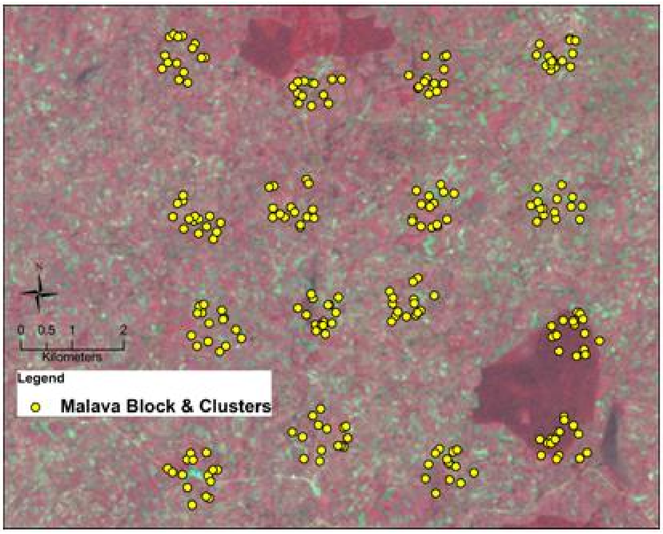


Figure 6.2 The 10 km × 10 km sampling block with the sampling clusters in the Malava block

Due to financial and logistical challenges, rationalization was done on the extent of sampling and field measurements. The Sidindi block was used for exploratory purposes and for training in the application of the LDSF approach. Only 10 out of the 16 clusters were sampled. All the 16 clusters in Malava block were sampled and detailed field measurements undertaken. Soil sampling was not conducted in the Bunyala block. However, site visits were conducted and general field observations made on the land uses and degradation types present. Across the two blocks sampled, 640 samples (2 blocks × 160 samples × 2 depths) were collected.

6.2.2 Plot and sub-plot level measurements

Plot-level measurements

Navigation to the randomly allocated points was done using a Global Positioning System, field maps, Google Earth maps and with guidance from the local field assistants. At the plot level, basic site characteristics were described and recorded in standardized data entry sheets. All plots were given an identification number (ID) and the center point was georeferenced using a GPS. Other data recorded at plot level included slope and presence or absence of soil and water conservation structures. The position of the plot along the topographic sequence was also described as either being upland, ridge/crest, midslope or footslope.

Land cover of the plot was recorded using a simplified version of the FAO Land Cover Classification System (LCCS) (http://www.africover.org). Using the binary phase of the classification, the plots were assigned to any of the following broad land cover classes:

(i) Cultivated or managed terrestrial areas
(ii) Natural or semi-natural vegetation
(iii) Cultivated aquatic or regularly flooded areas
(iv) Natural or semi-natural aquatic or regularly flooded vegetation, and
(v) Bare areas

Vegetation in and around each plot was broadly classified as indicated in Table 6.1.

Table 6.1 Vegetation type classes in the study area

Vegetation type class	Description
1. Forest	A continuous stand of trees, their crowns interlocking
2. Woodland	An open stand of trees with a canopy cover of 40% or more. The field layer is usually dominated by grasses
3. Bush land	A mix of trees and shrubs with a canopy cover of 40% or more
4. Wooded grassland	Land covered with grasses and other herbs, with woody vegetation covering between 10% and 40% of the ground
5. Cropland	Cultivated land with annual or perennial crops
6. Freshwater aquatic	Herbaceous freshwater swamp and aquatic vegetation/wetland

Adapted from (White 1983)

Sub-plot level measurements

Each plot consisted of four sub-plots, which were sampled and characterized for land degradation indicators as per the layout in Figure 6.3.

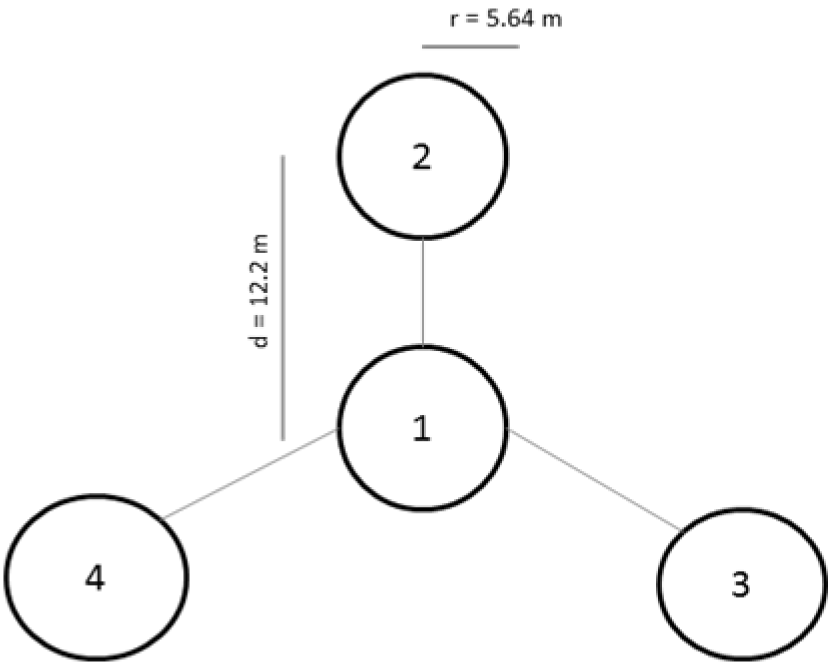


Figure 6.3 Plot and sub-plot sampling layout

6.2.3 Land degradation indicator and attribute mapping

Table 6.2 shows the main attributes and the indicators used to assess land degradation in the study area. Selection of the indicators was made in line with the three main attributes, namely soil and site stability, hydrologic function and biotic integrity (Pellant et al. 2005). Soil and site stabiity is defined as the the capacity of the site to limit redistribution and loss of soil resources (including nutrients and organic matter) by wind or water. Hydrologic function is the capacity of the site to capture, store and safely release water from rainfall. Integrity of the biotic community refers to the capacity of the site to support characteristic functional and structural communities in the context of normal variability, capacity to resist loss of this function and structure due to disturbance, and capacity to recover after disturbance. The occurrence and/or severity of the indicators were qualitatively and quantitatively measured and scored using ordinal or categorical scales.

Table 6.2 Attribute indicators for land degradation assessment

Indicator	Attribute		
	Soil and site stability*	Hydrologic function†	Biotic integrity#
Proportion of bare ground	✓	✓	
Presence of pedestals; rocks or plants where soil has been eroded from the base	✓	✓	
Presence of rills and gullies	✓	✓	
Soil surface loss (sheet erosion)	✓	✓	✓
Invasive plants			✓
Functional/structural groups of vegetation (herbaceous and wood cover)			✓
Indicator weeds, e.g., Striga			✓
Crop and pasture health and performance			✓

Adapted from: .Pellant et al., (2005)

In each of the four sub-plots, signs of visible erosion were recorded and classified as rill, gully or sheet. Percent rock/stone/gravel cover on the soil surface was also recorded. Woody and herbaceous cover rating was done following the Braun-Blanquet approach (Braun-Blanquet 1928; Westhoff and van der Maarel 1973) where vegetation rating was scaled from 0 (bareland) to 5 (>65% cover). The impacts of human activity on the surroundings were also scored. The impact factors considered were tree-cutting, fire, agriculture, grazing, urban and industrial activities, alien/invasive species and fuel wood collection.

6.2.4 Soil sampling and analysis

Soil samples were collected from each of the sub-plots at 0-20 cm and 20-30 cm depth using a 5-cm diameter and 40-cm long *Eijkelkamp* (model 04.17) undisturbed Split-Tube-soil sampler. Upon sectioning, the soil samples from the two depths were pooled into separate buckets, thoroughly mixed, and a representative sub-sample scooped for each depth, packed and labeled and submitted to the laboratory for further processing and analysis.

The soil samples were analyzed using a combination of two approaches: Near Infra Red Spectroscopy (NIRS) and the conventional wet chemistry approach. NIRS is an innovative technique used at the ICRAF laboratory as a rapid and cheap method of analyzing large numbers of samples (Shepherd et al. 2003). Confirmatory assessments have shown good correlations between results of wet chemistry and NIRS thereby justifying the use of this methodology in this research.

Soil spectral reflectance analysis

All the soil samples in this study were analyzed by diffuse reflectance spectroscopy using a FieldSpec FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, Colorado) at wavelengths from 0.35 to 2.5 µm with a spectral sampling interval of 1 nm using the optical setup described in set up as described in Shepherd et al., (2002) and Shepherd et al. (2003). The spectral diversity was inspected and indicated distinct differences between the Siaya and Malava blocks. Therefore, the two sites were treated independently in subsequent analyses. The soil spectral data were analyzed by conducting a principal component analysis of the first derivative spectra and computing the euclidean distance based on the scores of the significant principal components. Random samples were then selected from each quartile of the ranked euclidean distances to constitute the 20% that would undergo conventional wet chemistry analysis (Shepherd and Walsh 2002; Shepherd and Walsh 2007).

Conventional wet chemistry analysis

The selected reference soil samples were then analyzed for selected properties following conventional wet chemistry methods for tropical soils (Anderson and Ingram 1993; ICRAF 1995; Okalebo et al. 2002). These analyses were conducted at the Crop Nutrition (Cropnut) Laboratory in Nairobi. Soil pH was determined in 1:2.5 (w/v) suspensions, exchangeable acidity by NaOH titration using a 1:10 soil/solution ratio. Samples with pH >5.5 were assumed to have zero exchangeable acidity and samples with pH <7.5, zero exchangeable Na. Exchangeable Ca and Mg was determined by 1 M KCl extraction, and exchangeable K and available P by 0.5 M $NaHCO_3$ and 0.01 M EDTA (pH = 8.5) using 1:10 soil/solution ratio extraction method. Soil texture was determined using a Bouyoucos hydrometer after pre-treatment with H_2O_2 to remove organic matter (Gee and Bauder Page 1986). Total carbon and nitrogen were analyzed at ICRAF laboratory by dry combustion using a C/N analyzer.

Spectral prediction of soil properties

Measured values of the soil samples selected for conventional laboratory analysis were calibrated to the first derivative of the reflectance spectra using partial least squares regression (PLSR) implemented using the Unscrambler software (CAMO Inc., Corvallis, OR, USA). The regression models were then used to predict soil values for the rest of the samples under investigation.

Spatial interpolation of soil properties

To present the variation graphically, the soil properties were interpolated to create a surface layer over the entire block using the ordinary kriging technique (Webster and Burgess 1980; Webster and McBratney 1987; Sigua and Hudnall 2008). The underlying assumption when selecting this approach is that nutrient concentrations are continuously variable and tend to change gradually rather than abruptly. As a result, the nutrients may be envisaged as continuously varying statistically across the surfaces, hence can be displayed using isarithmic maps (Webster and McBratney 1987). This assumption may not always be the case, since some studies have shown that soil properties can vary in a substantially random fashion (Webster and Burgess 1980). Despite this observation, kriging was adopted as the most simple and practical approach for interpolation of the soil properties. For each soil property, 160 sampling point measurements were used.

6.2.5 Data analysis

Descriptive statistics (mean, standard deviation (SD) and minimum-maximum values and coefficient of variation (CV), skewness) were calculated for the measured soil properties for the different depths. Pearson correlation and regression analyses were performed to understand the relationships among the soil properties. PCA was computed to identify the important factors that explain the variability in soil properties observed across the Malava block. Prior to performing PCA, the suitability of data for factor analysis was assessed by computing the correlation matrix. A correlation matrix was used because it standardizes data with zero mean and unit variance thus making it possible to compare soil properties that have different dimensions (are measured and presented in different units). Other test statistics computed during the PCA included the Kaiser-Meyer-Oklin (Kaiser 1970, 1974) and the Barlett's Test of Sphericity (Bartlett 1954), which support the factorability of the correlation matrix. The eigenvalues - the amount of variance explained by each factor- were then computed. The principle components with eigenvalues greater than 1 were retained while those with eigenvalues less than 1 were not considered further because these explained less variance than that for a measured attribute (Shukla et al. 2006). This was further proved by the inspection of the scree plot at each soil depth (Catell 1965; Catell 1966) and further supported by the results of the Monte Carlo PCA for parallel analysis (Watkins 2000). The retained PCs were subjected to varimax rotation to maximize the correlations between PC and the measured attributes by distributing the variance of each factor. Statistical procedures were conducted using SPSS.

6.3 Results

6.3.1 Attributes and indicators of land degradation

Figure 6.4 (a-h) illustrates some of the main attributes and the indicators used to assess land degradation in the study area. The most prevalent indicators included proportion of bare ground, dominant vegetation structure, presence of pedestals, presence of rills and gullies, soil surface loss, and indicator plant species.

a) Presence of rock fragments

b) Surface crusting

c) Proportion of bare ground

d) Exposed roots

e) Presence of rills and gullies

f & g) Indicator weeds, e.g., Striga and unpalatable pasture species

Figure 6.4 Some indicators of land degradation across the study area

Assessment of the general vegetation structure showed that over 70% of the land was under cropland (Table 6.3). Forests accounted for 8% of the points sampled and represented the Malava and Chesero forest fragments.

Table 6.3 Vegetation structure in Malava block

Vegetation structure	Frequency	Percent (%)
Cropland	119	73.9
Wooded grassland	25	15.5
Woodland	4	2.5
Forest	13	8.1
Total	161	100.0

Vegetation cover assessment in the Malava block showed that the area has sparse wood cover but high herbaceous cover (Table 6.4). The high herbaceous cover rating is due to the patches of sugarcane production fields that dominate the farming systems.

Table 6.4 Wood and herbaceous cover rating in Malava Block

Cover rating	Wood cover (%)	Herbaceous cover (%)
Absent	34.4	1.3
<4%	33.1	9.2
4-15%	17.2	13.7
15-40%	5.3	29.4
40-65%	7.3	30.1
>65%	2.6	16.3
Total	100.0	100.0

Over 55% of the farms sampled completely lacked soil and water conservation (SWC) technologies (Figure 6.5). Where present, famers used either structural or vegetative SWC techniques or a combination of the two. The most common structures present were cut-off drains and drainage trenches, terraces planted with fodder species such as Napier grass, and use of stone bounds and trash lines (Figure 6.6).

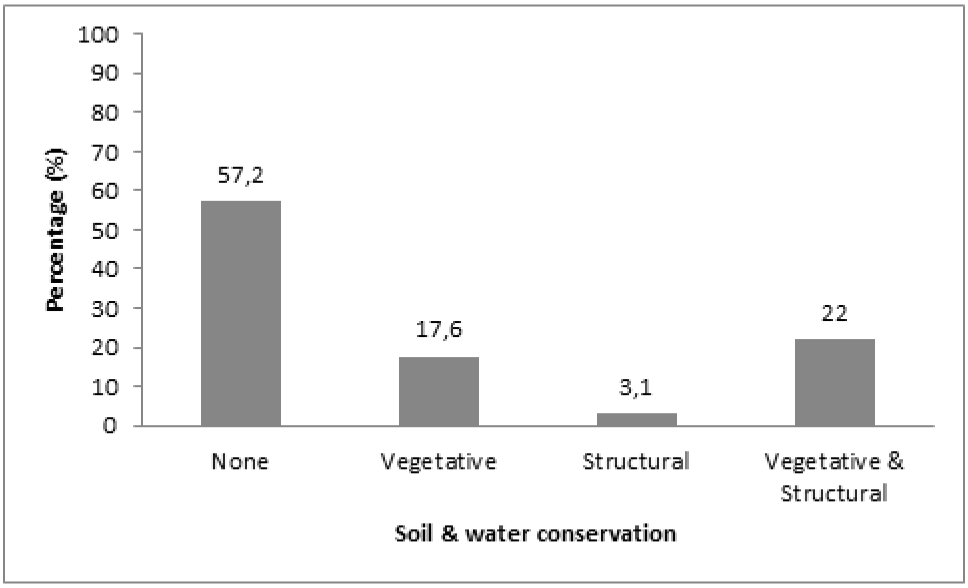


Figure 6.5 Soil and water conservation practices on farms in Malava block

Figure 6.6 Stone bounds and trash lines for soil erosion control in Malava block

Sheet erosion was the most dominant form of soil loss in the Malava block, and was observed in over 70% of the farms sampled (Figure 6.7). Sheet erosion has a significant impact on the general soil fertility since it involves removal and loss of the top soil layer that holds most of the nutrients needed by the crops.

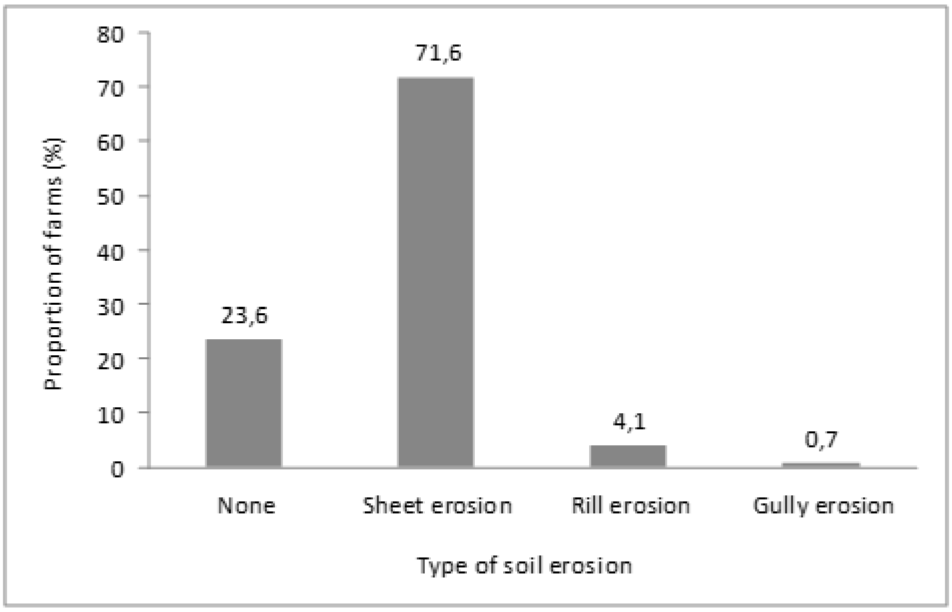


Figure 6.7 Types of soil erosion in the study area

Agriculture (crop cultivation) was identified as the main activity with highest impact on the habitat (Table 6.5). As indicated earlier, the wood cover rating in the study area was low, and this translated to the low impact of tree cutting and fuel wood collection at farm level. The low grazing impact can also be explained by the increased land fragmentation and conversion to crop production thereby leaving little area for livestock rearing.

Table 6.5 Impact of human activities on habitat

Impact scale	Tree cutting	Agriculture	Grazing	Fire	Urban activities	Erosion	Fuel wood collection
None	35.2	15.7	53.8	98.1	90.6	19.4	39.0
Low	52.8	12.6	22.8	0.6	3.8	53.8	50.9
Medium	6.9	26.4	18.4	1.3	5.0	18.8	6.9
High	5.0	45.3	5.1	-	0.6	8.1	3.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The most prevalent types of land degradation in the study area are presented in Figure 6.8. The lower Siaya area was dominated by overgrazing and extensive soil erosion, mainly sheet, rill and gully erosion. Deforestation was observed in the Malava and

Bunyala blocks. A general decline in soil fertility was observed in all the blocks, and this was confirmed by the soil analysis results.

a) Soil erosion (sheet, rill and gully)

b) Deforestation

c) Soil fertility decline

d) Overgrazing

Figure 6.8 Land degradation types in the study area

6.3.2 Calibration and prediction of soil chemical properties

Table 6.6 shows the correlation coefficient and the root mean standard errors of calibration (RMSEC) between the wet chemistry and the NIRS results for Malava block. The large correlation between the two results (R^2 > 0.5) for C, N, Ca, Mg, CEC, silt, sand, suggests quite a strong relationship between the results of the wet chemistry and the NIRS analysis procedures. Soil pH showed medium correlation (R^2 = 0.3 - 4.9) while small correlation (R^2 < 0.3) was observed for K and available P. These results especially for the large correlation are to a large extent similar to those reported by (Shepherd and Walsh 2002; Vågen et al. 2006; Terhoeven-Urselmans et al. 2010). Small to medium correlations observed could be improved by increasing the number of samples used in the calibration, using a wider spectral library in the prediction as well as by using mixed effect models during the prediction. Despite these observations, the data were deemed reasonable enough to facilitate further use in this study.

Table 6.6 Calibration results for selected soil properties for Malava Block

Property	RMSEC	R-squared
Total carbon (%)	0.26	0.85
Total nitrogen (%)	0.27	0.81
pH (H_2O)	0.09	0.33
Av. P (mg/kg)	0.67	0.15
K (mg/kg)	0.52	0.28
Ca (mg/kg)	0.41	0.67
Mg (mg/kg)	0.29	0.76
C.E.C. (C mol /100g)	0.25	0.75
Silt (%)	0.39	0.62
Sand (%)	0.09	0.73
Clay (%)	0.13	0.7

Variation in soil properties in Malava Block

There was distinct variation in the soil properties between the topsoil (0-20 cm) and the subsoil (20-30 cm) (Table 6.7 and 6.8). Notable are the high carbon, nitrogen and CEC in the top soil compared to the sub soil. However, the soil variability as expressed by the CV was generally higher in the top soil compared to the sub soil. Using CV as criteria for expressing variability, Ca, TON, Mg, TOC and silt were the most variable soil properties for the 0-20 cm depth. Moderate variability (CV 0.15-0.35) was observed for CEC, P, K and clay, while Na, sand and pH showed the least variability (CV< 0.15). For the subsoil, Ca, Mg and silt were the most variable; TON, TOC, P, CEC, K, Clay were moderately variable, while Na and sand were the least variable (Table 6.7).

For the topsoil, the skewness was positive (ranged from 0.20 to 2.47) for all soil properties except clay, which had a negative skewness of -0.30 (Table 6.7). A similar pattern was observed for the subsoil where only sand showed a negative skewness (Table 6.8). Both negative and positive kurtosis was observed for selected soil properties at the different soil sampling depths.

Table 6.7 Variation in soil properties for Malava block (0-20 cm depth)

Soil property	Min	Max	Mean	Std. dev	Skewness	Kurtosis	CV
TOC	1.00	5.96	2.10	0.82	2.19	6.08	0.39
TON	0.07	0.51	0.16	0.07	2.47	7.59	0.43
pH	4.80	5.85	5.18	0.20	0.77	0.97	0.04
CEC	5.14	26.59	10.46	3.60	2.32	6.81	0.34
P	3.31	13.73	6.82	1.82	0.95	1.85	0.27
K	67.75	232.45	116.95	27.17	1.71	4.39	0.23
Ca	256.74	3550.42	859.80	471.79	2.47	8.94	0.55
Mg	49.26	403.22	129.26	54.81	2.10	6.35	0.42
Na	31.62	51.96	40.28	3.79	0.20	0.24	0.09
Sand	47.25	73.52	61.25	5.38	-0.30	-0.34	0.09
Clay	17.84	44.59	29.71	5.42	0.38	-0.70	0.18
Silt	2.48	25.94	7.66	3.12	1.64	6.48	0.41

TOC- total organic carbon (%); TON- total organic nitrogen (%); CEC- cation exchange capacity (C mol /100g); P- phosphorus (mg/kg); Ca- calcium (mg/kg); Mg- magnesium (mg/kg); Na- sodium (mg/kg); sand, clay and silt (%)

Table 6.8 Variation in soil properties for Malava block (20-30 cm depth)

Soil property	Min	Max	Mean	Std. dev	Skewness	Kurtosis	CV
TOC	0.85	3.71	1.74	0.56	1.04	1.11	0.32
TON	0.06	0.31	0.13	0.04	1.16	1.67	0.34
pH	4.77	5.67	5.15	0.18	0.35	-0.29	0.04
CEC	5.24	19.70	8.75	2.42	1.42	3.05	0.28
P	3.06	12.00	5.98	1.74	1.05	1.33	0.29
K	62.27	191.32	101.43	20.98	1.00	1.70	0.21
Ca	201.35	2505.52	635.90	308.11	2.07	8.23	0.48
Mg	43.44	305.25	101.72	37.72	1.60	4.93	0.37
Na	32.55	61.50	43.65	4.74	0.16	0.41	0.11
Sand	47.80	80.27	63.45	5.94	-0.08	-0.32	0.09
Clay	15.69	46.95	30.31	6.07	0.50	-0.20	0.20
Silt	1.66	18.62	5.89	2.44	1.35	3.95	0.41

TOC- total organic carbon (%); TON- total organic nitrogen (%); CEC- cation exchange capacity (C mol /100g); P- phosphorus (mg/kg); Ca- calcium (mg/kg); Mg- magnesium (mg/kg); Na- sodium (mg/kg); sand, clay and silt (%)

Correlation of soil properties

Tables 6.9 and 6.10 show the Pearson product moment correlation coefficients of soil properties for the top- and subsoil for the Malava block. Significant correlations ($p<0.05$) were observed among six of the soil attribute pairs at the 0-20 cm depth. Weak but significant positive correlation was observed between clay and CEC ($r = 0.182$, $n = 160$, $p<0.05$). Negative significant correlations were observed between Ca and P ($r = -0.197$, $n = 160$, $p<0.05$), Mg and P ($r = -0.192$, $n= 160$, $p<0.05$), and sand and P ($r = -0.162$, $n = 160$, $p<0.05$), clay and pH ($r = -0.192$, $n = 160$, $p<0.05$) and sand and pH ($r = -0.176$, $n = 160$, $p<0.05$). For the subsoil, significant positive correlation was observed between TOC and pH ($r= 0.196$, $n = 160$, $p<0.05$) and negative correlation between clay and Ca ($r= -0.172$, $n = 160$, $p<0.05$).

Table 6.9 Pearson product moment correlations between soil properties in Malava block for the 0-20 cm depth

Soil property	TOC	TON	pH	CEC	P	K	Ca	Mg	Na	Sand	Clay	Silt
TOC	1											
TON	.996(**)	1										
pH	.563(**)	.623(**)	1									
CEC	.918(**)	.944(**)	.802(**)	1								
P	-0.074	-0.135	-.656(**)	-.253(**)	1							
K	.967(**)	.969(**)	.631(**)	.954(**)	-0.024	1						
Ca	.817(**)	.852(**)	.810(**)	.961(**)	-.197(*)	.903(**)	1					
Mg	.846(**)	.878(**)	.817(**)	.975(**)	-.192(*)	.925(**)	.996(**)	1				
Na	-.366(**)	-.334(**)	0.02	-.344(**)	-.736(**)	-.507(**)	-.421(**)	-.433(**)	1			
Sand	-.846(**)	-.802(**)	-.176(*)	-.612(**)	-.162(*)	-.774(**)	-.458(**)	-.504(**)	.378(**)	1		
Clay	.532(**)	.474(**)	-.192(*)	.182(*)	0.132	.364(**)	-0.01	0.033	0.001	-.839(**)	1	
Silt	.674(**)	.701(**)	.702(**)	.838(**)	0.023	.823(**)	.940(**)	.933(**)	-.632(**)	-.357(**)	-0.153	1

** Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed); Depth = 0-20 cm*

Table 6.10 Pearson product moment correlations between soil properties in Malava block for the 20-30 cm depth

Soil property	TOC	TON	pH	CEC	P	K	Ca	Mg	Na	Sand	Clay	Silt
TOC	1											
TON	.994(**)	1										
pH	.196(*)	.292(**)	1									
CEC	.829(**)	.879(**)	.635(**)	1								
P	.356(**)	.287(**)	-.605(**)	0.054	1							
K	.959(**)	.972(**)	.329(**)	.915(**)	.364(**)	1						
Ca	.675(**)	.741(**)	.693(**)	.944(**)	0.055	.825(**)	1					
Mg	.722(**)	.783(**)	.686(**)	.962(**)	0.081	.859(**)	.995(**)	1				
Na	-.609(**)	-.590(**)	0.06	-.548(**)	-.799(**)	-.717(**)	-.570(**)	-.595(**)	1			
Sand	-.889(**)	-.847(**)	0.125	-.543(**)	-.409(**)	-.770(**)	-.321(**)	-.379(**)	.481(**)	1		
Clay	.571(**)	.500(**)	-.437(**)	0.062	.297(**)	.353(**)	-.172(*)	-0.118	-0.097	-.843(**)	1	
Silt	.608(**)	.663(**)	.591(**)	.855(**)	.238(**)	.786(**)	.959(**)	.956(**)	-.711(**)	-.259(**)	-.234(**)	1

** Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed); Depth = 20-30 cm*

Soil texture

The soils in the study area are generally well drained. Textural analysis indicated that sand was the most dominant soil component of the soils in the Malava block with a mean of 61% followed by clay (31%) and silt (8%). The soils in Malava can therefore be described as Sandy Clay Loams according to the USDA textural triangle.

Soil pH

Soil analysis in the top layer (0-20 cm) revealed that the Malava block was dominated by acidic soils with pH values ranging between 4.80 and 5.85; the values decreased to between 4.77 and 5.67 in the subsoil (20-30 cm). About 94% of the farms sampled in the Malava Division showed very strongly acidic pH values (pH <5.5), while 6% of the farms had moderately acidic (pH 5.6-6.0) soils. For the Malava block, forest areas had the highest pH values averaging 5.5, while values declined in grasslands and croplands. Extrapolating the point measurements showed a clear pattern of soil pH and hence soil acidity for the Malava block with areas northeast of Malava town having more acidic soils (Figure 6.9).

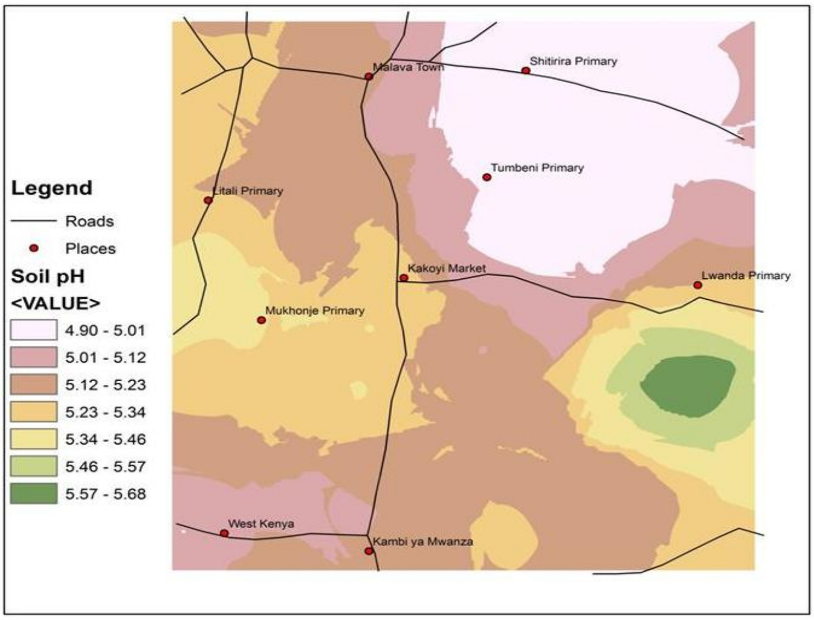


Figure 6.9 Soil pH pattern in the 10 × 10 km Malava block

Soil total organic carbon and nitrogen

High variation in soil organic carbon (SOC) was observed across the study area (Figure 6.10). The values ranged from 1% to 5.9% for the topsoil. A critical look at the carbon variation shows that 55% of the farms sampled in the Malava block had less than 2% SOC Soil organic carbon also varied with land use. In the Malava block, for example, forest or areas adjacent to forests (Malava and Chesero forests) showed the highest SOC averaging about 4% compared to 1.9% SOC for most cultivated areas. The pattern of SOC varied depending on other factors such as soil type, pH, and CEC among others. A pattern similar to that observed for SOC was also noted for total organic nitrogen (TON) (data not shown).

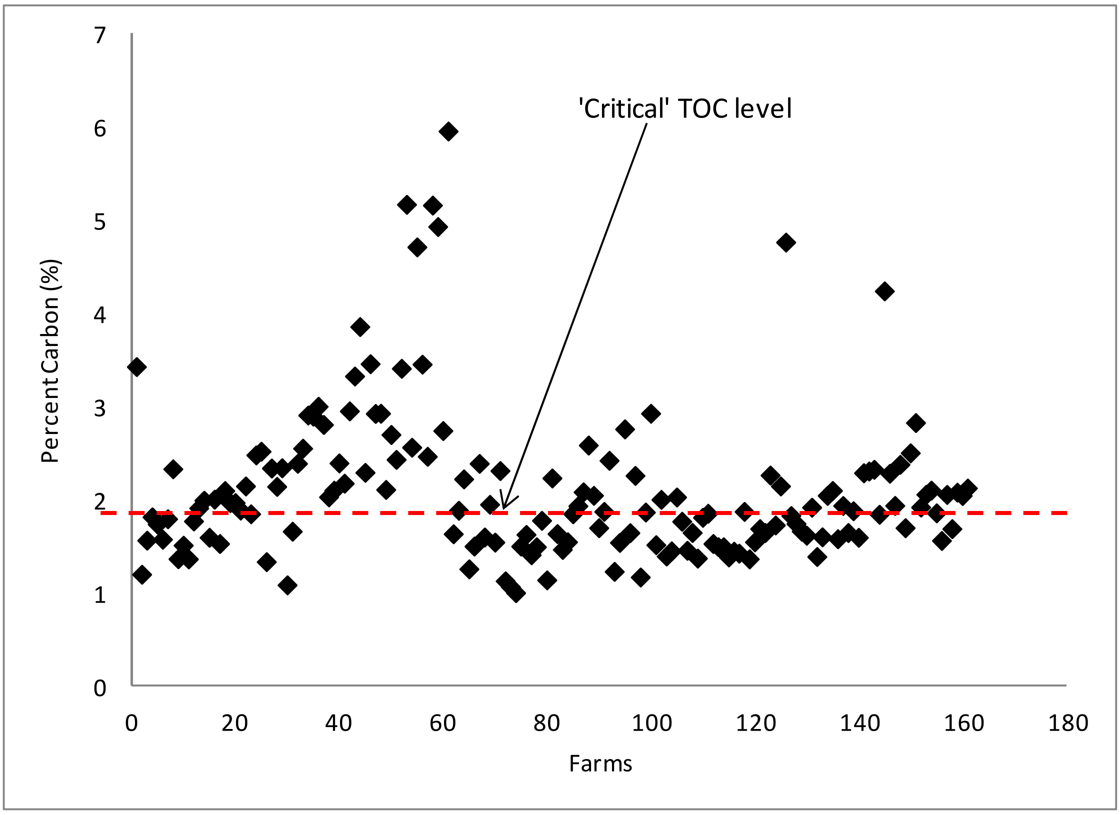


Figure 6.10 Soil organic carbon (SOC) variation across farms in Malava block (0 - 20 cm)

Cation exchange capacity

Cation exchange capacity (C.E.C) varied with land use and was in the order forest>grassland>cropland>woodland. There was a strong positive correlation between C.E.C and TOC (Figure 6.11). This can be due to the observation that C.E.C is highly determined by the level of soil organic matter.

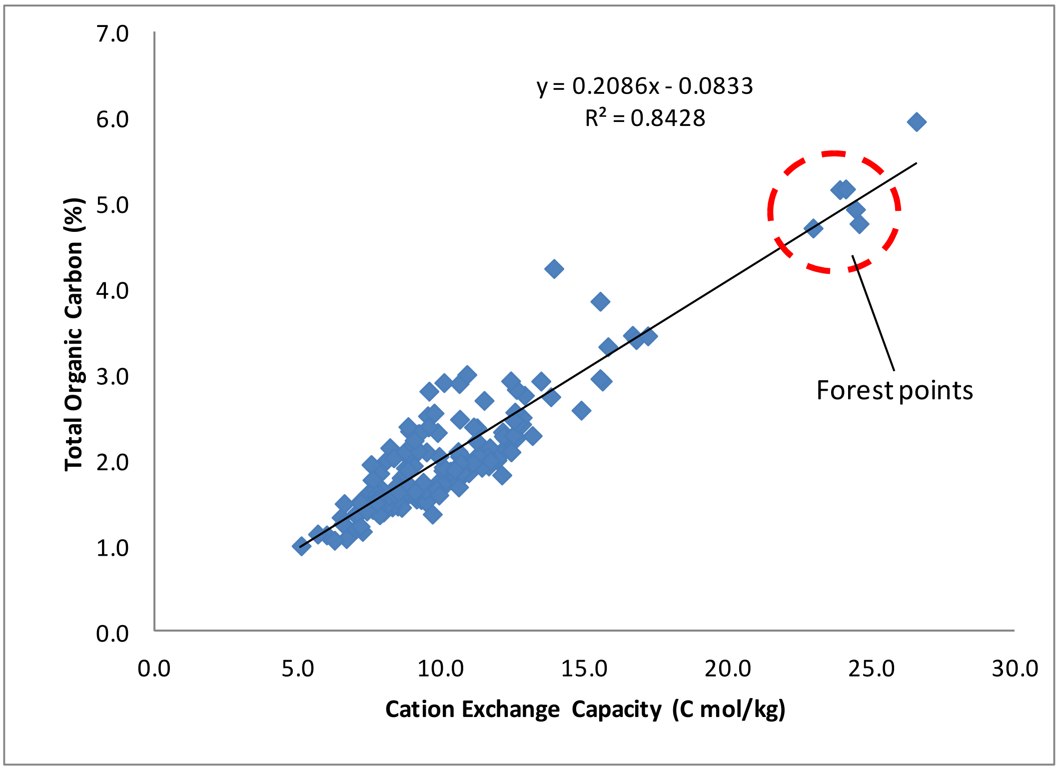


Figure 6.11 Correlation between cation exchange capacity and soil organic carbon across farms in Malava block

6.3.3 Principal components analysis (PCA) of soil properties

Results of the PCA for 0-20 cm depth

Principal components analysis (PCA) for the 0-20 cm soil depth revealed the presence of three components with eigenvalues exceeding 1, explaining 63.9%, 19.5% and 14.7% of the variance, respectively (Table 6.11).

Table 6.11 Eigenvalues and proportion of variance to the total variance for the principal components for soil properties in Malava block

Component	†Initial eigenvalues		
	Eigenvalue	% of variance	Cumulative %
1	7.664	63.866	63.866
2	2.343	19.521	83.387
3	1.760	14.664	98.051

†*Eigenvalue <1 are not presented*

Following the varimax rotation, the three-component solution explained 98% of the variance, with Component 1 contributing 57.1%, Component 2 contributing 23.9% and Component 3 contributing 17.1%. The rotated solution revealed the presence of complex structures, with the components showing a number of strong loadings but also some variables loading on more than one component (Table 6.12).

Table 6.12 Rotated factor loadings for the three principal components (PC) for Malava Block for 0-20 cm depth

Soil property	PC1	PC2	PC3
Mg	**.987**	.142	-.038
Ca	**.987**	.096	-.037
CEC	**.945**	.302	.054
Silt	**.942**	-.070	-.286
pH	**.867**	-.106	.440
K	**.866**	.469	-.153
TON	**.804**	.581	.005
SOC	**.763**	.634	-.044
Clay	-.110	**.986**	-.004
Sand	-.380	**-.889**	.188
P	-.252	.106	**-.952**
Na	-.406	-.040	**.896**
% of variance explained	57.05	23.92	17.09

For the top soil, the first component (PC1) was represented by high loadings on SOC, TON, pH, CEC, K, Ca, Mg, and silt. These variables have to do with the organic matter component and exchangeable base status and are very relevant in explaining the potential fertility levels of the soil. The second component (PC2) gave high loadings on sand and clay. The SOC, TON and CEC, which are important components of SOM, partly belonged to PC2. Sand and clay play a major role in influencing soil physical properties such as texture, bulk density, available pore space and the capacity to store and release plant nutrients. Soil physical properties influence the amount of SOM and hence CEC in any soils. The negative loading of sand in particular implies that soils with high sand content will generally tend to have low SOM and CEC. The third component (PC3) gave high negative loading for P and high positive loading for Na. Soil pH partly belonged to PC3. Since the soils in this region do not have major problems of sodium, this component can be taken to represent the phosphorus availability in the soil. The co-loading of pH, P and Na on this PC shows the influence of soil acidity on P availability.

Results of the PCA for 20-30 cm depth

At the 20-30 cm depth, the initial principal components analysis revealed the presence of three components with eigenvalues exceeding 1, explaining 61.3%, 24.6% and 12.2% of the variance, respectively (Table 6.13). Upon rotation, the three components explained 98.2% of the total variance with PC1 explaining 50.9%, PC3 explaining 28.9% and PC3 explaining 18.4% of the total variance.

Table 6.13 Eigenvalues and proportion of variance to the total variance for the principal components for soil properties at 20-30 cm depth for Malava Block

Component	†Initial eigenvalues		
	Eigenvalue	% of variance	Cumulative %
1	7.356	61.302	61.302
2	2.954	24.618	85.920
3	1.469	12.243	98.163

†Eigenvalue <1 are not presented

Upon rotation, PC1 accounted for 50.89% of the variance with high loadings on Ca, Mg, Silt, CEC, pH and K (Table 6.14). This component also had co-loading for SOC and TON. These variables best explain the fertility component of the soil. The PC2 had high negative loading for sand and positive loading for clay, SOC and TON. The soil properties in this component best explain the relationship between soil physical properties and SOM. Soils with low clay content will tend to have lower SOM contents. The third component (PC3), as in the top soil, had high positive loading for P and negative loading for Na. This component also had negative loading for pH. This component represents P availability.

Table 6.14 Rotated factor loadings for the three principal components (PC) for Malava block for the 20-30 cm depth

Soil property	PC1	PC2	PC3	CE
Ca	**.986**	.091	.068	0.985
Mg	**.984**	.148	.079	0.997
Silt	**.948**	-.021	.278	0.997
CEC	**.926**	.350	.009	0.980
pH	**.779**	-.197	-.560	0.960
K	**.767**	.574	.272	0.991
Clay	-.272	**.946**	.089	0.978
Sand	-.228	**-.936**	-.228	0.979
TOC	.602	**.764**	.212	0.990
TON	.675	.715	.154	0.991
P	-.030	.214	**.970**	0.988
Na	-.520	-.171	**-.815**	0.965
% of variance explained	50.89	28.85	18.42	

6.4 Discussion

The study identified key indicators to monitor the extent of land degradation of the farms sampled. Rating the indicators on a categorical scale facilitated assignment of a degradation score on the plot. The greatest variability for the topsoil was observed for Ca, TON, Mg, SOC and silt. This variability could be due to spatial differences in soil forming processes as well as in land management practices. Different soils have different behavior as far as their physical and chemical properties are concerned (Momtaza et al., 2009). Similarly, the variability could be due to the sampling design, since the sampling locations were randomly allocated and the unknown locations only accessed using the GPS. This type of sampling enabled the capturing of diverse locations in the landscape such as managed and natural ecosystems, major land forms (upland, crest, bottomlands) and different gradients (level, sloping, steep). Seyfried and Wilcox (1995) and Momtaza et al., (2009) observed that the distribution and variability of soil properties are scale dependent, i.e., the bigger the scale the higher the variability and vice versa. Despite this pattern, the variability provided a better view of the status of the soil across the study area. Such information on the soil variability can also be used to guide researchers the design of future sampling exercises where the soil properties with the highest CV will require the highest number of samples to estimate their mean value within a certain percentage at any significance level.

In this study, the use of documented 'critical' values of some soil properties enabled gauging the quality of the soil (Okalebo et al. 2002). Soil acidity was noted to be a major problem across the study sites. Studies indicate that acid soils cover over 500,000 ha of maize-growing areas in Kenya (Kanyanjua et al. 2002). In western Kenya alone, about 57,670 ha of the soils are acidic. Soil acidity can reduce yields through reduced P availability and increase Al and Mn toxicity (O'Hallorans et al. 1997; Hue and Licudine 1999). Crop tolerance to soil acidity varies. For example, maize, the staple crop grown by most farmers in the region, lies in the medium tolerance range and would do well in soils of pH 5.5-6.0. As indicated, most soils have a pH below this critical level. Strategies to manage soil acidity are needed, including the use of agricultural lime, growing acid tolerant crop varieties, change of crops grown and use of organic manure and rock phosphates that are rich in calcium.

The results indicate that the majority (55%) of the farms had very low SOC contents (< 2%). Researchers generally agree that despite variation in the behavior of different types of soils, 2% SOC (ca. 3.4% SOM) is a critical threshold below which serious decline in soil quality is likely to occur (Kemper and Koch 1966; Greenland et al. 1975; Pretty 1998; Loveland and Webb 2003). This implies that the soils in the study area are threatened by degradation if not well managed. SOM is important as a "revolving nutrient fund", and as an agent to improve soil structure, maintain tilth and minimize erosion (FAO 2005; Bationo et al. 2007a). It contributes to the CEC of a soil, which determines a soil's ability to retain positively charged plant nutrients such as NH^{4+}, K^{+}, Ca^{2+}, Mg^{2+}, and Na^{+}. Soils with low SOM have low nutrient availability and poor water holding capacity and also exhibit poor response to fertilizer application (Tittonell et al. 2005).

This first principal component of the soil chemical properties encompassed high loading for TOC, TON, pH, CEC, K, Ca, Mg, and silt. These variables have to do with organic matter content of the soil and exchangeable base status, and are thus very relevant in explaining the '*potential fertility*' levels of the soil. A study by Titilope et al. (2011) separated the measured soil variables into five components of which the first component containing Mg, K, Ca, ECEC, ECEC and CLAY and was referred to as the 'potential fertility' component while the third component with high loadings of C and N and was referred to as the 'organic matter' component. In another study, Kosaki and Juo (1989) identified PC1 as 'inherent fertility' when it was dominated by Mg, sand, silt, Ca, K and clay. In the present study, however, the variables explaining '*inherent soil fertility*' and '*organic matter*' were grouped together. This explains the intricate relationship between improving soil fertility and SOM in these smallholder cropping systems. Soil organic matter plays a key role in improving the exchangeable bases especially in highly weathered soils such as those found in the study area. Efforts to improve plant nutrition should aim at achieving balanced nutrition by providing all the key elements and at the same time improving the capacity of the soil to store the same by increasing the SOM content. This observation supports the current initiatives on integrated soil fertility management (ISFM) being promoted among the farmers in the region (Bationo et al. 2007b; Bationo and Waswa 2011).

This study identified PC2 as characterized by high loadings for sand and clay and described this PC as the 'soil physical properties' component. The fifth component in the study by Titilope et al. (2011) had high positive loadings for silt and sand, and was termed as the 'sand-silt' component. Sand and silt explain soil physical properties such as texture, bulk density, available pore space and the capacity to store and release plant nutrients (Troeh and Thompson 2005).

The third component (PC3) in this study gave a high negative loading for P and high positive loading for Na. Since the soils in the region do not have major problems regarding Na, this component can be taken to represent the '*phosphorus availability*' of the soil. (Kosaki and Juo 1989) described their second component (PC2) as 'available P' since it was dominated by P and Ca. Similarly, Titilope et al. (2011) defined PC2 as the 'available phosphorus' component due to the high loadings for P, K, exchangeable acidity and Mn. Studies in western Kenya show that P is one of the main limiting nutrients for crop production (Sanchez 2002; Bunemann 2003). Phosphorus deficiency in many of the soils is largely due to the inherent low P concentration in the parent material (Bunemann 2003) as well as P-fixation (Van der Eijk 1997). The PCA results confirm the importance of P as a key parameter for understanding the soil fertility problem in the study area.

There is a wide variation in the results observed from the use of PCA to understand soil variability. For example, a study by Oluwole (1985) identified three PCs' for soils in Nigeria. PC1 represented texture, PC2 soil acidity and PC3 the SOM pool. The author concluded that the main variation in the soils of the study area could be due to the differences in clay content, and the associated differences in soil nutrient levels and pH values, as well as differences in the organic matter status brought about by differences in land use. In another study, Adhikari et al. (2011) was able to group soil properties into 4 PCs explaining soil sodicity (PC1), water transport through the soil (PC2), soil texture (PC3) and organic matter (PC4). The variations observed across studies could be attributed to the specific soil forming processes, management-related factors and soil conditions, which are site specific (Jiang and Thelen 2004). Despite the differences, PCA is able to help assign soils to functional groups thereby facilitating targeting of management options.

6.5 Conclusions

The complexity of ecosystems means that land degradation cannot be viewed from a single lens but by examining indicators associated with ecosystem attributes or factors of interest. The study evaluated various indicators of soil and site stability, hydrologic function and biotic integrity and noted that the presence and magnitude of these indicators varied across the landscape. The study area had sparse wood cover but high herbaceous cover. Over 55% of the farms sampled completely lacked soil and water conservation (SWC) technologies. Sheet erosion was observed in over 70% of the farms. Assessment of the general vegetation structure showed that over 70% of the land was under cropland and 8% under forests. There was a high variability in the soil properties measured. Soil acidity and general low soil organic carbon were evident across the study area. By grouping soil C and major macro nutrients together, the PCA revealed the importance of soil organic matter and nutrient availability in ensuring sustained food production in these cropping systems that are already facing problem of declining soil fertility and reduced productivity. The PCA results further affirm the need for integrated soil fertility management (ISFM) as a strategy to ensure nutrient availability while at the same time building the natural nutrient reserve through soil organic matter build up.

7 POTENTIAL NUTRIENT SUPPLY, UPTAKE AND CROP PRODUCTIVITY IN SMALLHOLDER CROPPING SYSTEMS OF WESTERN KENYA

7.1 Introduction

Land productivity in sub Saharan Africa (SSA) has remained low due to declining soil fertility resulting from many years of nutrient loss through crop harvest as well as through processes such as soil erosion and leaching (Sanchez 2002). The amount of major nutrients (nitrogen- N, phosphorus- P and potassium- K) lost far exceeds the amounts replaced through processes such as fertilizer and manure application, natural deposition and biological fixation. Smaling et al., (1997) estimated that farming systems in the East African Highlands lose nutrients at rates of 130 kg N, 5 kg P and 25 kg K ha/yr. Statistics indicate that yields of major cereals (maize, millet, sorghum) in smallholder farming systems in Kenya average <1 t/ha compared to reported yields of 9 t/ha in highland environments (KARI 2005). On the other hand, fertilizer use among smallholder farming systems is low. Fertilizer use in SSA is estimated to average 9 kg of nutrients per hectare compared to 86 kg/ha, 104 kg/ha and 142 kg/ha for Latin America, South Asia and Southeast Asia, respectively (Crawford et al. 2006). Equally, production of organic resources in the smallholder systems is low because of the already impoverished soils. Often the organics are not returned to the farms due to other competing uses such as roofing, animal feed (Ikombo et al. 1994) and fuel (Tittonell et al. 2005; KIPPRA 2010) or are burnt during land clearing (Muasya 1995). In Uasin Gishu district, for example, 4 to 6 t/ha of crop residue is burnt each season to facilitate land clearing and ploughing for the subsequent cropping season (Muasya 1995).

With increasing land degradation and varied management practices, there is high heterogeneity in soil properties across the cropping systems of many smallholder farms (Prudencio 1993; Smaling and Braun 1996; Tittonell 2003). According to Tittonell et al., (2005) and Tittonell et al., (2007) soil fertility heterogeneity at farm scale may be associated with topography, soil types, land degradation intensities, sharp physical discontinuities, land-use history or distance from the homestead and livestock facilities. This heterogeneity results in a mosaic pattern of yields across the landscape which therefore requires adoption of different land management practices depending on the conditions of a particular site. Farmers are not interested in the soil properties per se, but the implication of the soil status on ultimate productivity. Yield mapping is therefore a logical starting point for site-specific nutrient management and also effective for the identification of potential management zones (Boydell and McBratney 2002).

Management zones can be defined as sub-regions within a landscape, farm or plot with homogenous yield-limiting factors (Doerge 1999). Variation in soil physical, chemical and biological properties are considered the most important factors responsible for yield variability across the landscapes (Ping et al. 2005). The magnitude and balance of the different soil properties result in varying nutrient supply and uptake potential thereby affecting ultimate crop productivity. Hence, understanding the variation of intrinsic soil fertility is the key factor for site-specific fertilizer and soil amendment applications as well as for planning effective soil sampling (Mann et al. 2011a; Mann et al. 2011b).

Site-specific management zones can be delineated based on variability in color of bare soil, farmers' perception of field topography and their knowledge of past production practices (Corbeels et al. 2000; Khosla et al. 2002; Fleming et al. 2004; Mairura et al. 2007; Mairura et al. 2008). For example, Mulla and Bhatti (1997) observed that low-, medium- and high-organic-matter zones were found to correspond with top, middle and bottom slope landscape position, and that there were increasing grain yields with increasing soil organic matter content. Other studies have used variation in soil physical properties, nutrient levels, and water content to define the management zones (Gaston et al. 2001). Gaston et al. (2001) reported that that variability in clay and soil carbon influenced the location and density of weeds.

Classifying fields into different levels of productivity management zones is a concept that is rapidly being adopted as a management tool for soils especially under precision agriculture systems (Doerge 1999; Khosla et al. 2002; Ping et al. 2005). This is in recognition of the high variability in crop responses at farm level as well as the fact that most farmers cannot afford application of recommended rates of fertilizer while production of organic inputs at farm level is limited. Knowledge about management zones can help develop prescription maps that can allow the land users to apply different rates of fertilizer at different locations of a field thereby reducing production costs and maximizing returns on investment by reducing fertilizer application to unproductive areas of fields where nutrient uptake is low and losses may occur (Mulla and Bhatti 1997; Mann et al. 2011a; Mann et al. 2011b). This knowledge on management zones can also help when making decisions about the land use in poor or degraded areas. These degraded areas can either be excluded from production or possibly improved by applying appropriate amendments.

Soil fertility research has generated interpretation guidelines for evaluating the measured soil properties (Sanchez et al. 1982; Tekalign and Haque 1991; Okalebo et al. 2002; FAO 2006, 2008). These guidelines can be used to group soils as fertile or not fertile or as degraded or non-degraded as a first step towards delineating the management zones. Such guidelines serve to standardize and facilitate comparison of results across regions especially when determining recommendation domains for particular soil fertility management technologies. Further, estimates of crop yields as a function of availability of nutrients in the soil can be done using models (Burrough 1989; Janssen et al. 1990; Lal et al. 1993; Smaling and Janssen 1993; Mulder 2000). QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) is one such model that was designed for the quantitative prediction of maize yields on unfertilized tropical soils, although it can be adjusted for other crops and soils (Janssen et al. 1990). This model was validated in Kenya by Smaling and Janssen (1993) and adapted so that it could be used to estimate yield response to fertilization with N, P and K. This way, results from QUEFTS modeling can be used to complement crop response data in nutrient omission plots (Witt and Dobermann 2002). In this way, the model could contribute to a more efficient use of mineral fertilizer at both regional and farm level (Smaling and Janssen 1993). The model combines both empirical and theoretical approaches to modeling; thus it is based on data produced through observation or experimentation as well as on theories of known physical or physiological relations of crop growth (Mulder 2000). The model's main advantage is its simplicity, since it uses relatively standard soil data commonly analyzed in routine laboratory procedures. The ability of QUEFTS to predict nutrient supply, nutrient uptake and crop productivity as well as to establish site-specific fertilizer application makes the use of this model a good starting point for determining management zones in the smallholder cropping systems in SSA.

The study therefore assessed nutrient supply, nutrient uptake and crop productivity potentials across smallholder farming systems in Western Kenya using QUEFTS model.

7.2 Methodology

7.2.1 Study area

This assessment was conducted for the croplands in Kabras Division, of western Kenya. This area is represented by the Malava block (Figure 7.1). The area is located 30 km north of Kakamega town, and is inhabited by the Kabras speaking community. It covers an area of 424.4 km^2. The division lies within a relatively high agricultural potential area, with a third of its landmass falling within the high potential Upper Midland and Lower Midland agro-ecological zones (Jaetzold and Schmidt 1982; Jaetzold et al. 2005). The Division experiences a bimodal rainfall pattern with the long rains falling between March and July while the short rains between August and November. The average rainfall for the area is between 1,500 and 1,800 mm per year, while the mean annual temperature is 22-29° C. The soils in this region are highly variable with the most dominant being the Nito-rhodic Ferralsols. Other soil types include Acrisols, Combisols and Gleysols. The Nito-rhodic Ferralsols are mainly developed from granites and are well drained, very dark, dusky red to yellowish red and in some places friable clay loams with acid humic topsoil (Jaetzold and Schmidt 1982; Jaetzold et al. 2005).

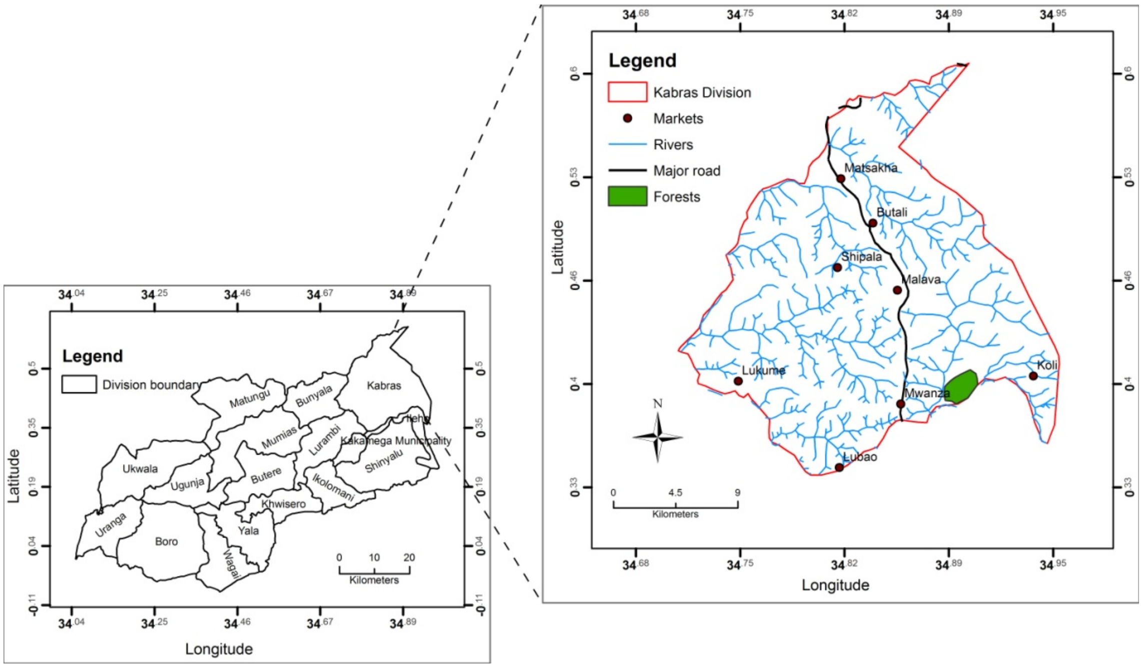


Figure 7.1 Location of Kabras Division, Western Kenya

7.2.2 Soil sampling and analysis

The soil sampling and analysis procedures are as described in Chapter 3 and Chapter 6. Nutrient supply and uptake as well as crop productivity potential were evaluated only for the plots characterized as cropland. These are represented by 119 out of the 160 farms sampled. The soil chemical properties were determined following both conventional wet chemistry and the near infra-red spectroscopy (NIRS) methods.

Table 7.1 shows the minimum soil parameters needed to run the QUEFTS model. The table also shows the recommended boundary values of the soil properties for modeling using QUEFTS. The model is applicable for soils with pH (H_2O) in the range of 4.5-7.0, total organic carbon (TOC), available phosphorus (P) and exchangeable potassium (K) below 70 g/kg, 30 mg/kg and 30 mmol/kg, respectively (Smaling and Janssen 1993). These authors proposed that available P should be determined using the Olsen P method. However, available P in this study was determined following the Mehlich method (Mehlich 1984), because this method is widely adopted for routine analysis by soil laboratories in Africa due to the suitability of the Mehlich method for a wide range of soil pH ranges and especially for acidic soils as is the case of the study area. Studies have also shown a good correlation between Mehlich and Olsen methods for available P determination (Mallarino 1997).

Table 7.1 Minimum dataset and boundary values for QUEFTS

Soil property	Units	Boundary values
pH	g/kg	4.5 – 7.0
Organic carbon	g/kg	≤ 70
Organic nitrogen	mg/kg	≤ 7
P (Olsen)	mg/kg	≤ 30
Total P	mg/kg	≤ 2000
Exch. K	mmol/kg	≤ 30

Source: Janssen et al (1990); Smaling (1993)

7.2.3 Interpretation of the soil chemical properties

The measured soil chemical properties were compared to documented soil fertility thresholds for tropical soils (Tables 7.2 – 7.4) to gauge the soil fertility status; information that would be useful for interpretation of subsequent results.

Table 7.2 Guidelines for the interpretation of soil organic carbon and total nitrogen levels in soils

Rating	Organic carbon (%)	Total nitrogen (%)
High	>3.0	>0.25
Moderate	1.5 – 3.0	0.12 – 0.25
Low	0.5 – 1.5	0.05 – 0.12
Very low	<0.5	<0.05

Source: Tekalign and Haque (1991); Okalebo et al. (2002)

Table 7.3 Guidelines for the interpretation of soil pH levels in soils

Degree of acidity	pH range
Extremely acidic	<4.5
Strongly acidic	4.5 – 5.0
Moderately acidic	5.0 – 6.0
Slightly acidic	6.0 – 6.5
Near neutral	6.5 – 7.0

Source: Legger (1978); Kanyanjua et al. (2002)

Table 7.4 Guidelines for the interpretation of exchangeable cation levels in soils

Rating	K	Mg	Ca
	Measured value (mg/kg)		
Very high	>300	>180	>2400
High	175 - 300	80 – 180	1600 – 2400
Medium	100 - 175	40 – 80	1000 – 1600
Low	50 – 100	20 - 40	500 – 1000
Very low	<50	<20	<500

Source: Okalebo et al. (2002)

To assess nutrient supply and uptake as well as production potential across the cropland areas, the plots were classified into three fertility classes based on their soil carbon content (Table 7.5). Plots with total carbon contents above 3% were classified as High Fertility-HF, those with carbon content between 1.5 and 3.0% were classified as Moderately Fertile- MF those with carbon content less than 1.5% were classified as Low Fertility- LF farms. Nutrient supply, uptake and productivity potential were then evaluated across these fertility classes using QUEFTS model.

Table 7.5 Soil fertility classes of the plots sampled in Malava block

Soil fertility class	Soil carbon content (%)
High Fertility- HF	>3
Moderate Fertility- MF	1.5-3
Low Fertility- LF	<2

7.2.4 Predicting nutrient supply, uptake, yield gap and productivity using QUEFTS

As discussed earlier, QUEFTS model was developed and calibrated to estimate fertilizer requirements and grain yield of tropical maize in Kenya (Janssen et al. 1990; Smaling and Janssen 1993). Predicted yields using QUEFTS are an indication of attainable yields given the nutrient availability from soil and fertilizers. The model includes four analytical steps, with the outcome of each step being a prerequisite for the next (Janssen et al. 1990; Smaling and Janssen 1993).

Step 1: Calculation of supply of nutrients (N, P, K)

The first step involves quantification of the potential native soil supply of N (SN), P (SP) and K (SK) using soil chemical data. This calculation incorporates a correction factor due to the influence of soil pH on nutrient supply.

$$SN = max[1.7 \times (pH - 3) \times org.C, 0] \quad \text{(Eq. 1)}$$

$$SP = max[0.35 \times (1 - 0.5 \times (pH - 6)^2) \times org.C + 0.5 \times P.Olsen, 0] \quad \text{(Eq. 2)}$$

$$SK = max\left[\frac{250 \times (3.4 - 0.4 \times pH) \times exch.K}{2 + 0.9 \times org.C}, 0\right] \quad \text{(Eq. 3)}$$

where:

SN = Supply of nitrogen; SP = Supply of phosphorus; SK = Supply of potassium

Step 2: Calculation of the uptake of nutrients (N, P, K)

The second step involves estimation of the actual crop nutrient uptake of N (UN), uptake of P (UP) and uptake of K (UK) as a function of the native soil supply of a nutrient. Table 7.6 presents the constants used in this stage.

$$U1 = S1 \times e^{(0.5 \times (c1 \times S1/S2 + c2 \times S1/S3))} \quad \text{(Eq. 4)}$$

Table 7.6 Parameters for the modified version of QUEFTS

N	P	K	c1	c2
1	2	3	-0.05	-0.35
2	1	3	-1.15	-0.40
2	3	1	-0.35	-0.07

Step 3: Calculation of yield ranges

The third step involves estimation of N-, P- and K-determined yield ranges as a function of calculated nutrient uptake. This enables determination of the yield boundaries at maximum dilution and maximum accumulation for the respective nutrient (e.g., YNA: yield at maximum N accumulation, YND: yield at maximum N dilution, etc.)

$$YNA = 30 \times max[0, UN - 5] \qquad \text{(Eq. 5)}$$

$$YND = 70 \times max[0, UN - 5] \qquad \text{(Eq. 6)}$$

$$YPA = 160 \times max[0, UP - 0.4] \qquad \text{(Eq. 7)}$$

$$YPD = 600 \times max[0, UP - 0.4] \qquad \text{(Eq. 8)}$$

$$YKA = 30 \times max[0, UK - 2] \qquad \text{(Eq. 9)}$$

$$YKD = 120 \times max[0, UK - 2] \qquad \text{(Eq. 10)}$$

where:

YNA and YND (YPA and YPD, YKA and YKD) are yields obtained when nitrogen (phosphorus, potassium) in the crop is maximally accumulated and diluted, respectively. Yields are expressed in kg/ha

Step 4: Estimation of yield

The final step involves estimation of the ultimate yield by accounting for the interactions between N, P and K. This gives the average yield estimates calculated for each possible pair of nutrients.

Part 1: Calculation of YNP, YNK, YPN, YPK, YKN, YKP

This step enables the calculation of maize yield (Y12) for a combination of two nutrients taking into account the yield range of the third nutrient. (e.g., YNP: yield of maize under N and P supply as influenced by P availability, etc.). Table 7.7 presents the parameters used in QUEFTS for yield estimation.

$$Y12 = Y2A + \frac{2(MIN - Y2A)(U1 - r1 - Y2A/d1)}{(MIN/a1 - Y2A/d1)} - \frac{(MIN - Y2A)(U1 - r1 - Y2A/d1)^2}{(MIN/a1 - Y2A/d1)^2} \qquad \text{(Eq. 11)}$$

where:

Y2A = yield corresponding with maximum accumulation of Nutrient 2
Y2D = yield corresponding with maximum dilution of Nutrient 2
Y3D = yield corresponding with maximum dilution of Nutrient 3
U1 = actual uptake of Nutrient 1
r1, d1 and a1 = are parameters for estimating yield (Table 7.7)

Table 7.7 Parameters for yield estimation

Nutrient (1,2)	a	d	r
N	30	70	5
P	200	600	0.4
K	30	120	2

where:

a= Maximum accumulation of N, P and K; d- Maximum nutrient use efficiency (NUE) for maize (kg grain per kg) of N, P and K;

r- Minimum nutrient intake for grain filling to take place (kg/ha)

NB: If Y3D is less than Y2D, Y3D should be substituted for Y2D using the following formula

$$MIN = min[Y2D, Y3D, Ymax] \qquad \text{(Eq. 12)}$$

Part 2: Calculation of ultimate yield estimate (YE)

Averaging the paired yields calculated in Step 4/Part 1 gives the ultimate yield estimate (YE) under the soil conditions under consideration.

$$YE = \frac{YNP + YNK + YPN + YPK + YKN + YKP}{6} \qquad \text{(Eq. 13)}$$

In this study, nutrient supply (SN, SP and SK) was calculated based on the equations of the original version of QUEFTS (Janssen et al. 1990). This is also because total P and temperature were not measured. The estimated nutrient supply potentials of the soils were comparable irrespective of which equations, original or modified, were used. Subsequent steps (2, 3 and 4) were based on the modified version of QUEFTS (Smaling and Janssen 1993). The modified QUEFTS equation was chosen as it minimizes over-estimation of uptake of N and K (Smaling and Janssen 1993).

7.2.5 Statistical analysis

The mean values of the final results (nutrient supply and uptake, yield gap and yield estimates) were compared across the soil fertility classes and presented graphically.

7.3 Results

7.3.1 Interpretation of threshold values of soil chemical properties

Table 7.8 presents the average soil chemical properties of the cropland plots sampled. The values especially for pH, organic carbon, available P, and exchangeable K fall within the acceptable range for prediction using QUEFTS.

Table 7.8 Descriptive statistics of soil properties across cropland in Malava block (0-20cm depth)

Soil property	Minimum	Maximum	Mean	Std. Dev
Total carbon (mg/kg)	10.0	47.7	19.1	5.34
Total nitrogen (mg/kg)	0.7	4.0	1.5	0.43
CEC (C mol /100g)	5.1	24.6	9.7	2.43
P (mg/kg)	3.9	13.7	6.9	1.77
K (mmol/kg)	1.7	6.0	2.8	0.53
Ca (mg/kg)	256.7	3550.4	777.1	380.66
Mg (mg/kg)	49.3	403.2	119.0	42.99
Na (mg/kg)	31.6	50.4	40.3	3.85
pH	4.8	5.6	5.1	0.16
Sand (%)	51.2	73.5	62.2	4.90
Clay (%)	17.8	41.3	29.1	5.36
Silt (%)	2.5	25.9	7.3	2.99

Only 3% of the croplands sampled were classified as having high carbon levels (>3%). The majority of the farms had moderate (1.5% - 3%) to low (0.5% - 1.5%) soil organic carbon levels (Table 7.9). As with the case of C, the majority of the farms had moderate to low soil N contents.

Table 7.9 Evaluation of organic carbon and total nitrogen levels across croplands in Malava block

Rating	Organic carbon	Total nitrogen
	Proportion of farms (%)	
High	2.5	1.7
Moderate	79.0	77.3
Low	18.5	21.0
Very low	-	-
Total	100.0	100.0

The soils in the study area were found to be acidic with pH below values 7 (Table 7.10). About 90% of the farms sampled had moderate soil acidity (pH 5.0 – 6.0) while 11% were strongly acidic (pH 4.5 – 5.0).

Table 7.10 Evaluation of soil pH levels across croplands in Malava block

Rating	Number of plots	Proportion (%)
Strongly acidic	19	10.9
Moderately acidic	100	89.1
Total	119	100.0

Most plots sampled had low to moderate levels of K, medium to high levels of Mg but very low levels of Ca (Table 7.11). This trend supports the observation that acid soils have less Ca.

Table 7.11 Evaluation of exchangeable cation levels across croplands in Malava block

Rating	K	Mg	Ca
	Proportion of farms (%)		
Very high	-	4.2	-
High	0.8	80.7	1.7
Medium	70.6	15.1	20.2
Low	28.6	-	58.8
Very low	-	-	19.3
Total	100.0	100.0	100.0

7.3.2 Prediction of nutrient supply, uptake and production potential under high, medium and low soil fertility

Soil properties under three soil fertility classes

Table 7.12 presents the average soil chemical properties of the cropland plots after classification into three fertility classes (high, moderate and low). The high fertility (HF) soils were represented by 3 plots, while the moderate fertility (MF) and low fertility (LF) soils were represented by 94 and 22 plots, respectively. On average plots classified as HF had two and three times more carbon compared to those classified as MF and LF, respectively. Soil available phosphorus and pH were relatively similar across the three fertility classes. The HF soils recorded significantly higher contents of CEC, K, Ca and Mg compared to the LF soils. These variations clearly capture the diversity in soil fertility status of the plots in the study area, hence a justification for comparison of the plots classified as either degraded or non-degraded.

Table 7.12 Soil properties under high, medium and low soil fertility in Malava block

	High Fertility (N = 3)		Moderate Fertility (N = 94)		Low Fertility (N = 22)	
Soil property	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
TOC (mg/kg)	37.4	9.17	19.9	3.70	13.1	1.46
TON (mg/kg)	3.0	0.91	1.5	0.29	1.0	0.12
pH	5.4	0.36	5.2	0.16	5.1	0.13
CEC (C mol /100g)	17.6	6.85	10.0	1.66	7.3	1.04
P (mg/kg)	8.0	3.15	7.0	1.85	6.6	1.14
K (mmol/kg)	4.6	1.18	2.9	0.34	2.2	0.25
Ca (mg/kg)	2023.1	1371.54	799.9	261.85	509.5	179.64
Mg (mg/kg)	255.6	133.66	122.7	30.92	84.5	21.71
Na (mg/kg)	34.3	3.83	39.8	3.56	43.3	3.26
Sand (%)	52.8	1.25	61.0	3.99	68.3	2.67
Clay (%)	33.2	5.19	29.9	5.45	25.5	2.99
Silt (%)	15.8	8.87	7.5	2.34	5.2	1.91

Nutrient supply potential under three soil fertility classes

The potential nutrient supply of the soils was interpreted based on the values shown in Table 7.13. Over 80% of the farms had moderate to low potential to supply N. Sixty

(60) percent of the farms had low potential to supply P and majority of the farms had moderate to low levels of K supply potential (Table 7.14).

Table 7.13 Interpretation values of the nutrient supply estimated using QUEFTS

Rating	SN	SP	SK
		kg/ha	
High	>90	>16	>80
Moderate	40-90	8-16	40-80
Low	<40	<8	<40

Table 7.14 Nutrient supply potential of the croplands in Malava

	SN	SP	SK
Nutrient supply rating		Proportion of farms (%)	
High	15	1	-
Moderate	81	40	97
Low	4	59	3
Total	100	100	100

There was a wide variability in the potential nutrient supply of the soils across the plots sampled. The plots classified as HF had three times higher potential supply of N (SN) and supply of P (SP) compared to the LF plots (Table 7.15). Conversely, the supply of K (SK) was highest in the LF followed by the MF and lowest in the HF plots.

The predicted uptake of N (UN) and P (UP) was in the order HF>MF>LF, but uptake of K was similar across the three fertility classes (Table 7.15). The UN as a proportion of the supply of N (SN) was 37%, 60% and 71% for the HF, MF and LF classes, respectively. The uptake of P as a proportion of the potential supply of P was above 90% across the three fertility classes. On the other hand, the proportion of uptake of K (UK) to supply of K (SK) was 85%, 71% and 57% for the HF, MF and LF classes, respectively.

Table 7.15 Potential supply and actual uptake of nitrogen, phosphorus and potassium in high, moderate and low fertility soils, Malava block

	High Fertility (N = 3)		Moderate Fertility (N = 94)		Low Fertility (N = 22)	
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Potential supply (kg/ha)						
SN	153.6	57.18	73.3	14.85	45.9	6.52
SP	14.3	4.42	8.0	1.24	5.8	0.74
SK	40.4	4.23	49.5	3.94	56.0	2.81
Potential uptake (kg/ha)						
UN	56.9	3.33	44.2	4.89	32.5	3.82
UP	13.2	3.72	7.6	1.14	5.7	0.71
UK	34.4	1.62	34.9	1.77	32.1	2.52

Yield gap across fertility classes

Figures 7.2 to 7.4 illustrate the yield bounds following uptake of N, P and K in the croplands in the study area. The upper line represents a situation where the nutrient (N, P or K) is the main yield limiting factor and hence is *maximally diluted* in the plant. At this point, the yield is the highest possible since most of nutrient is taken up. On the other hand, the lower lines represent a scenario where the nutrient concerned is excessively available. At this point, the nutrient is *maximally accumulated* and yield is limited by other factors other than this nutrient, hence the yields are at the lowest level. A comparison of potential yield at a given uptake level between the maximally accumulated and the maximally diluted bounds gives the yield gap for the respective nutrient.

When N was maximally accumulated in the plant (i.e., least efficiently utilized), the yield was between 572 kg/ha and 1,661kg/ha. When N was maximally diluted in the plant (i.e., most efficiently utilized), the yield was between 1,527 kg/ha and 4430 kg/ha (Figure 7.2). For P, the yield was between 626 kg/ha and 2,707 kg/ha at maximally accumulation and 2,361 kg/ha and 1,015 kg/ha at maximally dilution (Figure 7.3). On the other hand grain yield varied from 741 kg/ha to 1,129 kg/ha and from 2,964 kg/ha to 4,519 kg/ha at maximum accumulation and maximum dilution respectively, for K (Figure 7.4). These estimates are for individual nutrients and assume that there are no other growth-limiting factors. The data show that there is great potential to improve production with proper management of N, P and K. Of the three nutrients, P had the widest yield gap followed by K and N. This confirms the observation that P is the most limiting nutrient in the region, and that its application can significantly increase cereal production (Hinga 1973; Nziguheba et al. 2000).

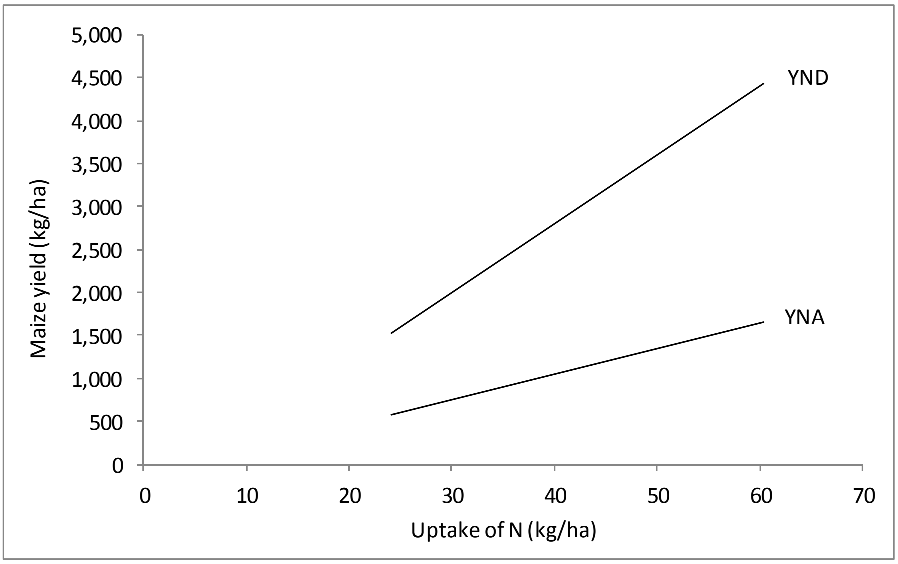


Figure 7.2 Relationship between uptake of nitrogen (UN) and maize yield potential in croplands in Malava block

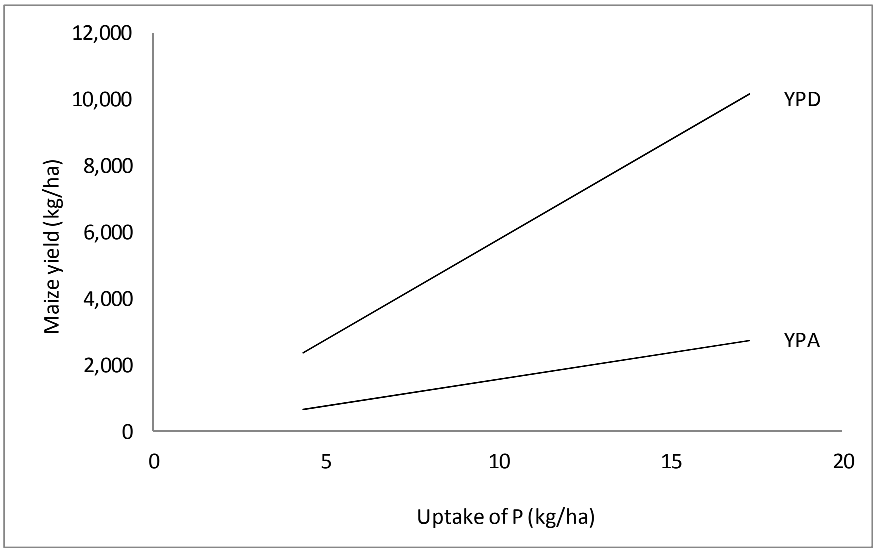


Figure 7.3 Relationship between uptake of phosphorus (UP) and maize yield potential in croplands in Malava block

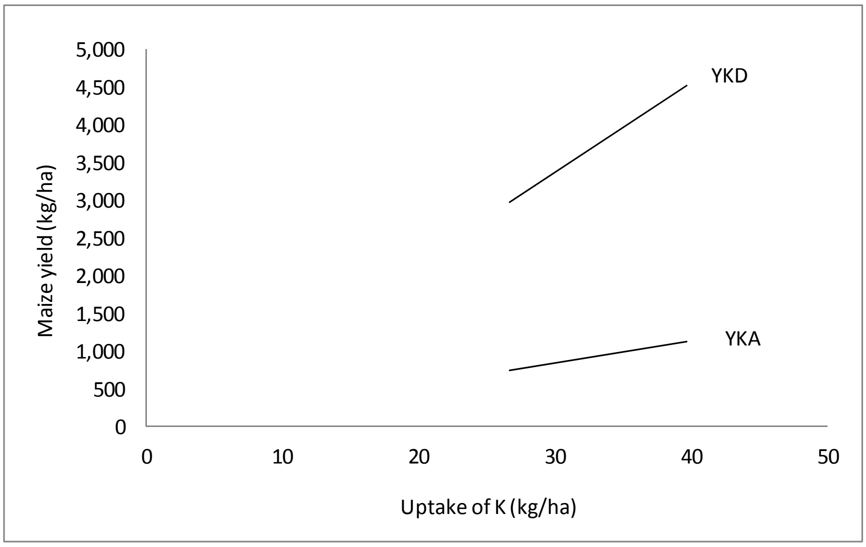


Figure 7.4 Relationship between uptake of potassium (UK) and maize yield potential the croplands in Malava block

Table 7.16 presents predicted yields of maize with paired nutrient uptake as influenced by the third nutrient. These yields lie within the yield bounds (maximum dilution and maximum accumulation) predicted above. Further, the predicted yields under paired nutrients are lower than those observed for the individual nutrients. This is due to the effect of interactions between the nutrients. The nutrient combinations with P as the main nutrient had higher yields compared to the combination with N and K as the main nutrients. This confirms the earlier observation that P is the most limiting nutrient in these cropping systems. Taking the average maize yield at different nutrient supply combinations, the HF soils have potential to produce 2,835 kg/ha of grain yield compared to 2,165 kg/ha for the MF soils and 1,628 kg/ha for the LF soils.

Table 7.16 Estimated yield in high, moderate and low fertility soils, Malava block

Nutrient combination	High Fertility (N = 2)		Moderate Fertility (N = 93)		Low Fertility (N = 24)	
	Maize yield (kg/ha)					
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
YNP	2,796.0	267.54	2,136.3	240.46	1,546.0	208.99
YNK	2,568.4	102.46	2,105.5	214.00	1,559.0	201.36
YPN	3,414.6	378.39	2,389.2	333.95	1,707.9	228.55
YPK	3,372.2	410.20	2,355.0	315.80	1,721.9	221.96
YKN	2,296.5	71.12	2,011.1	153.27	1,616.4	177.81
YKP	2,565.7	349.51	2,005.4	167.48	1,619.4	177.95
Yield estimate (YE) (kg/ha)	2,835.6	260.35	2,167.1	235.74	1,628.4	202.27

There was a strong correlation (R^2 = 0.78) between soil organic carbon and grain yield, implying that increasing soil organic matter, which is synonymous with increasing soil fertility, would result in increased productivity of the cropping systems in the study area (Figure 7.5).

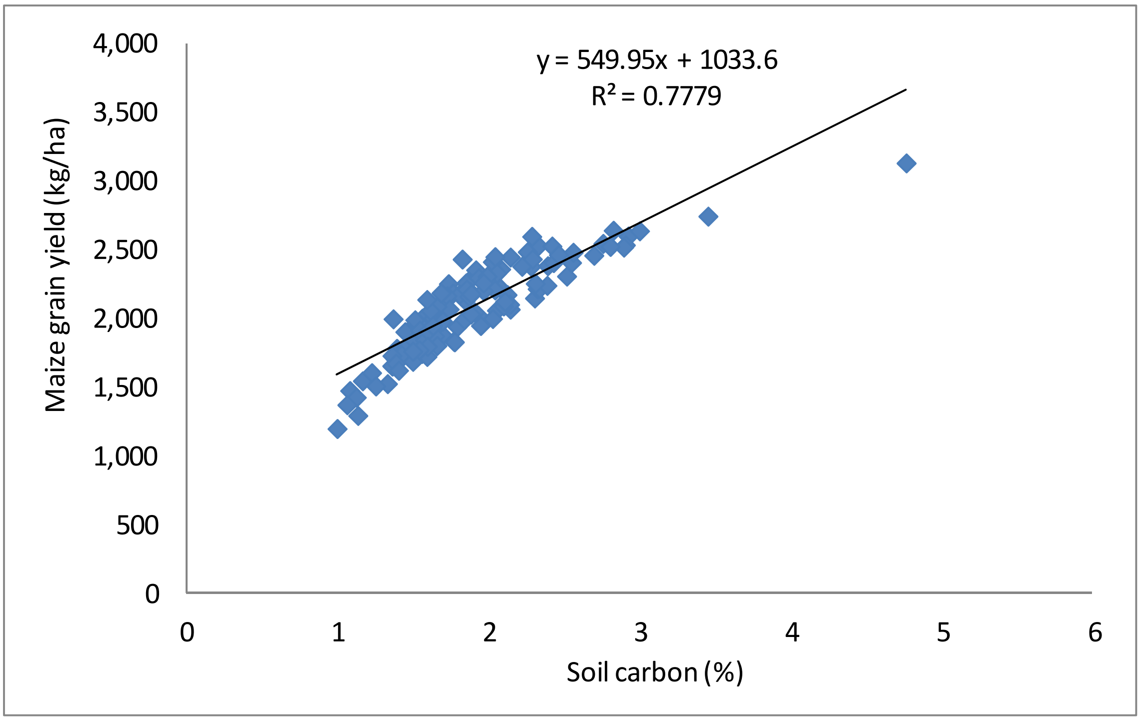


Figure 7.5 Correlation between measured soil organic carbon and predicted maize grain yield across croplands in Malava block

7.4 Discussion

Western Kenya like other humid and sub humid tropics is dominated by kaolinitic-rich soils characterized by weak buffering capacity, low P availability, toxicities of Al, Fe and Mn, deficiencies of Ca, Mg, K, Zn, S and Mo, and low cation exchange capacity (Clark et al. 1988). These deficiencies or toxicities often interact to limit overall crop production. The majority of the farms sampled in this study had moderate to low levels of major soil properties such as carbon, pH, K, P, C.E.C, Ca and Mg. In addition to being as a result of inherent soil fertility, the low levels of major soil chemical properties is a manifestation of decades of continuous cropping with minimal external inputs (Rao et al. 1999).

Soil acidity was found to be a major problem in the study area. Soil pH plays an important role in influencing nutrient availability (Brady and Weil 2002). Availability of N, P, S, Ca, Mg, Na, and Mo is limited under acidic conditions. In acidic soils (pH lower than 6), P reacts with aluminium (Al) and iron (Fe) to form insoluble compounds making P unavailable to plants. Al and Mn toxicity is a common problem in most tropical soils that have pH equal to or less than 5.4. These toxicities limit crop yields, since most crops are not tolerant. Soil pH also affects biological N-fixation (Giller and Wilson 1991). The survival and activity of Rhizobium, the bacteria responsible for N fixation, declines as soil acidity increases (Sanginga et al. 1995). Different crops have various degrees of tolerance to acidity and growing crops in soils with pH values below the lower limit results in low yields and poor crop quality (Kanyanjua et al. 2002). To address soil acidity problem requires growing acid-tolerant crops, use of organic manure, and use of agricultural lime among other options.

There was a wide variation in soil organic carbon (SOC) across the croplands ranging from 0.1% to 4.7%. This variation is a reflection of the management regimes (organic residue, fallow, land surface preparation) employed by the farmers as well as of the differences in soil and climatic conditions. In a study of the long-term experiment at Kabete Kenya, Swift et al. (1994) observed a decline in SOC from 2.1% in the initial coffee plantations to 1.2% C after nearly two decades of cropping maize and beans. Soil organic carbon is not a requirement for plant growth, but the levels in the soil influence several soil chemical, physical and biological properties. Soil organic carbon is a major constituent of soil organic matter (SOM) which affects soil aggregation (Tisdall and Oades 1982; Oades 1984; Carter and Stewart 1996). Well aggregated soils have improved drainage. SOM also improves the soil-moisture holding capacity (Wolf and Snyder 2003) and cation exchange capacities (Oades et al. 1989). Soil carbon is the main food substrate for microorganisms, which play an important role in nutrient availability through the process of mineralization. SOM contains 58% C, 5% N, 0.5% P and 0.5% S (Euroconsult 1989). Studies show that, irrespective of soil type, it may not be possible to obtain potential crop yields sustainability if SOC is below 1% (Loveland and Webb 2003). Also, with SOC values less than 2%, soil aggregates are considered unstable (Krull et al. 2004). For all these reasons, changes in SOM status are therefore an important indicator of chemical, physical and biological degradation of the soil. It is on this basis that measured soil organic carbon was used to group the plots in high, medium or low fertility.

Trends in soil N followed a similar pattern as that of SOC because SOM is the major source of N in tropical soils (Euroconsult 1989). Nitrogen is a plant nutrient taken up in greatest quantities by crops, and together with P is the most limiting nutrient in tropical soils (Bekunda et al. 1997). It is difficult to build a reserve of soil N, hence a continual supply is necessary (Giller et al. 1997). Soil P and N are intricately related especially when it comes to biological N fixation. Nitrogen fixation is limited in P-deficient soils (Giller and Wilson 1991). Legumes in P-deficient soils can only fix up to 10 kg N/ha against an annual requirement of 30 kg N/ha needed to offset estimated N losses in smallholder systems (Giller et al. 1997).

Deficiency of P in most soils in Western Kenya is a result of low occurrence of P-containing minerals, P-fixation, and continuous cropping (Hinga 1973; Nyandat 1981; Sanchez et al. 1997; Smaling et al. 1997; Van der Eijk 1997; Bunemann 2003). Maintaining soil P requires continuous application from organic and or inorganic sources. Whereas K has been perceived to be non-limiting in most soils in Kenya, the losses due to soil erosion and crop harvest are changing the situation resulting in cases of K deficiencies being observed across cropping systems (Gikonyo and Smithson 2004).

The recommended fertilizer N application rate for western Kenya is 60 kg/ha (FURP 1994), although studies have shown that unlocking the yield potential may require fertilization beyond this application rate (Mugwe et al. 2009; Macharia et al. 2010). The actual uptake of N from the soils in the study area ranged from 33 kg/ha in the LF soils to 57 kg/ha in the HF soils. With the majority of the soils falling in the medium to low fertility class with an actual N uptake of 33-44 kg/ha, the soils cannot supply the required N to achieve optimum yields. To achieve the recommended application rates, farmers would require to apply an additional 16 to 27 kg/ha from external sources. The uptake of N in this study was within the range reported by Okalebo et al., (1999) in a study at Chepkoilel. These authors recorded N uptake ranges of 34-69 kg/ha in unfertilized (control) soils.

Actual uptake of P was 100% lower in LF soils compared to the HF soils and was in the order HF>MF>LF. In particular, the uptake of P in the LF (5.6 kg/ha) plots was similar to that reported by Okalebo et al., (1999) for an unfertilized plot (4-5 kg/ha). The soils in western Kenya are known to be P deficient (Rao et al. 1999). This could be a result of the low native P and P-fixation by Al and Fe oxides in the predominantly acid soils, in addition to mining of P from the soil that is estimated at 1.5-13 kg/ha/yr from smallholder mixed farms (Smaling et al. 1993).

Actual uptake of K was similar across the soil fertility classes and covered only 50% of the recommended application rate of 60 kg/ha. Similarity of K uptake across the soil fertility classes could be due to the fact that K is readily available in most soils in this region. Soil fertility studies frequently omit quantifying K uptake, hence there was no data to compare the results of this study with. Tittonell et al. (2008) using QUEFTS to quantify nutrient supply and uptake observed relatively higher N, P and K uptake levels for soils in Aludeka, Shinyalu and Emuhaya in Western Kenya. These higher amounts could be due to calculation using the original QUEFTS equation which, according to Smaling et al. (1993), tends to overestimate N and K uptake in soils. Despite this, the trend was similar with lower nutrient uptake levels were observed in the degraded than in non-degraded soils.

Uptake of a particular nutrient is dependent on the supply of the other nutrients in the soil as explained under the Liebig's Law of Minimum. When the supply of one nutrient is very low compared to the others, the whole supply of that nutrient will be taken up by the plant. The other nutrient that is relatively abundant will not be fully taken up by the crop. This explains why most of the available P is likely to be taken up by the plants. The implication of this to crop production is that with increased production, more of the P is removed from the soil making the soil P-deficient. Therefore, its replacement using external sources is essential to increase and/or maintain production. Conversely, the proportion of N taken up in the HF plots was 32% of the potential supply, meaning that a large proportion of the readily available N could be lost through leaching during periods of heavy rainfall. For increased efficiency, there is need to ensure that the soils have a balanced supply of all the nutrients. Secondly, storage of nutrients in the soil can be increased by increasing the proportion of the SOM pool through regular application/use of organic residues and manure. An integrated approach to plant nutrition that ensures balanced application of plant nutrients from both organic and inorganic sources is proposed for system sustainability.

The ultimate yield estimates predicted in this study for the different soil fertility classes are within observed production levels for the region. The yields account for 20-35% of the production potential of 8 t/ha under researcher-managed conditions. The data on yield gap showed that there is greater potential to achieve higher production on the more fertile soils compared to the less fertile soils. It is worth noting that the nutrient supply, uptake and yield estimated in this study using QUEFTS assume that all other conditions of production are optimal. The actual estimates could be greatly different under real conditions, since there could be deficiencies of other nutrients other than those considered under QUEFTS. The yields could also be influenced by the crop management (variety, sowing time, weeding, and spacing) as well as by the weather conditions. All these factors could be contributing to the average yield of 1 t/ha reported for maize for the study area.

Various authors have observed the existence of soil fertility gradients in smallholder cropping systems, where higher yields were observed in fields closer to the homestead (home fields/infields) compared to the fields further away (away fields/outfields) (Prudencio 1993; Dembele et al. 2000; Vanlauwe et al. 2007). For example, Fofana et al. (2008), in a study in West Africa, observed that millet grain yield across years and fertilizer treatments was (1,360 kg/ha) on infields (non-degraded) compared to (800 kg/ha) on outfields (degraded). According to these authors, fields closer to the homestead have enriched soil fertility through regular application of household waste including ash, crop residues and animal manure. In contrast, the fields further away are characterized by continuous cropping and grazing with little or no inputs leading to nutrient depletion and decline in soil fertility. According to Bationo et al. (2006), degraded soils with low soil organic matter exhibit weak response to fertilizer application and have very low fertilizer recovery. This observation was affirmed by Fofana et al. (2008) in a study in West Africa who reported recovery of N fertilizer in the range 17- 23% on outfields as compared to 34-37% on infields.

Average recovery of P was 31% on infields and 18% on outfields. Considering that the majority of the plots sampled in this study fell within the moderate to low fertility class, increasing production would require investment in fertility improvement through use of organic and inorganic nutrient resources coupled with improved agronomic practices.

7.5 Conclusions

Improving crop productivity for food security is the main goal of most smallholder farmers in the study area. But this cannot be achieved sustainably if the soil is degraded. Interpretation of the soil chemical properties revealed that there is wide variability in soil properties across the landscape as evident from the high, medium and low fertility classes. The soils in the study area are low in major nutrients, and this translates to low yield potential if no external inputs are used.

The use of the QUEFTS model offers an opportunity to rapidly evaluate the ability of the soil to support production. The results of the model indicated that the soils in the study area had nutrient supply potential, and that the actual nutrient uptake was far below crop requirements. This means that optimal production cannot be achieved unless additional nutrients are applied from external sources. Information about soil properties and yields from the different management zones within a field can be used for fertilizer and soil amendment recommendations, and then the variable fields can be managed on a site-specific basis. This study only provided quick estimates of the production potential based on the laboratory soil data. There is need to validate this through agronomic field trials.

The knowledge generated in this study can help develop prescription maps that can help the land managers to match production practices with variations in crop growth, soil type and soil fertility. This knowledge is also useful when designing soil sampling programs. Equipped with this knowledge, land users will be able to apply different rates of fertilizer at different locations of a field thereby reducing production costs as well as fertilizer wastage in cases where the fertilizer is applied to unproductive areas of the field where nutrient uptake is low and losses could occur.

Being able to delineate nutrient deficient areas can also help in decision making, either to completely exclude these areas from production or possibly rehabilitate them by applying appropriate amendments.

8 LAND DEGRADATION FROM THE LAND USERS PERSPECTIVE: A CASE OF WESTERN KENYA

8.1 Introduction

People tend to have a notion about the degree of degradation of their ecosystems although they may not directly use the term land degradation (Okoba and Sterk 2006; Mairura et al. 2008). This notion has been built from the day-to-day observation of changes in the capacity of the ecosystems to support their livelihoods. Such knowledge has come to be referred to as traditional or indigenous knowledge (Purcell 1998; WIPO 2005).

Depending on the natural and human effects, different agro-ecologies experience varied types of land degradation. Overgrazing is most rampant in the rangeland areas used for livestock production. These areas may also be prone to widespread soil erosion by both water and wind. The rangelands receive low rainfall and are often found in the arid and semi-arid zones. Pastoralists living in these regions may consider land degradation from the perspective of reduced palatable above ground vegetation for the livestock. On the other hand, the humid areas that receive high rainfall are predominantly used for cultivated agriculture. These regions are more prone to soil fertility decline and soil erosion by water. The land users in these regions may be more concerned about the reduction in yields of a particular crop. However, differences in perceptions can also occur among people in the same geographical location sharing the same resources. Such differences may be due to age, gender, level of education, and poverty level of the land users, among other varied individual differences (Sureshwaran et al. 1996).

Studies on perception and awareness are important determinants of environmental behavior (Napier 1991; Traoré et al. 1998). They are important in identifying areas of conflict among and between land users and researchers. The information can also help to identify barriers to participation in development activities and the rationale behind continued use of practices that cause land degradation

(Davies et al. 2010). All this information is useful during the design of effective land management practices.

This study complements the previous chapters on biophysical assessments by seeking to understand how land users in the study area perceived the problem of land degradation.

8.2 Methodology

8.2.1 Description of study area

This study was conducted in the Kabras Division of western Kenya. The general characteristic of the division are as described in Chapter 7. The study targeted the households where the biophysical assessments discussed in the preceding chapters had been conducted.

8.2.2 Survey

Data were obtained from a random sample of 126 farmers using interviews, semi-structured questionnaires and field observations. The questionnaire was modeled around the 'household livelihoods interview' structure proposed for use under the LADA project (FAO 2011a, 2011b). The questionnaire incorporated direct questions to determine the profile of the households (gender, age, literacy, family size), resource endowments (equipment, land, livestock), perception of status of croplands, grasslands, forests and woodlands and water resources, perception on types, extent and causes of land degradation, vulnerability to environmental risks and adaptation mechanisms of the household (Appendix III & IV).

Pre-testing of the questionnaire was done before the actual data collection, and appropriate modifications made. The enumerators were trained on field quantification skills, basic arithmetic- converting of local units to International Systems of Units (SI), research ethics and probing skills. The questionnaire was designed in English but translated to Kiswahili for ease of comprehension by the enumerators and the respondents. Kiswahili is the national language of Kenya.

The farmer survey was undertaken in July/August 2011 using a single-visit, face-to-face survey approach. The survey targeted household heads (male or female) in Kabras Division, northern Kakamega. These are the same households where soil sampling and characterization discussed in previous sections had been undertaken.

8.2.3 Data analysis

The collected household data were summarized and analyzed using Statistical Package for Social Sciences (SPSS, Version 15.0). Descriptive statistics such as means, percentages and standard deviations were used to present the results.

8.3 Results

8.3.1 Household socio-economic characteristics

Demographic characteristics

The study interviewed 126 household heads of whom 84% were males and 16% females. The household family size averaged 6.9 persons (Table 8.1). The age of the respondents varied from 16 – 84 years with the mean age of 49 years.

Table 8.1 Household characteristics of respondents in Kabras Division, western Kenya

Household characteristic	N	Min	Max	Mean	Std. Dev
Age of the respondent	119	16	84	49.0	14.68
Number of adult males in household	126	0.0	16	3.3	3.00
Number of adult females in household	126	0.0	15	3.6	2.90
Household adults	126	1.0	31.00	6.9	5.52

Education and literacy

Of the respondents, 55% had attained basic education (primary school level), 34% had secondary education, while 8% had attained tertiary education (Figure 8.1). Only 3% of the residents had no formal education. The statistics show that the literacy level was fairly high in the study area.

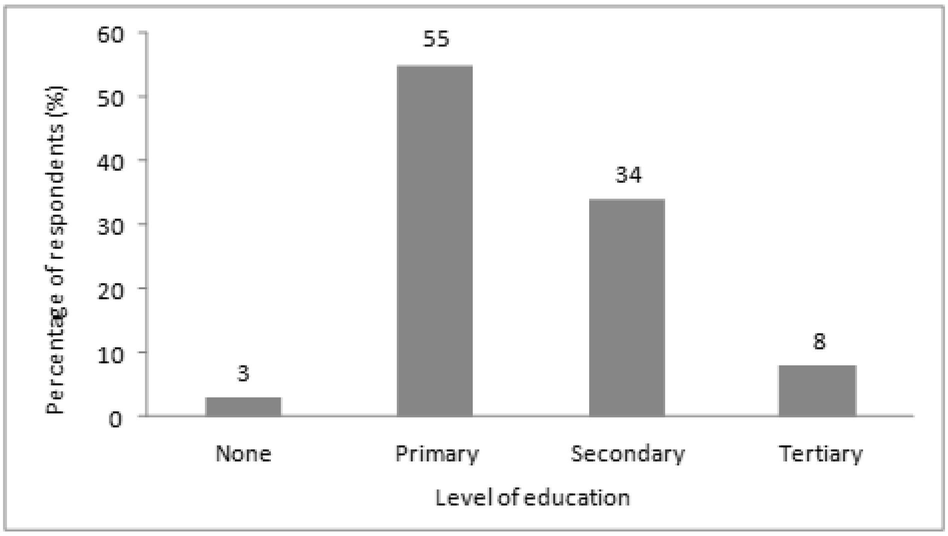


Figure 8.1 Level of education of the respondents in Kabras Division, western Kenya

Resource ownership

Table 8.2 illustrates some indicators of resource endowment of the households' categorized based on mobility, access to information and technology, level of farm mechanization and general financial and social status. The majority (77%) of the households owned a bicycle while 15% owned a motor bike. The survey revealed that a large proportion of the households owned a radio (93%). A significant proportion also owned a television or a mobile phone. Close to 50% of the households owned an ox-plough for land preparation. Over 85% of the households had an iron-roofed main house as opposed to the traditional grass-thatched house.

Table 8.2 Household assets in Kabras Division, western Kenya (N = 126)

Category of asset	Asset	Proportion of respondents (%)*
Mobility	Vehicle	8.9
	Motor bike	15.3
	Bicycle	77.2
Access to information and technology	Television	47.6
	Radio	92.7
	Mobile phone	83.1
Level of mechanization	Ox-plough	48.4
Financial well being and social status	Stone-walled house	21.1
	Cemented floor	30.3
	Iron sheet roofed house	85.2

**Totals more than 100% due to multiple responses*

Land tenure and ownership

The size of land per household varied from 0.2 ha to 32.8 ha with an average of 3.0 ha. Acquisition of the land was mainly through inheritance (85.6%), purchase (9.6%) and both inheritance and purchase (4.8%). The mode of ownership of the land was sole title although many younger households maintained user rights, since the land had not been subdivided by the heads of the households. Land tenure in the study area was generally considered to be secure.

Land use allocation

On average, 2.1 ha of the land were allocated to crop production, 0.4 ha to grazing and pastures and 0.2 ha to other uses including woodlots and farms forests (Table 8.3). Of the area under crop production, 33.6% was allocated to food crop production while the remaining 66.4% was allocated to cash crop production, mainly sugarcane.

Table 8.3 Allocation of land across different uses in Kabras Division, western Kenya

Land-use allocation	No. of respondents (N)	Area (ha)		
		Min.	Max.	Mean
Land size owned by household	125	0.2	32.8	3.0
Cropping	124	0.2	28.4	2.1
Grazing/pasture	124	0	2.4	0.4
Woodlots/forests	122	0	2.4	0.2
Food crops	126	0	4.1	0.7
Cash crops	125	0	20.3	1.4

Agricultural enterprises

The majority of the households (97%) identified maize as their major crop (Table 8.4). This was followed by sugarcane (93%), bananas (64%), sweet potatoes (48%) beans and cassava (28% each). Some 21% of the households deliberately grew Napier grass for their livestock or for sale. Other crops mentioned but by a few households were groundnuts, millet, sorghum, tomatoes, arrow roots, onions and pineapples.

Table 8.4 Crops cultivated in Kabras Division, western Kenya

Crop	No. of respondents (N = 126)	Proportion (%)*
Maize	122	96.8
Sugarcane	117	92.9
Bananas	81	64.3
Sweet potatoes	61	48.4
Beans	35	27.8
Cassava	35	27.8
Napier grass	26	20.6
Groundnuts	7	5.6
Others*	-	<5.0

**Tomatoes, millet, pineapples, arrow roots, onions, sorghum*

The significance of livestock was reflected in the high proportion (89.7%) of households owning at least one type of livestock (Table 8.5). Cattle and poultry were the most dominant types of livestock reared by smallholders. The main mode of feeding, especially for the large livestock types, was by confined grazing (tethering) on the farms or open grazing along the roadsides and riverbanks.

Table 8.5 Livestock possession per household in Kabras Division, western Kenya

Livestock	Min.	Max.	Mean	Std. Dev
Cattle	0	20	4.1	3.42
Goats	0	8	0.7	1.62
Sheep	0	8	0.8	1.63
Donkeys	0	2	0.02	0.18
Poultry	0	50	9.6	9.03

Agricultural input use

Table 8.6 illustrates extent of input use by the households in the study area. The proportion of farmers using inorganic fertilizer was 95%. The use of manure was reported by 89% of the households. Only 29% of the households used agricultural lime to correct for the soil acidity. Other soil fertility enhancement practices by the households included intercropping cereals with leguminous plants, mainly maize and beans, and agroforestry practices using improved fallow species.

Table 8.6 Input use at household level in Kabras Division, western Kenya (N = 126)

Inputs	No. of respondents (N = 126)	Proportion of respondents (%)*
Inorganic fertilizer	119	95.2
Farm yard manure	111	88.8
Lime	36	29.3
Compost	29	23.2

**Totals more than 100% due to multiple responses*

Household sources of energy

All the respondents in the study area used fuel wood as their main source of energy, mainly for cooking (Table 8.7). This was followed by the use of kerosene and charcoal. The cumulative proportion of households using dried sugarcane and maize stover as a source of energy was 73.8%. Other sources of energy, though with a smaller contribution included liquefied petroleum gas and electricity.

Table 8.7 Sources of energy at household level in Kabras Division, western Kenya

Source of energy	No. of respondents (N = 126)	Percentage (%)*
Fuel wood	126	100.0
Kerosene (paraffin)	121	96.8
Charcoal	107	85.6
Crop residues	93	73.8
Cooking gas	17	13.5
Electricity	9	7.1
Solar energy	1	0.8

**Totals more than 100% due to multiple responses*

Household sources of income

The main source of income for the households in the study area was sale of crop and animal products (Table 8.8). Sugarcane and maize were identified as the main sources of income from crops. A high dependence on forest/wood products was also noted among 48% of the respondents. Remittances especially from family members in major towns in Kenya were identified by 34% of the respondents as another source of income. Other sources of income included formal employment as teachers or civil servants as well as revenue from businesses established in nearby markets.

Table 8.8 Source of household income in Kabras Division, western Kenya

Source of income	No. of respondents (N = 126)	Proportion (%)*
Sale of crop products	124	98.4
Sale of livestock products	117	92.9
Remittances	43	34.1
Forest/wood products	61	48.4
Off-farm employment	56	44.4
Business	41	32.5
Fishing	7	5.6

**Totals more than 100% due to multiple responses*

8.3.2 Perception of changes in land productivity

Table 8.9 summarizes the perception of the households on the status of the different resources in the study area. There was a general consensus that the productivity of the different resources had decreased. Natural forests and croplands were scored as the most degraded resources. Those that observed declined productivity cited historical changes in crop yields, production per unit area, poor health (vigor) and leaf color as indicators. Due to the close linkage between crop performance and soil quality, some respondents cited soil color and indicator weeds to justify their observations. Decline in productivity of livestock was singled out by 68% of the respondents. As for the forests, 94% and 58% of the residents indicated that natural and planted forests, respectively, had declined.

Fifty seven percent (57%) of the respondents reported that the quantity of the water had declined. They cited the amount of water in the rivers, seasonality of the springs, changes in rainfall patterns, distances to water collection points, and depth of water wells as indicators of changes in water quantity. The water scarcity was most prevalent during the dry months of December to March.

Table 8.9 Perceived changes in resource productivity in Kabras Division, Western Kenya (N = 126)

	Crop productivity	Livestock productivity	Natural forests	Planted forests	Water quantity	Water quality
Improved/increased	14.3	24.2	4.9	36.3	12.7	27.8
Declined/decreased	79.4	68.3	94.3	58.1	57.1	44.4
No change	6.3	7.5	0.8	5.6	30.2	27.8
Total	100.0	100.0	100.0	100.0	100.0	100.0

8.3.3 Types of land degradation

The respondents scored the severity of different types of soil degradation as summarized in Tables 8.10. Between 62% and 73% of the respondents scored sheet, gully and river bank erosion as severe. Landslides and wind erosion were scored as light. In terms of chemical soil degradation, 81%, 70% and 60% of the respondents scored soil fertility decline, soil organic matter decline and soil acidity, respectively as moderate-severe. Forty-six percent of the respondents reported that reduced vegetation cover was severe, 22% moderate, 16% light and 15% none. The majority (64%) of the respondents scored habitat loss as severe while 38% scored species diversity loss as severe.

Table 8.10 Perception of severity of soil degradation in Kabras division, western Kenya

Degradation type	Severity of degradation				Total
	None	Light	Moderate	Strong/severe	
Soil erosion					
Riverbank erosion	7.3	19.4	23.4	50.0	100
Sheet erosion	8.9	13.7	38.7	38.7	100
Gully erosion	16.9	21.0	25.8	36.3	100
Wind erosion	45.1	15.6	18.0	21.3	100
Landslides	87.7	4.1	4.1	4.1	100
Soil chemical erosion					
Soil organic matter decline	7.3	17.7	27.4	47.6	100
Soil acidity	17.4	22.3	16.5	43.8	100
Soil fertility decline	5.6	13.7	42.7	37.9	100
Soil biological degradation					
Habitat loss	6.5	14.5	15.3	63.7	100
Reduced vegetation cover	15.3	16.1	22.6	46	100
Species diversity loss	8.9	22.8	30.1	38.2	100

8.3.4 Causes of degradation

Direct and indirect causes of land degradation

In terms of the direct causes of land degradation, poor soil and crop management and deforestation were ranked first, while natural causes were ranked second (Table 8.11). Overgrazing was ranked lower than these three since most households had few livestock. On the other hand, high population pressure was ranked as the main indirect cause of land degradation. This was followed by poverty and lack of awareness. Access to agricultural inputs, infrastructure, governance and land tenure were considered to contribute less to land degradation.

Table 8.11 Perception of direct and indirect causes of land degradation in Kabras Division, western Kenya

Causes of land degradation	Frequency	Percentage (%)
Direct causes		
Poor soil and crop management	92	73
Deforestation	92	73
Natural causes	82	65.1
Overgrazing	54	42.9
Industry and mining	26	20.6
Urbanization	23	18.3
Indirect causes		
High population pressure	96	76.2
Poverty	75	59.5
Lack of awareness	65	51.6
Weak land tenure system	46	36.5
Poor infrastructure	34	27
Poor governance	32	25.4
Lack of inputs	27	21.4

NB: Values more than 100% due to multiple responses

8.3.5 Vulnerability of the household to impacts of land degradation

The vulnerability of the households to impacts of land degradation was assessed by determining the number of months the household lacked a particular resource (Table 8.12). Seventy nine percent (79%) of the households experienced frequent crop failure. The food-deficit periods ranged from 0-12 months per year with an average of 5.1 months. An estimated 43% of the households reported experiencing chronic food shortages lasting more than 5 months in a year (Table 8.13). Households that suffered food deficits adapted by purchasing from the markets, through reliance on neighbors and government support, off-farm employment to earn income, change the eating patterns, diversification of crops grown with focus on drought-resistant varieties, sale of tree products, and loans and credit from neighbors.

Table 8.12 Scarcity of major resources at household level in Kabras Division, western Kenya

Resource	Scarcity months			
	Min.	Max.	Mean	Std. Dev
Food	0	12	5.10	2.35
Water	0	8	1.78	1.99
Grazing/pastures	0	7	3.13	1.86

Table 8.13 Food insecurity at household level in Kabras Division, western Kenya

Food deficit duration	No. of respondents	Percentage (%)
None	7	5.6
Mild (<0-2 months)	10	7.9
Moderate (2-5 months)	55	43.7
Chronic (>5 months)	54	42.9
Total	126	100.0

On average, the household experienced 1.8 months of water scarcity, especially during the driest months (December to March) (Table 8.12). To overcome this, the household members travelled long distances to available water points, queued for long hours at existing points, used unsafe water directly from the rivers, and extended the boreholes to access deeper groundwater. Others resorted to rainwater harvesting and storage techniques.

The households experienced scarcity of pastures for an average of 3.1 months per year (Table 8.12). During this time of scarcity, the household used unconventional feed types such as sugarcane leaves and banana stocks, travelled long distances to access pastures along the river banks, purchased fodder (Napier grass) from neighbors, or sold part of the livestock.

Only 38% of the households were self-sufficient in energy supply. To address the energy deficiency, the households were forced to walk long distances to look for fuel wood from the nearby forests, others bought split fuel wood from the markets or used low quality crop residues (dried sugarcane), while some resorted to using dried animal waste. Some households also planted their own woodlots for fuel wood.

8.3.6 Soil and water management technologies

The survey indicated that 55% of the farms lacked any form of soil and water conservation (SWC) technologies. Where present, famers used either structural and/or vegetative SWC techniques. The most common SWC technologies were cut-off drains and drainage trenches, terraces planted with fodder species such as Napier grass, contour ploughing, use of stone bounds and trash lines, and tree planting. Farmers used manure, inorganic fertilizer and compost to address the problem of declining soil fertility. Agricultural lime was used to address the problem of soil acidity.

Of the respondents, 28% indicated that access to agricultural extension services was good, while 72% indicated that it was moderate to poor (Table 8.14). The majority of the households got information on sustainable land management mainly through the electronic media, mainly the radio. Other sources included farmer field days conducted by the Ministry of Agriculture and the Kenya Agriculture Research Institute (KARI) staff, learned from other farmers, attended agricultural shows and from reading newspapers.

Table 8.14 Access to agricultural extension services in Kabras Division, western Kenya

Access level	Frequency	Percent (%)
Good	30	27.5
Medium	40	36.7
Poor	39	35.8
Total	109	100.0

8.4 Discussion

8.4.1 Implication of household characteristics on land degradation

The population structure in western Kenya is dominated by a youthful population aged between 20 and 50 years with an average age of 49 years. The average household size (6.9 members) observed in this study was similar to the average of 6 members observed for this region (WAC 2002; Chianu et al. 2008). Such a population means that labor for agriculture may not be a major problem.

As in most places in Africa, there was a noticeable variation in land holding size in the study area. The land holding in Kabras Division ranged from 0.2 ha to 32.8

ha (average 3 ha). The average land size reported in this study is relatively higher than the regional average of about 1 ha (De Wolf et al. 2000; Place et al. 2006). Kabras Division with a density of 424 km^2 is considered moderately populated compared to the other divisions of the western Kenya region (Republic of Kenya 2005b). For example, divisions in Vihiga District are considered the most densely populated with 886 persons per square km and an average land size of 0.5 ha per household (Kristjanson et al. 2004). The study found out that land tenure in the study area is considered to be secure hence could be an incentive for long-term investment in sustainable land management (SLM) (Scherr and Yadav 1996). Neef (2001) argues that the willingness to invest in long-term soil and water conservation practices such as terracing and tree planting is significantly higher on operated-owner fields than on leased, borrowed, or pledged fields with only medium- or short-term user rights.

The literacy level was high with only 3% of the respondents having no formal education. Place et al. (2006), in a study in the Vihiga and Siaya regions reported that 20% of the land users had no education, 24% had lower primary education, 40% had upper primary education and 17% had secondary education. The high literacy levels mean that understanding of the land degradation problem and of the interventions to avert land degradation should not be a challenge.

Mobility is an important aspect in rural areas as it affects ability of the households to travel to markets to access inputs and output markets. Kabras Division is a rural area, and bicycles and motor bikes are a common means of transport. Chianu et al., (2008) observed that 86% of the households owned a bicycle. Farmers use these means of transport to move fertilizer and seed to the farms and the produce to the market. These are also used as an alternative source of employment for the youth who offer transport services to the residents. However, a shift towards ‘boda boda’ transport means that labor previously used in agriculture is diverted, since the most energetic youth prefer to serve as transporters than to work on the farms.

A significantly high proportion of households owned a radio or a mobile phone. These results are in conformity with a survey conducted by the InterMedia Survey Institute, which reported that 71% of Kenyans possessed a mobile phone, while

87% owned a radio (InterMedia Survey Institute 2010). The use of mobile phones has been promoted by the mobile banking facilities where farmers can send and receive cash using their phones. Radio, television and mobile phones are important technologies for information access and communication. Knowledge on sustainable land management could be channeled through these modes of information dissemination (Sanginga and Woomer 2009; Adolwa et al. 2010; Masuki et al. 2011).

The level of mechanization in most rural areas was low with most farmers using hand-held tools such as hoes and machetes. This results in drudgery and limits the amount of land that can be prepared for crop production. An average a farmer can only prepare 200 m^2 of land per day using a hand hoe (Sanginga and Woomer 2009). Farmers with ox-plough can prepare larger areas of land much faster and better compared to the households that rely on the use of hand hoes. The proportion of households with ox-ploughs (48%) in Kabras Division was higher than the 21% reported by Chianu et al. (2008) for Siaya and Vihiga. The difference between these two studies could be attributed to the size of the land holding with farmers in Kabras Division having fairly large parcels of land compared to those in Vihiga.

High crop diversity is a common feature of many smallholder farms in SSA. This study documented over 15 different crops grown across the farms in the study area. However, maize or maize–bean intercrops were the most dominant due to their significance for household food security. On the other hand, sugarcane was the most dominant cash crop. Crop diversity is a safety net measure to maximize on the resources (water, nutrients, labor), as an insurance against adverse weather conditions and to ensure food availability throughout the year. Crop diversity is also a soil fertility and pest management strategy, e.g., when legume crops are integrated or rotated in the system.

Out of the total land size of 267 ha owned by the respondents in this study area, 177.8 ha (66%) were under cash crop production, i.e., a ratio of 2:1. The shift towards sugarcane production has also been precipitated by the availability of sugar processing factories in the area, perceived higher returns from sugarcane as a cash crop, high cost and scarcity of fertilizer and improved seed for food and especially maize production, low output prices of cereals, low and declining cereal productivity and soil acidity (Kennedy 1989; Thuo 2011). Although large areas are taken out of food production, the extra revenue from the cash crops can supplement household income and be used to purchase basic food from the markets and meet other household needs such as medication and schooling. The main challenge, however, is how to bridge the lack of revenue occasioned by the long waiting time between planting the sugarcane and harvesting, usually 2-3 years.

The survey showed that 90% of the households owned livestock, with cattle and poultry as the most dominant types. In a study in Siaya and Vihiga of western Kenya, Wangila et al. (1999) observed that 4% of the farms had improved cattle, 53% had local cattle, 17% had sheep and goats and 72% had chicken. The proportion of livestock in this region is small, most likely because of livestock diseases, lack of veterinary services, and shortage of browse caused by land scarcity (Place et al. 2006). Herd sizes are also difficult to increase or maintain because livestock plays a key role in the local cultural obligations such as initiation, marriage and funerals. Type of livestock, size of the herd and mode of feeding affect the quantity and quality of manure available at farm level for soil fertility management. As a result of the small herd size comprising mainly of local zebu breeds, the quantity of manure supplied is low. Within open livestock grazing systems there is no direct cycling of manure to croplands, as most manure is left on the grazing sites (Delve and Ramisch 2006). However, substantial quantity of manure is readily available for collection from the overnight livestock holding areas (boma).

Statistics show that SSA has the lowest fertilizer use rates (less than 10 kg N/ha) compared to other regions of the world (Kelly 2006). Despite this, pockets of moderate to high fertilizer use have been reported in areas with good market access such as central and western Kenya (Palm et al. 1997; MSU 1999). This confirms the relatively high proportion (95%) of the households using inorganic fertilizers in Kabras Division. However, as in many other smallholder systems in SSA, most of the farmers interviewed used fertilizer but at quantities much lower than the recommended application rates (Ruigu and Schulter 1990; Heisey and Mwangi 1996). Studies attribute this pattern to factors such as availability of cash and access to credit, and access to input and output markets (Makokha 2001; Waithaka et al. 2007). The low use of fertilizer was supplemented by the use of farm yard manure collected from the open night sheds/kraals and applied to the farm with or without processing. Studies have shown that manure use is widespread in areas where cattle are a component of the mixed cropping systems (Lekasi et al. 2003; Waithaka et al. 2007). However, the actual quantity of manure used was low and the quality was poor due to poor animal feed, high proportion of sand in manure, and poor handling, which all result in nutrient losses through leaching and volatilization (Lekasi et al. 2003; Waithaka et al. 2007).

A sizeable proportion of respondents identified soil acidity as a major land degradation problem affecting crop production. As discussed in Section 6.4/Chapter 6 soil acidity is a major problem in western Kenya. Despite the magnitude of the problem, strategies to address soil acidity for example the use of agricultural lime have been minimal due to general lack of information regarding the efficacy of lime in agriculture, a scarcity of proper soil sampling to ascertain the pH of the soil, and the perceived difficulty in sourcing and obtaining quality agricultural lime (Kabambe et al. 2012). However, initiatives to promote the use of lime are being made through extensive research to determine recommendation rates, through raising awareness of farmers regarding the problem, and by making the lime available by supporting agrodealers (Mbakaya et al. 2010).

8.4.2 Perception of land degradation

The land users in the study area understood the effects of land degradation, although they did not describe this problem using scientific terms but used local indicators of reduction in land productivity. They attributed land degradation mainly to the reduction in crop productivity and scarcity of key resources such as fuel wood and pastures. The use of crop productivity as a proxy of land degradation has been cited by several authors (Mairura et al. 2007; Odendo et al. 2011). In a study in Siaya and Vihiga in western Kenya, the farmers cited decline in crop yields, poor crop growth vigor and general crop health as indicators of declining soil fertility (Odendo et al. 2011). In addition to crop productivity, other studies have identified abundance and types of weeds and soil color as local indicators of soil fertility decline (Barrios and Trejo 2003; Mairura et al. 2007).

A decline in the productivity of livestock was observed by 68% of the respondents. Indicators included reduction in herd sizes, scarcity of animal feed, poor quality of grazing lands, and reduction in area and range of grazing. As a result of feed scarcity, farmers were forced to feed the livestock with unconventional feed types such as dry sugarcane leaves and banana stocks. Other farmers had resorted to purchasing Napier grass feed from neighbors (Nandasaba et al. 2008).

People living close to forests depend on the forest for a wide range of products, among them firewood, thatch grass, medicinal plants and pasture (Guthiga and Mburu 2006). It is estimated that about 3 million people live adjacent to and depend on forests for their livelihoods (KIFCON 1994; Mogaka et al. 2001). Wood provides about 73% in rural areas and 93% in urban areas of total energy consumption, mainly as fuel wood for cooking and heating (Government of Kenya 1997; Mwaniki 2000; Mahiri and Howorth 2001). With the increasing human population and scarcity of land, the pressure on forests has grown resulting in increased incidences of illegal logging, cultivation, charcoal burning in the forest, practices that have contributed to the degradation of the forest resources (Mathu 2007).

Although the western Kenya region receives high rainfall, residents in the study area reported changes in water quality and quantity, which could be attributed to impacts of land degradation. Mismanagement of land degrades water quality and reduces water productivity (Molden et al. 2003). Intensified land use in upper catchments results in increased sediment discharge and elevated nutrient loads, which reduces water quality and availability downstream (Githaiga et al. 2003). Water quantity changes can be seasonal or temporal and tend to follow the rainfall pattern. This explains why water scarcity was a major concern especially during the drier months of December to March. Although viewed as a natural pattern, the severity of the water scarcity in the drylands could be attributed to the land-use changes taking place in the region.

8.4.3 Direct causes of land degradation

Poor soil and crop management and deforestation were jointly ranked as the main direct causes of land degradation while natural causes were ranked second. Overgrazing was rated lower since most households had few livestock. Poor soil and crop management is a manifestation of high rates of soil erosion and low and declining soil fertility at farm level. Soil erosion across many parts of the country is estimated to be above the permissible amounts (10 tons/ha/year) with some regions recording losses of up to 32 tons/ha/year (Ongwenyi et al. 1993). Kenya is classified among the countries with the highest soil nutrient losses (>60 kg NPK/ha/yr) in Africa (Stoorvogel and Smaling 1990). The losses are even higher when considered at a meso-scale level (Smaling et al. 1993). These negative nutrient budgets result from high nutrient losses due to soil erosion and losses through crop harvest. The losses cannot be compensated by the natural processes of land regeneration, since the fallow periods have been shortened or completely abandoned. As discussed earlier, the use of external inputs (fertilizer and manure) is low. Integrated strategies are therefore needed to address the causes of nutrient decline while empowering the households to adopt sustainable land management strategies.

Deforestation was ranked highly as a direct cause of land degradation in the study area. The region has two small forest fragments, Kisere (400 ha) and Malava (100 ha), which are detached from each other and from the larger Kakamega forest (Brooks et al. 1999). As discussed in Chapter 5, there has been a significant reduction in area under forests in western Kenya. This has led to fragmentation of the forests into numerous smaller patches, among them Malava and Kisere forests located in the study area. Such small and isolated forest patches are at greater threat of deforestation than larger forests (Broadbent et al. 2008), since fragmentation increases the proportion of the remaining forest located in close proximity to the forest edge (Saunders et al. 1991). In two separate studies of forests in western Kenya, Lung and Schaab (2006) and Mutangah (1996) reported that the edge effect for forests extended at least 100 m and 500 m, respectively. Elsewhere, studies report that the effect can extend up to 1 km (Murcia 1995), or even 5–10 km (Curran et al. 1999) depending on the forest size and the intensity of use by the adjacent communities. A walk through the Malava and Kisere forests revealed extensive patterns of indiscriminate logging, grazing, debarking and clearing.

The role of natural factors as a driver of land degradation was captured by 65% of the respondents. They singled out changes in rainfall patterns and intensity, increased incidence of droughts and landslides as some of the natural events observed in the area. Whereas it was not possible to directly quantify the impacts of the natural phenomena on land degradation, a review of meteorological data showed evidence of extreme climatic conditions over the past years. The country experienced severe weather phenomena as evident from the El Niño (1997/98) that brought anomalously wet weather, with extreme flooding; and the La Niña (1999/2000), that was evidenced by unusually dry conditions (SEI 2009). Incidences of landslides have been reported in the study area with the major one occurring at Kubasali in Kabras Division in 2007 (Achoka and Maiyo 2008). Landslides cause mass movement of soil resulting in alteration of the landscape (Knapen et al. 2006). Whereas landslides are a natural phenomenon, human activities such as construction, cultivation, deforestation and excavation in steeplands decrease the margin of hillslope stability thus creating favorable conditions for mass soil movement during the rainy seasons (Knapen et al. 2006).

8.4.4 Indirect causes of land degradation

High population pressure was ranked as the main indirect cause of land degradation followed by poverty and lack of awareness. In 1969, Kenya's population was only 10.9 million people, but by 2009 – 40 years later – the population had soared to 39.4 million (KNBS and ICF Macro 2010). The bulk of Kenya's population (80%) is concentrated on the arable land, which is about 20% of the country's area. Most of this 'high potential' land is located in central, coastal and western Kenya and the central Rift Valley. An extensive review of the relationship between population and land degradation is presented in the UN Population report (http://www.un.org/popin/fao/land/land.html). It is worth noting that, population per se may not be the cause of the degradation but rather the land-use activities or practices adopted by that population. (Tiffen et al. 1994) observed that high population can be an incentive for soil and water conservation. An increasing human population, however, results in the shrinking of the farm sizes. Without expansion areas, the intensity of land use is increased leading to depletion of nutrients. A large population means higher demand for fuel wood and land for cultivation and settlement, and these impacts on forests and water leading to the degradation of these resources.

Sixty percent of the households interviewed attributed the land degradation to high levels of poverty. The Welfare Monitoring Survey II conducted in 1997, found that 58% of the population in the Kakamega District were living below the poverty line (Republic of Kenya 2005b). Resource-poor farmers cannot afford the use of agricultural inputs to replenish the nutrients lost from the farm. Equally, the households lack sufficient labor to invest in soil and water conservation. Pressures leading to land degradation are stronger in cases of social inequality. Studies have shown that poor landowners tend to be pushed to marginal areas such as those with low soil fertility, steep slopes and dryland areas (Kelley 1983). Over time, these fragile areas become overexploited as their occupants cannot afford to invest in sustainable management practices.

Lack of awareness of the problem of land degradation and how to address its impacts was singled out by 52% of the respondents as an indirect cause of land degradation. The respondents were able to easily recognize and identify indicators of soil erosion, nutrient decline and deforestation, although they did not describe these in the terms used by scientists. Okoba (2005) in a study in central Kenya observed that farmers were aware of soil erosion processes, which they defined as “carrying away of soil or removal of top-soil by water”. The older members of households, having had long-term interaction with their environment, were able to compare past and current production trends when describing the patterns of land degradation. Other respondents were aware of the problem of land degradation through interaction with neighbors and agricultural researchers and extension staff, listening to radio and television and reading books and newspapers. Awareness or recognition of any land degradation problem is an important component in the adoption process of any sustainable land management practice (De Graaff et al. 2008). These authors observed that there are several reasons why land users may not be aware of the land degradation problems. First, most land degradation problems develops gradually and only become apparent in the long run. Farmers may not recognize the symptoms of degradation if they do not visit their land regularly or when symptoms appear very slowly and/or are masked by climatic fluctuations. Second, even if the farmers were able to take notice of the symptoms, they may not know the effects of the degradation type due either to a lack of education and/or to traditional beliefs. Third, even if the land users know the effects they may not consider it serious enough for action.

8.4.5 Vulnerability and adapting to land degradation

Adapting to shock and stress is one dimension of rural livelihoods. As discussed in previous sections, land degradation and the associated effects enhance the vulnerability of rural households to food, pasture and fuel wood deficits. The high proportion of households (42.9%) in the study area that experienced chronic (> 5 months) food deficits compares to observations by Kassie et al., (2012) in a comparative study on food security across genders for western and eastern Kenya. These authors reported that 47% of the male-headed households (MHHs) were food insecure compared to 58% of the female-headed households (FHHs). This study further noted that of the food-insecure proportion, 11% FHHs and 5% of MHHs suffered from chronic food insecurity.

Only about 60% of the Kenyan population can be said to be food secure (Republic of Kenya 2008). The food and nutrition insecurity situation can further be linked to the poverty levels in the country. About 50% the Kenyan population falls below the poverty line (Republic of Kenya 2008), and growth of agricultural production has not kept pace with the rapidly growing population. In addition, the country has over the last decades experienced several episodes of food deficits, so that per capita food availability has declined by more than 10% over the last three decades (Republic of Kenya 2008).

As discussed earlier, fuel wood is the main source of energy for rural households (Mahiri and Howorth 2001). But the majority (62%) of the respondents lacked sufficient energy, especially fuel wood for cooking. Lack of trees on the farms was forcing people to rely on the forests or to buy fuel wood from the markets. Most of the rural households cannot afford to buy fuel wood. Due to limited options, most of households had resorted to low-calorie energy sources such as dried sugarcane, maize stocks and dried animal waste (Guthiga 2007; Sikei et al. 2009). The use of such organic materials for energy reduces the amount of crop residues recycled back to the farm thereby affecting soil fertility maintenance. Some households had resorted to the use of energy saving cooking stoves. Tree planting at farm level was also being adopted as a long-term investment aimed at overcoming the fuel wood deficits.

8.5 Conclusions

This assessment provided information on how land users perceived the problem of land degradation. Considering the complexity of land degradation, it was not possible to assign one measure for the problem; rather land users understood the problem by disaggregating it into observable change indicators of the various resources. The study area, like many similar smallholder systems in SSA, is highly heterogeneous and this could be the reason for the varied responses on the extent and causes of land degradation. There was a general consensus that the productivity of the various resources (land, livestock, forests, water) had declined. Declining crop productivity, scarcity of fuel wood and pasture were identified as the main indicators of land degradation. Soil erosion (sheet, gully and river bank), soil fertility decline, soil organic matter decline, soil acidity and forest habitat loss were identified as the most prevalent types of land degradation. Poor soil and crop management, deforestation and natural causes were ranked highest as the main direct causes of land degradation, while high population pressure, poverty and lack of awareness were identified as the main indirect causes. The study also highlighted some of the adaptation mechanisms to mitigate the impacts of land degradation.

The results of this study to a great extent complement the observations made in the other parallel assessments using remote sensing, field observations and soil sampling, and form a platform for consensus building especially when designing any sustainable land-use strategies. As observed by Blaikie and Brookfield (1987), land degradation is the result of many factors some outside human control and that it is futile to search for a uni-causal model of explanation considering the variability of conditions at local level and the complexity of the interactions among various socio-economic and biophysical factors. Effective intervention to address the problem of land degradation will therefore require the adoption of the concept of "chain of explanation" (Blaikie and Brookfield 1987), which calls for understanding the role of land managers and their direct relations with the land, understanding the linkages and interactions among the land users, the land and the wider society, and how this is driven by the external market and economic factors.

9 SYNTHESIS AND CONCLUSION

9.1 Introduction

The overall objective of this study was to assess patterns of land degradation in Kenya as basis for making recommendations for sustainable land management. Four specific objectives were pursued: 1) mapping patterns and quantifying extent of land degradation, 2) assessing long-term land-use/land-cover changes, 3) evaluating causes of the observed land degradation patterns, and 4) assessing the impacts of land degradation as basis for enhancing awareness and capacity of stakeholders for restoration and rehabilitation. This final chapter synthesizes the key lessons learnt and their implications for research and policy.

9.2 Major findings

9.2.1 Mapping land degradation patterns

In pursuant of the objectives 1 and 3, the study assessed the patterns of land degradation at a national scale (Chapter 4) using the MODIS normalized difference vegetation index (NDVI) and long-term rainfall data. The relationship between vegetation as depicted by the NDVI and mean annual precipitation (MAP) dynamics was computed using Pearson's correlation coefficient; linear regression was performed to determine the magnitude of change of the NDVI over time (inter-annual change). The assessment revealed clear patterns of vegetation changes across the different agro-ecological zones across the country, suggesting that there are various drivers of degradation or improvements in these regions. Correlation between NDVI and MAP at national and regional levels revealed that areas around Lake Turkana and the eastern districts showed the greatest risk of degradation. Positive and significant changes in the NDVI slope were observed for some selected locations such as Wajir and Baringo, which are located in the dryland areas showing that the vegetation cover was increasing over the years. Image differencing between the baseline (2000-2003) and the endline (2007-2009) showed that 21% of the land was experiencing significant decrease in the vegetation cover, 12% an increase, while the remaining 67% was stable. A review of literature singled out declining soil fertility, soil erosion, deforestation and overgrazing as some of the contributors to the declining aboveground biomass. Positive and significant changes in the NDVI slope were observed for locations such as Wajir and Baringo despite the fact that these areas are located in the dryland areas. It could be seen that the vegetation cover was increasing over the years, implying a 'greening' of the drylands. These arid lands are inhabited by plant species adapted to the harsh climatic conditions, poor soil fertility, and grazing pressure. Such plants are also able to recover rapidly when conditions become favorable. The greening could also be attributed to the government-initiated soil and water conservation programs in the early 1960s. Not all greening of the drylands is desirable, which is evident from the case of the invasive shrub *Prosopis juliflora* in Baringo and other parts of the country. Although the assessment revealed visual patterns of long-term vegetation changes, the assessment using NDVI was not able to isolate the actual causes of degradation or improvements. This means that there is need to complement NDVI change assessments with actual field observations at identified spots of interest.

9.2.2 Land-use- land-cover changes

The second objective focused on assessing long-term land-use/land-cover change (LULC) in the study area. LULC change is an important starting point for any land degradation assessment efforts. The study employed the use of time-series Landsat images for the period 1973, 1988 and 2003 (Chapter 5). Land-cover classes were derived by classifying the NDVI values calculated for each assessment period. Supervised and unsupervised classification was also used to classify the images into broad LULC classes. Both approaches enabled understanding the changes taking place in the study area. This being a rural district, the assessment showed that the area under agricultural production increased from 28% in 1973, to 51% in 1988 and to 70% in 2003. The area under natural forests decreased from 3.9% to 3.4% from 1973 to 2003. The LULC changes can be closely linked to the growing human population in the study area. The population in the study area increased by a factor of 3.3 between 1963 and 2009. With such an increase, the demand for food, feed and energy also increased thus putting more pressure on the existing land resource. LULC changes can have negative impacts on the capacity of the environment to provide ecosystem goods and services.

9.2.3 Evaluating indicators of land degradation

The study evaluated indicators of land degradation at selected sites in western Kenya (Chapter 6). The attributes and indicators of land degradation were quantified either qualitatively or quantitatively. The indicators were grouped into three broad categories: soil and site stability, hydrologic function and biotic integrity. The most prevalent visual indicators of land degradation included proportion of bare ground, dominant vegetation structure, presence of pedestals, presence of rills and gullies, soil surface loss, and indicator plant species. The study area had sparse wood cover but high herbaceous cover, and over 70% of the land was under crop cultivation. Over 55% of the farms sampled lacked any form of soil and water conservation technologies. Sheet erosion was the most dominant form of soil loss, and was observed in over 70% of the farms. Over 55% of the farms had soil-organic carbon below 2%. About 94% of the farms in Malava district showed very strongly acidic pH values (pH 4.5-5.5), while 6% of the farms had moderately acidic (pH 5.6-6.0) soils. Principal component analysis (PCA) identified three main explanatory factors for soil variability in the study area: ‘soil fertility potential’ explained by PC1 (TOC, TON, pH, CEC, K, Ca, Mg, and silt), ‘soil physical properties’ by PC2 (sand and clay) and ‘available P’ by PC3 (available P). These results point to the need for an integrated approach to soil fertility management that aims at increasing the capacity of the soil to supply the required nutrients as well as at increasing the soil-organic matter pool.

Crop productivity is considered a key indicator of the status of the land in the study area. The study estimated the nutrient supply, nutrient uptake and productivity potential of the soils in the croplands using QUEFTS (Chapter 7). This assessment revealed that most of the soil chemical properties were below the documented thresholds needed to support high production of the staple crop maize. Based on soil carbon, the soil fertility on the farms was classified as high, moderate or low. These three fertility classes exhibited distinct soil properties: The farms classified as high fertility (HF) showed favorable levels of soil chemical properties and highest crop yield potential compared to those classified as moderate (MF) and low fertility (LF). Without fertilization and assuming that no other constraints to crop production existed, the potential production across the low to high fertility classes was between 1,628 kg/ha and 2,835 kg/ha. However, production in these farms averages only 1 t/ha. This could be due to yield-reducing constraints such as soil-micronutrient deficiency, poor agronomic practices, poor quality seed and unpredictable rainfall.

9.2.4 Implications of land degradation on land users

The results of the survey on how land users perceived the problem of land degradation and how this was impacting on the livelihoods (Objective 4) are presented in Chapter 8. Despite the complexity of the land degradation problem, there was a general consensus that the productivity of the various resources (land, livestock, forests, water) had declined. The respondents reported decline in crop productivity and scarcity of fuel wood and pasture as the main indicators of land degradation in the study area. Soil erosion (sheet, gully and river bank), soil fertility decline, soil organic matter decline, soil acidity and forest habitat loss were identified as the most prevalent types of degradation. Poor soil and crop management, deforestation and natural causes were ranked highest as the main direct causes of land degradation, while high population pressure, poverty and lack of awareness were identified as the main indirect causes of land degradation. The results of the survey complement the outcomes of the biophysical assessment.

9.3 Research and policy implications

The study area has undergone significant LULC changes some of which have resulted in negative impacts on the capacity of the land to provide ecosystem goods and services. The threat of agricultural expansion and demand for fuel wood and pasture on forests and other natural vegetation is immense. There is a need to promote intensification of production on existing land holdings to minimize the increasing demand for virgin land. Strategies are needed to promote afforestation and to diversify energy sources to minimize the pressure on existing forests. Promotion of off-farm income generation activities can also help reduce overreliance on land.

The productivity of the soils in the study area is low due to the current low and declining soil fertility status. Improving plant nutrition and hence crop production will require systematic adoption of strategies that aim at achieving balanced plant nutrition by providing the key elements and at the same time at improving the capacity of the soil to store nutrients by increasing the soil organic matter content. This can be achieved through adoption of an integrated soil fertility management strategy. This process cannot be achieved within a short time but only gradually while taking into consideration the farmers' socio-economic status.

Land degradation is a complex process that requires a multi-pronged approach of assessment. There is no single most comprehensive approach to mapping patterns and quantifying extent of land degradation. However, combining methods and approaches enables capturing different insights on the problem of land degradation depending on the scale of assessment. The use of remote sensing and GIS techniques offers opportunities to better understand the spatial distribution of environmental phenomena. These approaches also enable integration of multiple biophysical and socio-economic datasets thereby enabling better understanding of interactions of factors driving environmental change. Direct field measurements based on georeferenced sampling strategies on the other hand offer the opportunity to identify and quantify the actual causes of land degradation and also for long-term monitoring of change. There is need to use multiple indicators and attributes, bridge scales, and link the degradation types to economic benefits so that land users can appreciate and be willing to invest in rehabilitation and restoration activities.

This study was limited to the humid region of western Kenya. The assessment at the national level revealed other areas that have experienced significant changes in vegetation. Such areas offer great opportunities for further research to confirm the causes of the changes. Such studies could also focus on the impact of climate change and how the communities are adapting to such changes.

On a global level, the ‘greening’ of the drylands can be seen as a positive development, but there is need to assess the impact of such vegetation change on the overall ecosystem health. The case of *Prosopis juliflora* in Baringo and other parts of the country is an excellent example of how a land management initiative can turn out to be an environmental disaster with a serious socio-economic impact on the people there.

This study provides a rapid estimate of the nutrient supply and crop productivity potential of the croplands based on the laboratory soil data. There is need to validate this information by comparing it with ongoing agronomic field trials in the region. Doing so will enable generation of a fertilizer recommendation tool kit for use by researchers and extension officers in the study area. This aspect of research and extension is currently ongoing with other partners working in the study area.

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APPENDICES

Appendix I: Theory behind the pixel-based application of inter-annual NDVI data

Adopted from Vlek et al. (2008)

1. Theory

Assuming *X* and *Y* have a stochastically linear relationship:

$$\gamma = AX + B + \varepsilon$$

where: *A*- slope, *B*- intercept, and *ε* – random error/disturbance

We thus define:

$$S_{xx} = \sum (X_i - X)^2$$

$$S_{yy} = \sum (Y_i - \bar{Y})^2$$

$$S_{xy} = \sum (X_i - \bar{X})(Y_i - \bar{Y})$$

Hence, the least square estimator for slope *A* and intercept *B* are:

Slope: $A_{Cal} = \frac{S_{xy}}{S_{xx}}$

Intercept: $B = \bar{Y} - A_{Cal}\, \bar{X}$

The coefficient of determination is given by:

$$R^2 = \frac{S_{xy}^2}{S_{xx} S_{yy}}$$

Suppose we want to test the hypothesis that the true value of *A* is zero:

***H0*: *A* = 0**

It follows that the test for significant of *A* is the ratio:

$$t_0 = \frac{A_{Cal}}{SE(a)}$$

where *SE*(*A*) is the standard error of the slope coefficient:

$$SE(A) = \sqrt{Var(A)} = \sqrt{Var(\varepsilon)/S_{xx}}$$

The variance of error *Var(ε)* can be unbiasely estimated by:

$$Var(\varepsilon) = \frac{RSS}{n-2} = \frac{S_{yy} - A_{Cal} S_{xy}}{n-2}$$

Thus, we have:

$$SE(A) = \sqrt{Var(\varepsilon)/S_{xx}} = \sqrt{\frac{S_{yy} - A_{Cal}S_{xy}}{(n-2)S_{xx}}}$$

Suppose $t\alpha$,df is the theoretical ratio (obeying t-distribution) at a confidence level 1-α and a degree of freedom *df* (known from *t*-table), we can reject or accept the hypothesis *H0* by comparing *t0* and $t\alpha$,df:

- If $|t0| \geq t\alpha$,df: The hypothesis *H0* is rejected. This means the calculated slope coefficient is significantly different from zero.

- If $|t0| < t\alpha$,df: The hypothesis *H0* is accepted. This means the calculated slope coefficient is not significantly different from zero.

2. Application of the pixel-based theory in land degradation assessment

Based on the above theory, the pixel-based application for inter-annual NDVI was applied to the dataset for the study area by specifying the parameters as below:

Let: *Xi* is considered year, *i* = 2000 to 2009

Yi is mean annual NDVI, *i* = 2000 to 2009

df = 10 – 2 = 8

For each pixel, the slope coefficient *(Acal)*, the standard error of the slope coefficient (*SE(A))* and the ration of these two *(t0 = Acal/SE(A))* were calculated. This yielded P-values which were checked against the t-test table for significance based on the argument below:

- If $|t0| \geq t_{0.25,8} = 0.706$ then the calculated *Acal* is significantly different from zero at the confident level of 75%
- If $|t0| \geq t_{0.1,8} = 1.397$ then the calculated *Acal* is significantly different from zero at the confident level of 90%
- If $|t0| \geq t_{0.05,8} = 1.860$ then the calculated *Acal* is significantly different from zero at the confident level of 95%

This computation was done using the raster calculator in Spatial Analyst- an extension of ArcGIS 9.3.1

Appendix II: Pixel-based test of hypothesis concerning correlation coefficient

Adopted from Vlek et al. (2008)

1. Theory

The correlation between *X* and *Y* can be measured by the Pearson's coefficient *Rxy*

$$R_{xy} = \frac{\sum(X_i - \bar{\bar{X}})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}}$$

Suppose we want to test the hypothesis that the correlation of *X* and *Y* (*Rxy*) is zero:

***H0*: *Rxy* = 0**

We can use Fisher's transformation from *Rxy* to *Z* value that obeys normal distribution:

$$Z = \frac{1}{2}\ln(\frac{1 + R_{xy}}{1 - R_{xy}})$$

The standard error of *Z* can be approximated to:

$$SE(Z) = \frac{1}{\sqrt{n-3}}$$

It follows that the test of hypothesis *H0* is the ratio

$$t_0 = Z/SE(Z)$$

which has a *t*-distribution with *df* = *n*-2. Suppose *tα,df* is the theoretical ration (obeying t distribution) at a confident level 1-*α* and the degree of freedom *df*, we can reject or accept hypothesis *H0* by comparing *t0* and *tα,df* :

- If |*t0*|≥ *tα,df* : hypothesis *H0* is rejected. This means the correlation coefficient is significantly different from zero.
- If |*t0*|< *tα,df* : hypothesis *H0* is accepted. This means the correlation coefficient is not significantly different from zero.

2. Application of the pixel-based test of hypothesis concerning correlation coefficient theory in land degradation assessment

The above theory was applied to the dataset for the study area by specifying the parameters as below:

Let: *Xi* is the mean annual precipitation (MAP), *i* = 2000 to 2009

Yi is mean annual NDVI, *i* = 2000 to 2009

df = 10 – 2 = 8

For each pixel:

- Calculating *Z*, *SE*(*Z*) and the ratio *t0* = *Z* / *SE*(*Z*)
- If |*t0*|≥ *t0.25,8* = 0.706 then the calculated *Rxy* is significantly different from zero at the confident level of 75%.

- If $|t0| \geq t0.1,8$ = 1.397 than the calculated *Rxy* is significantly different from zero at the confident level of 90%.
- If $|t0| \geq t0.05,8$ = 1.860 then the calculated *Rxy* is significantly different from zero at the confident level of 95%.

This computation was done using the raster calculator in Spatial Analyst- an extension of ArcGIS 9.3.1

Appendix III: Field observation data sheet

Site Name/Block: ………………………………………………………… Site Number: ………………………………………………….

Latitude: …………………………… Longitude: ………………………… Altitude: …………………….

District: …………………………… Location: …………………………… Village: ……………………….

Name of Farmer: ……………………………………………………………………………….

Date sampled: ……………………………………………………………………………………

Sampled by: ……………………………………………………………………………………..

Number of samples taken: ………………………………………………………………..

Sampling method: ……………………………………………………………………………….

Average slope: …………………………………………… Slope length: ……………………………

Vegetation/land use at time of sampling:

………
……

Land use history:

………
……

Maximum depth of cultivation:

Major erosion events SINCE 1954:

Water: - ………..

Wind: - ………

Site conditions at time of sampling:

Percent ground cover: - ……………………………………………………………………………………………………

Presence of erosion features: - ……………………………………………………………………………………………….

- Relocated sediment ☐
- Rock pedestals ☐
- Exposed vegetation roots ☐
- Surface soil textural changes (crusting) ☐
- Surface water flow indicators ☐
- Vegetation mounding ☐

Presence of soil conservation features

Indicator vegetation ……………………………………………………………………………………………………

…….

Other features: - ………..

Appendix IV: Livelihoods assessment questionnaire

Household livelihoods interview

Objectives
The socio-economic (livelihoods) component aims to deliver an understanding of how socio-economic, cultural and institutional factors influence land-users' views and management of their land resources. These factors can enhance or constrain their ability to practice sustainable land management, land degradation control or rehabilitation.

Participants
Household head on his/her own or with other household members (depending on who is around/available).

Questionnaire No: ………………..

Enumeration Details
Date: ………………………….. Time: …………………
Name of enumerator: ……………………………..…………

Farm Identification

District: ………………………… Division: …………………………
Location: ………………………… Village: …………………………

Respondent Identification
Name of head of Household: ……………………………………………………………….………
Gender: Male: ☐ Female: ☐
Occupation:………………………… Age (years): …………………………………………………

Contacts (Mobile/email): ……………………………………………………..………………………

1. **Human capital and household composition**

1.1 Composition of household members

Composition of family members	Number
Total HH Size	
Adult Males (>15 years)	
Adult Females (>15 years)	
Children (<15 yrs)	
Others, e.g. migrants	

1.2 Educational level of household head
Primary ☐ Secondary ☐ Tertiary ☐

1.3 Which of these things do you own personally?

	Yes	No
Motor Vehicle / Car	☐	☐
Motorcycle	☐	☐
Bicycle	☐	☐
Television	☐	☐
Radio	☐	☐
Cell phone	☐	☐
Ox-cart	☐	☐

1.4 Nature of the main house:

	Yes	No
Stone/Burnt brick walls	☐	☐
Cement floor	☐	☐
Tin roof	☐	☐
Glass windows	☐	☐

2. Natural capital

a. Land

2.1 How many hectares/acres/pieces of farm land do you own? ……………………………

2.2 How did you acquire this land?
Inherited ☐
Bought land ☐
Rented land ☐
Others (Specify) …………………………………………………………………………

2.3 What is the type land ownership?
Individual/Sole title ☐ Communal ☐ Rental ☐ Allocation ☐

2.4 How has the total area of your parcels changed compared to 10 years ago?
Increased ☐ Decreased ☐ Remained the same ☐

2.5 Why has the total area of your parcels increased?
Inherited ☐
Bought more land ☐
Rented more land ☐
Others (Specify) ………………………………………………………………………………

2.6 Why has the total area of your parcels decreased?
Sub divided to children/ heirs ☐
Sold ☐
Stopped renting ☐
Others (Specify) ………………………………………………………………………………

2.7 What are the main uses of the land? How has this changed over the last 10 years

Household land use types	**Area of land (ha)**	**Changes** (Increased or decreased)
Cropping		
Pastures		
Forest/woodlands		
Others (Specify)		

b. Crops

2.8 Which crops do you grow and what are the household uses of major crops? Tick accordingly

Crop type	**Crop uses**			
	Consumption	Market/Money	Fodder	Others

2.9 What area of your land is under food and cash crop?

Food crop: ……………………..ha/acres Cash crop: ………………………..ha/acres

2.10 How has the production of the major food crops changed over the last 10 years?
Improved ☐ Decreased ☐ No Change ☐
Specify the major crop(s) and indicate past and present yields to justify your response above:
………

2.11 Which inputs do you use to improve soil fertility on your farm? (Fertilizer, manure, compost, lime, etc)
Compost ☐ Animal manure ☐
Fertilizer ☐ Lime ☐
Others (Specify) ……………………………

c. Livestock and grazing land

2.12 Do you own livestock? Yes ☐ No ☐
2.13 Which type livestock do you keep? What mode of feeding do you use? How has the size of livestock herds changed over the last 10 years?

Animal types	**Approximate numbers**	**Mode of grazing***	**Changes** (Increased, No change or decreased)
Cattle			
Goats			
Sheep			
Donkeys			
Poultry			
Others (Specify)			

**Z- Zero grazing, N- Nomadic/Free range (FR), T- Tethering*

2.14 Does the household own its grazing land(s)? Yes ☐ No ☐
If 'YES', what is the area of grazing land? …………………………..

If 'NO' then on what basis is the grazing land being used?

Rental ☐ Shared arrangement ☐ Open-access ☐

2.15 How far is the grazing land from the home? ……………………………………..

2.16 Has this distance to grazing lands changed in the last 10 years? Explain
Yes ☐ No ☐
………………………………………………………………………………

d. Trees and forest products

2.17 What types of forests/woodlands at farm or community level?
Natural ☐ Planted ☐

2.18 What are the major uses of forests/woodlands?
Fuel wood ☐
Fruits ☐
Medicines ☐

Honey ☐
Livestock feed ☐
Wild meat ☐
Others: ________________________

2.19 What are the household sources of energy?
Fuel wood ☐ Electricity ☐ Crop residues ☐
Paraffin ☐ Gas ☐ Charcoal ☐
Others (Specify) …………
2.20 Is the household self sufficient in accessing fuel wood? Yes ☐ No ☐

2.21 Where do you get fuel wood?
Onfarm ☐ Market ☐
Collect from forest ☐ Neighbors ☐
Others: ……………………………………………………………………………………
2.22 How far do you travel to collect fuel wood? …………………………………km

2.23 What changes have been observed on forests/woodlands on your land and neighborhood?

Resource	**Increased**	**Decreased**	**Remained the same**
Natural forest			
Planted forest			

2.24 What are the reasons for the ***increase***?
Afforestation ☐
Restricted cutting ☐
Others: ……………………………………………………………………………………….

2.25 What are the reasons for the ***decrease***?
Fuel wood collection ☐
Timber ☐
Conversion to agriculture ☐
Government excision ☐
Growth of urban areas (towns/roads) ☐
Others: ……………………………………………………………………………………..

2.26 What goods or services have you gained or lost as a result of the changes in forests described above?
……

2.27 What adjustments has the household made to adapt to the changes discussed above?
………

e. Water resources
2.28 What are the main sources and uses of water by the household?

	☑	Domestic	Livestock	Irrigation	Others
Borehole	☐	☐	☐	☐	☐
Open wells	☐	☐	☐	☐	☐
Springs	☐	☐	☐	☐	☐
Piped	☐	☐	☐	☐	☐
River	☐	☐	☐	☐	☐
Dams	☐	☐	☐	☐	☐
Others	☐	☐	☐	☐	☐

2.29 How far do you travel to access water for the following uses?
Domestic ………………………………(m/km/minutes)
Livestock ………………………………(m/km/minutes)
Irrigation ………………………………(m/km/minutes)

2.30 What changes have occurred in the **quantity** (Increased, No change or Decreased) of water sources listed above over the last 10 years? (Explain reasons for the change)

Increased ☐ Decreased ☐ No Change ☐

Explain: ………………………………………………………………………………………………………

2.31 What changes have occurred in the **quality** (Improved, No Change or Decreased) of water sources listed above over the last 10 years? (Explain reasons for the change)

Improved ☐ Decreased ☐ No Change ☐
Explain: ………………………………………………………………………………………………………

3. Land degradation

3.1 From your assessment, what is the status of the following land resources in your village?

	Improved	**No change**	**Declined**
Cropping lands	☐	☐	☐
Grazing lands	☐	☐	☐
Forested lands	☐	☐	☐
Water resources	☐	☐	☐

3.2 What are the indicators of changes/trends mentioned above

Resource	**Indicators**
Cropping lands	
Grazing lands	
Forested lands	
Water resources	

Examples: Change in productivity/ha, changes in soil physical and chemical properties, area/distances to the resource, change in vegetation type/vigor/quality, water quality/quantity, etc

3.3 Which of the following types of land degradation are occurring in your neighborhood? How do you rate the degree of degradation?

a. Soil *erosion*	**Occurrence**	**Degree of magnitude**		
	Yes/No	Light	Moderate	Strong
Loss of topsoil / surface erosion (sheet erosion)				
Gully erosion / gully erosion				
Riverbank erosion				
Mass movements / landslides				
Wind erosion				
Others: ………………………				
b. Chemical soil deterioration	Yes/No	Light	Moderate	Strong

Fertility decline				
Reduced organic matter content				
Acidification				
c. Physical soil deterioration	Yes/No	Light	Moderate	Strong
Compaction				
Sealing and crusting				
Water logging				
Others: ………………………				
d. Water Degradation	Yes/No	Light	Moderate	Strong
Change in quantity of surface water				
Change in groundwater / aquifer level				
Decline of surface water quality				
Decline of groundwater quality				
Others: ………………………				
e. Biological Degradation	Yes/No	Light	Moderate	Strong
Reduction of vegetation cover				
Loss of habitats				
Quality and species composition / diversity decline				
Increase of pests / diseases, loss of predators				
Others: ………………………				

3.4 In your opinion which of the following are the direct causes of land degradation in your village?

Poor soil and crop management ☐
Deforestation and removal of natural vegetation (domestic & industrial) ☐
Overgrazing ☐
Industrial activities and mining ☐
Urbanization and infrastructure development ☐
Natural causes (changes in temperature, rainfall, drought) ☐
Others Specify: ……………………………………………………………………………

In order of priority, list the three main direct causes of land degradation:
……
…………………………………………………………

3.5 In your opinion what are the indirect and indirect causes of land degradation in your village?

High population pressure ☐
Weak land tenure system ☐
Poverty ☐
Poor access to inputs (e.g. high input fertilizers prices) ☐
Poor infrastructure (roads, health, education facilities) ☐
Lack of awareness, access to knowledge and support services: ☐
Poor governance / institutional ☐

In order of priority, list the three main indirect causes:
……

4. Financial capital and production

4.1 What are the major sources of household income?

Crop production ☐
Livestock production ☐
Remittances ☐
Fishing ☐
Forest products ☐
Off farm employment ☐
Business ☐
Others (Specify): ……………………………………………………………..

4.2 Do you get additional financial support from the following sources?

Subsidies (Government of Kenya) Yes ☐ No ☐
Micro-credit project/program Yes ☐ No ☐
Food aid Yes ☐ No ☐
Borrowing money from relatives Yes ☐ No ☐
Social groups (Merry-go-rounds/women groups) Yes ☐ No ☐

5. Vulnerability context

5.1 Has the household faced the following crises in the last 10 years?

Crises	**Yes/No**	**When**
Drought		
Food Insecurity		
Crop failures		
Livestock losses		
Natural disasters		
Health problems		
Indebtedness		
Migration		
Others		

5.2 How many months in a year do you experience shortages or limited/difficult access to the following natural resources and what are your coping strategies?

Shortage/Limited access	**No. of Months**	**Coping strategies**
Food		
Grazing		
Fodder		
Water		
Others:		

6. Physical capital

6.1 Changes in services/infrastructures access in the last 10 years

Services/ Infrastructure	Access G- Good; M- Medium; P- Poor	Distance/ time	**Changes** (Positive, Neutral, Negative)
Market			
Medical centre			

School			
Farmers cooperative			
Agricultural extension/research office			
Water points			
Town/City			
Others			

7. <u>Social capital</u>

7.1 Household's membership of associations and benefits

Associations	**Yes/No**	**Direct Benefits[1]**
Local group		
Producer associations		
Womens' groups		
NGO		
Social/religious groups		
Water committee/users association		
Other:		

[1]Examples of benefits: Access to credit/borrowing money; Technical advice; borrowing farm equipment, social networking, conflict resolution

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