Monitoring Spatio-temporal Dynamics of Land Cover Changes in Lake Naivasha Drainage Basin, Kenya

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by

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Abstract

Land cover is a fundamental variable that impacts on, and links many parts of, the global environment. Changes in land cover can have far-reaching ramifications at local, regional and global levels. Thus, patterns of land cover must be understood at a range of spatial and temporal scales with a view to characterizing and predicting the potential environmental impacts. This work focused on the dynamics of land cover change occurring within the Lake Naivasha drainage basin in Kenya. The area has undergone rapid land use transformations since independence to date leading to land cover changes. This in turn compromises the natural resource base, hence, the need to monitor and avail reliable data for decision making on sustainable land use. The research objectives were two-fold: to determine the probable driving forces of land use that results in land cover changes in Lake Naivasha drainage basin and; to establish and map the magnitude, rates, nature and spatial distribution of the land cover changes that had occurred in the area.

Both remote sensing and GIS techniques were employed to collect the pertinent data needed for fulfilling the research objectives. Multi-temporal satellite data (ASTER 2007 and Landsat TM 1986&1995) were acquired and field survey conducted from, which land cover sample data were collected using the Global Positioning Systems (GPS) and mobile GIS. Data on the driving factors of land use were obtained through semi-structured interviews. The land cover sample data were then used for classification of the satellite images using object-based approach resulting in land cover maps for 1986, 1995 and 2007. These were further analyzed for changes using the post-classification technique. Since the multi-temporal remote sensing data only offered partial coverage, SPOT-NDVI data was used to delineate four representative units of the whole basin. These units were used for land cover change mapping and analysis. The analysis yielded results on the estimates of the magnitude and rates of land cover changes within the Lake Naivasha drainage basin as well as the geographic distribution of these changes. In overall, the forests, woodlands, grasslands and shrub lands showed declining trends in their rates and magnitude of change whereas the croplands and built-up land had a constant increase between 1986 and 2007. Friedman’s test was employed in the analysis of the driving factors of land use and its results concluded that the driving factors had different influences on land use in Naivasha basin. Both proximate and underlying processes constituted the driving factors of land use. These included: demographics (household sizes and numbers), market availability and prices, climate and sustenance (source of livelihood).

In light of the results obtained, a range of conclusions are drawn but the main one is that the overriding nature of land cover change in Naivasha basin had been the conversion of grasslands to croplands. These land cover changes were spread throughout the basin. Finally, exploration of better classification approaches, integration of old remote sensing data (aerial photos) and in-depth studies of land cover dynamics within smaller portions of Lake Naivasha basin are among the recommendations made for further research.

Key words: Monitoring, Land cover, Change, Lake Naivasha basin, Kenya.

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Dedicated to

the cherished memory of my beloved little brother, Master Teddy Otieno Were (1990 - 2006), whose promising life was untimely nipped in the bud before fulfilling his academic ambitions.

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1.0 INTRODUCTION

This chapter provides the theoretical background information underpinning the study and states the problem, objectives, hypotheses, questions, as well as the overall approach of the research.

1.1 Background Information

Land cover is a fundamental variable that influences many facets of the natural environment. Changes in land cover, hence land surfaces processes, are inherently dynamic and spatial and could impact the natural environment in a way that could, only, be paralleled to the effects of climate change (Aspinall and Hill 2008, Foody 2002). The growing human population has triggered alteration of the earth surface at unprecedented pace, magnitude and spatial extent (Lunetta and Elvidge 1999 and Lambin *et al.* 2001), thereby, making it difficult to find pristine lands any more. Transformations of land cover for agricultural, residential, industrial and urban development concomitant to the increasing population affects the functioning of environmental systems and processes in the long term. Since 1970s through to the current period, it has been constantly reported that land use and land cover changes impact on the bio-geochemical cycling leading to modifications in surface-atmosphere energy exchanges, carbon and water cycling, soil quality, biodiversity, ability of biological systems to support human needs and, ultimately, climate at all scales (Foody 2002, Lambin *et al.* 2003, Loveland *et al.* 1999, Overmars and Verburg 2005). This provides rationale for the recognition of land use /cover change as a fundamental agent of the global environmental change and a grand challenge in environmental science (Aspinall and Hill 2008, Bottomley 1998). Monitoring and detection of land cover changes is gaining currency in the scientific realm as a way of comprehending human relationships and interactions with the global earth systems in order to facilitate the management and use of natural resources, environmental change and evaluate the sustainability of development (Carpenter *et al* 2001, Bottomley 1998, Lu *et al* 2004).

Even though the terms, land use and land cover, *per se* have mostly been used interchangeably in change detection studies, they are quite distinct (Seto *et al.* 2002). The former alludes to the arrangements, activities and inputs that mankind undertake in a given land cover type to produce, change or maintain it (Gregorio and Jansen 1998, Campbell 2002). Land cover, on the other hand, refers to the conspicuous biophysical attributes of land surface inclusive of the natural, man-made, vegetative and non-vegetative aspects. Essentially, land use is an abstract concept embracing a mix of socio-economic, cultural and policy factors whereas land cover is concrete and directly measurable by remote sensing, examples of which include agriculture and grass respectively. Land cover is affected by land use and changes in land cover affects land use (Bottomley 1998). Lunetta and Elvidge (1999) categorized the land cover changes into conversions between land cover types (i.e. between-class changes) and modifications within a land cover type (i.e. within-class changes). Studies on land cover change patterns have inclined more towards the conversions between, rather than modifications within, land cover types. This is attributed to the spatial resolutions of the available remote sensor systems and data affordability. Moreover, Lambin *et al.* (2003) pointed out that the land cover conversions could either be progressive or episodic. Episodic changes depict periods of rapid and abrupt changes often caused by interactions between climate and land use factors in the short term (e.g. El Niño-driven droughts and wildfires), whereas progressive changes occur gradually (e.g. geomorphological and ecological processes such as soil erosion and vegetation succession).

The patterns of land use and land cover, as well as land management, are fashioned by complex interactions between the biophysical environment and societal (economic, social, political and technological) processes and forces at local, regional and global scale (Aspinall and Justice 2004, Campbell *et al.* 2003 and Overmars and Verburg 2005). In endeavour to appreciate changes in agricultural land use in Senegal, Wood *et al.* (2004) discovered that climate (i.e. drought and declining precipitation), population growth (constraint to arable land), development projects (i.e. irrigation projects), land ownership, cash crop production (i.e. cotton, peanuts and rice) and forestry practices (felling of trees for fuel and charcoal) were the principal drivers of land use change in the area. Besides these, urbanization, industrialization and economic measures were also reported as notable socio-economic drivers of land use/ cover change in China (Long *et al.* 2007, Seto *et al.* 2002). Lambin *et al.* (2003) summed up the foregoing factors into two major categories, namely, proximate (direct) and underlying (indirect) drivers of land use change. Proximate causes comprise of immediate actions that emanate from intended land use, thus affecting land cover and operate at local level, e.g. deforestation. Whereas, underlying causes are the extraneous forces that underpin the proximate causes, e.g. land use policies.

Knowledge about land cover changes that occur, where and when they occur and the rates at which they occur is requisite. Equally important is an awareness of the drivers and processes that instigate the land cover changes. The former presupposes availability of quantitative, fine resolution and spatially explicit data (Lambin *et al.* 2001), whereas enhanced appreciation of land cover dynamics demands qualitative (non-spatial) data on the driving forces of land use (Mugisha 2002). Satellite remote sensing has been the most adequate tool for provision of detailed, accurate, consistent, cost effective, repetitive, synoptic and timely data for the characterization of land cover, environmental monitoring and, hence, comprehension of the influence of anthropogenic activities on natural resource base. This utility has been demonstrated since the launch of the first Earth Resources Technology Satellite (ERTS-1, later renamed Landsat 1) in 1972 (Lunetta and Elvidge 1999). It has been boosted, further, by rapid development and maturity of automated techniques, which have greatly facilitated the detection of terrestrial land cover changes.

By and large, change detection involves identification of differences in land cover status over time using multi-date satellite images (Fan *et al.* 2007, Singh 1989). The two characteristic approaches of most change detection techniques include comparative analysis of independently produced land cover classifications and simultaneous analysis of multi-temporal dataset (Loveland *et al.* 1999). Details of these techniques, ranging from image regression and change vector analysis to image ratioing, univariate image differencing and thresholding, vegetation index differencing, multi-date principal component analysis, post classification comparison, neural networks, multi-temporal spectral mixture analysis, multi-dimensional temporal feature space analysis, knowledge-based expert systems and object-based image analysis, find their best review in the works of Coppin *et al.* (2004), Lu *et al.* (2004) Civco *et al.* (2002) Mas (1999), Lunetta and Elvidge (1999) and Singh (1989). Consequently, remote sensing has been widely applied in myriad studies to measure and monitor land cover changes in diverse environments ranging from coastal regions in China (Weng 2001) and Egypt (Shalaby &Tateishi 2007) to metropolitan areas in the Unites States of America (Yuan *et al.* 2005), estuarine ecosystems in the gulf of Mexico (Yang and Liu 2005), dry lands in Africa (Elmqvist n.d, Campbell *et al.* 2003) and water catchment areas in Taita hills and eastern Mau in Kenya (Pellikka *et al*. 2004, Kundu et al. n.d) among many other environments. Lu *et al.* (2004), however, stated that an ideal investigation into land cover changes should avail information on their magnitude and rate, spatial distribution and trajectories, as well as, assessment of the accuracies of change detection results.

In spite of the application of change detection studies in wide-ranging environments as revealed above, there still remains a gap in available land cover data sets, which afford detailed, reliable, temporal and quantitative spatial land cover information, and systematic evidence on the causes and consequences of land cover changes on local, regional and global scale (Loveland *et al.* 1999, Read and Lam 2002). This often impedes efforts to model land use, monitor land cover changes and improve the assessments of the implications of these changes.

1.1.1 Land Use and Land Cover Changes in Kenya

Most of land cover in east Africa is in a state of flux at a variety of spatial and temporal scale due to climatic variability and human activities (Kiage *et al.* 2007). Kenya, in particular, has undergone rapid land use and land cover transformations in response to the diverse political, economic, socio-cultural and demographic processes that have occurred in space and time. The early colonial period, i.e. 1900-1930, was characterized by extensive land expropriation, large scale agricultural production and European settlement (Campbell *et al.* 2003). The ensuing period leading to independence, i.e. 1930–1963, experienced the reduction of constraints on African land ownership and participation in commercial agricultural economy. This culminated in new interactions and conflicts among the agricultural and pastoral groups as farmers settled in high potential areas, which were formerly used by the pastoralists, for grazing, in times of drought. In the post independence era, the state fostered rural development, especially, the expansion of cash crop production in central and western highlands. More so, it encouraged diversification of land use in the arid and semi-arid lands (ASALs) through expropriation of land for wildlife tourism.

The state support began to wane, in the 1980s, following the introduction of structural adjustments programmes (SAPs) and emergence of corruption within the government. The 1990s saw a marked growth in population owing to increased medical care, individualized land tenure and international competition for agricultural produce and dairy products. The rising population imposed lots of pressure on the land resources in a country where approximately 75% of the populace engages in agriculture but only 20% of its land is arable. As a result, the shortage of arable land has led to expansion of cultivation into the wetter margins of rangelands, felling of forests (often with impunity) and the decline of the savannas and grasslands thanks to overgrazing, charcoal burning and other unsustainable land uses (Mwagore 2002, Campbell *et al.* 2003). These actions have far reaching implications on the integrity of natural resources and ecosystems in the country.

The Lake Naivasha drainage basin, situated in the Kenyan section of the Great Rift Valley, presents a good example of localities that have undergone extensive land use and land cover changes since the attainment of independence and a subsequent rise in its population (Onywere 2005, Mireri 2005 and Becht *et al.* n.d). These transformations have been a threat to the sustainability of its natural resource endowments, in the figure of the lake itself and land, which are the pillar of its economic growth. The changes and their repercussions require careful consideration, both at local and regional level, in order to facilitate the formulation of rational policies that effectively strike a balance between economic development and environmental conservation. Rational policy formulation, however, calls for accessibility to land cover information of sufficient reliability and temporal and geographic detail.

1.2 Problem Statement

The rapid land use and land cover dynamics in the lake Naivasha drainage basin are a threat to its core natural resource base i.e. land and water (Mireri, 2005). Pastoralism was widely practised in the area adjacent to the lake prior to colonization while mixed farming predominated in the colonial era. The post-colonial period, from 1963 henceforth, has experienced rapid land use transformations ranging from commercial ranching to a combination of commercial ranching, and increasingly growing small-size rural and urban human settlements. For instance, some of the large farms formerly owned by the European settlers around Kipipiri and Kinangop have been sold or granted to indigenous Kenyans and, subsequently, sub-divided in small-holding. The opening up of the catchment area to geo-thermal energy exploration and power generation, tourism, floriculture, intensive commercial agriculture and transport network has also triggered an influx of labour into the area culminating into a rise in human population (Onywere 2005, Mireri 2005, Becht *et al.* n.d).

In spite of the socio-economic benefits attendant to the economic growth of the area, the increasing economic activities, linked to the functional use of land and the subsequent population growth, are exerting equally enormous pressure on the natural resource base comprising of the lake, land and forests. The growing demand for space for human settlement, agricultural production, grazing, industrial and commercial purposes, is gradually diminishing the amount and sizes of arable (agricultural) and pasture land. For example, the large floricultural farms around the lakeshore have dramatically expanded over the last one and a half decades at the expense of pasture (grass) land, woodlands and sisal plantations which constituted the former land covers. This practice has also contributed to the degradation of water quality through discharge of agro-chemicals and affected surface and ground water through extraction of water for farm use. More so, the construction of residential estates like Banda and Kihoto on the eastern side of the lake to accommodate the rising population has not only reduced space for arable farming but also for wildlife. This causes conflict between the animals, i.e. hippopotamus and buffalo, and small scale farmers (Kenya Land Alliance 2006). The shortage of arable (agricultural) land has translated into excessive destruction of lakeshore vegetation (i.e. *Acacia xanthophloea* and *Cyperus papyrus*) and forests, woodlands and grasslands in Kinangop and Mau escarpments (Lamb *et al.* 2003 and Onywere 2005). Presently a meagre 10% of the area formerly covered by *Cyperus papyrus* remains leading to a reduction in submerged vegetation that supports aquatic life.

In the long term, these land use and land cover dynamics are bound to compromise the robust economy of the lake Naivasha drainage basin if their impacts, on land and water resources, are not mitigated. As such, it is imperative to map land cover and monitor temporal changes with a view to providing change estimates and patterns for a larger part of the drainage basin in order to facilitate informed decision making on mitigation measures. These are insufficient at the moment. Additionally, it is worthwhile to gain an insight into the unknown forces and processes that drive land use, and hence, land cover changes in Naivasha basin. Figure 1 illustrates a causal loop diagram of the foregoing phenomenon:

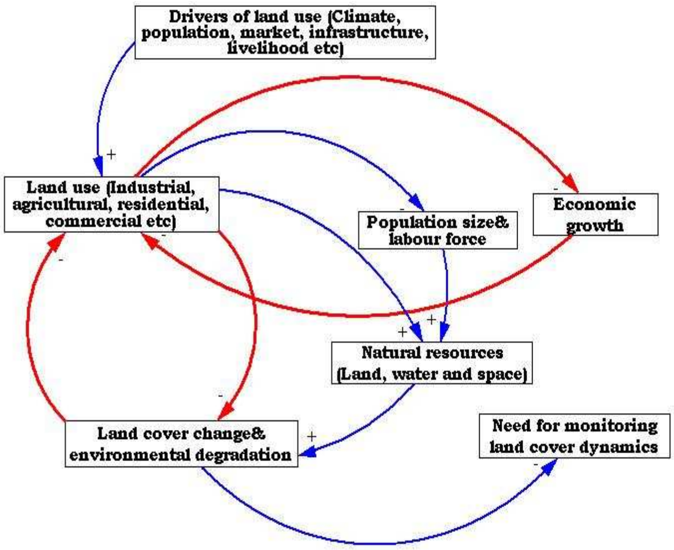


Figure 1: Causal Loop Diagram of the research problem

1.3 Research Objectives

Driven by the need to fill in the gap in available land cover information for effective and rational management of the natural resource base in Lake Naivasha drainage basin, the objectives of the research were as follows:

a) To establish the current land cover and the drivers of land use, that results in land cover changes within the lake basin;

b) To determine the magnitude, rate, spatial distribution and nature of land cover changes that had occurred within the lake Naivasha drainage basin based on three dates of remote sensing data i.e. 1986, 1995 and 2007.

1.4 Research Questions

a) What forces drive land use and are likely to have influenced changes in land cover within the lake naivasha drainage basin?

b) What is the magnitude, and the rate, of land cover changes that have occurred in the lake basin between 1986, 1995 and 2007?

c) What is the nature of the land cover changes that have taken place between 1986, 1995 and 2007?

d) What is the spatial distribution of the land cover changes within the lake basin?

1.5 Research Hypotheses

a) H_0: The magnitude and the rate of land cover changes have been zero (H_0: $\Delta = 0\%$).

H_a: The magnitude and the rate of land cover changes have been greater than zero (H_a: $\Delta > 0\%$).

b) H_0: Cropland is not the land cover type that has been greatly converted to other land cover types.
H_a: Cropland is the land cover type that has been greatly converted to other land cover types.

c) H_0: The distribution of most of the land cover changes has not been in the lower parts of the lake basin.
H_a: The distribution of most of the land cover changes has been in the lower parts of the lake basin.

d) H_0: The driving factors of land use have similar influence on land use in the lake Naivasha drainage basin
H_a: The driving factors, or at least one of them, have different influence on land use in the lake Naivasha drainage basin.

1.6 Research Approach

The approach that was adopted in the implementation of this research is summarized in Figure 2:

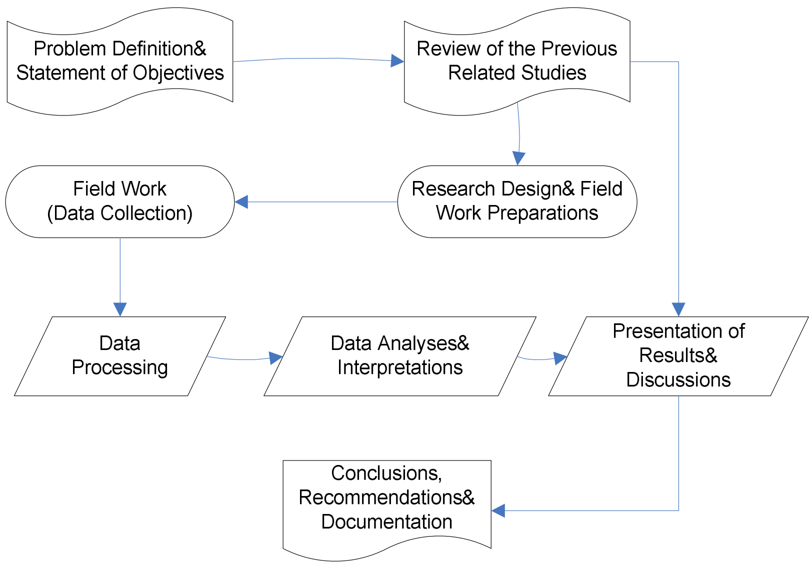


Figure 2: Flowchart illustrating the stages of the research

2.0 METHODS AND MATERIALS

This chapter describes the study area, methods and materials that were applied in the collection, processing, analysis and presentation of data with a view to fulfilling the set objectives and answering the research questions. Figure 3 summarizes this:

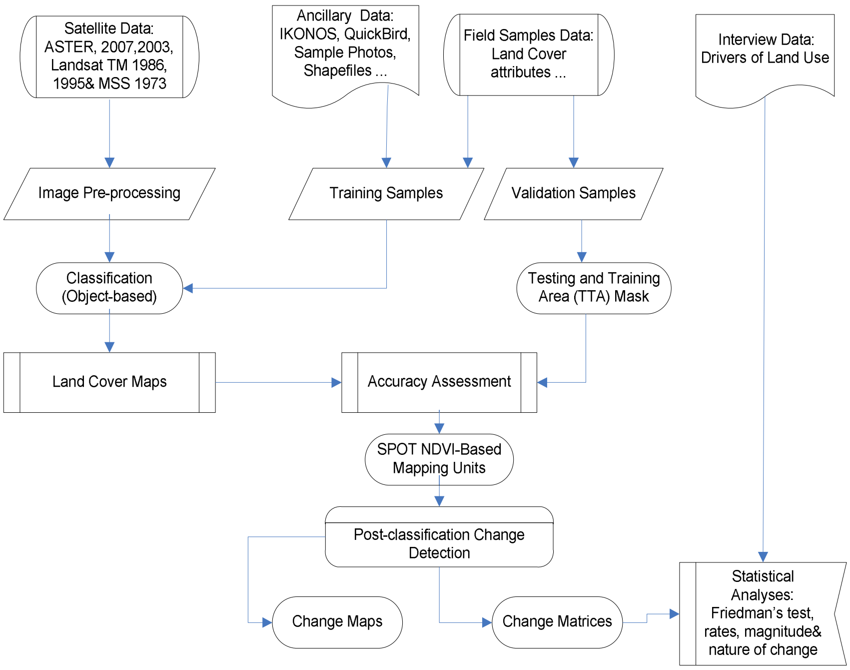


Figure 3: Schematic diagram summarizing the methods and materials

2.1 Study Area

The Lake Naivasha drainage basin, which spans approximately 3200 km^2, is bound by latitudes 0° 8' 35" S and 0° 54' 53"S and longitudes 36° 42' 24" E and 36° 4' 43" E. Its administrative limits cut through two provinces namely: Rift valley and Central. On the eastern side lies the Aberdares Mountain ranges while Mau escarpment flanks the south-western part; these receive ample rainfall, thus, defining the main catchment area. The lake obtains most of its waters from Karati, Malewa and Gilgil rivers.

The annual rainfall totals range from 630 mm at the riparian region to 1380 mm at the Aberdares Mountain ranges. March to May is the long rain season whereas October to mid December marks the short rain season. December through to February and July are considered the driest months, particularly, in the lower basin. Similarly, the mean annual temperature is 25°C and the maximum is about 30°C; July is the coldest month having a mean temperature of 23°C. Evapotranspiration around the lake region is about 1360 mm per annum, which surpasses its precipitation.

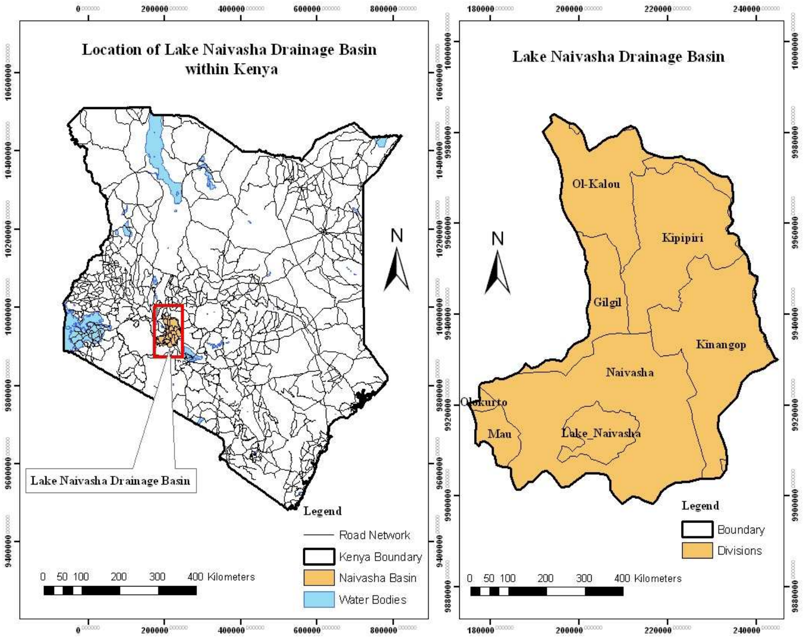


Figure 4: Location of Lake Naivasha Drainage Basin

The soils in Lake Naivasha drainage basin are formed from volcanic activity, which characterizes the better part of the Kenyan Rift valley. It belongs to agro-ecological zone V in Kenya, which has been characterized as environmentally fragile and susceptible to land degradation (FAO 1998). Thus, the rapid land use/ cover transformations taking place within it, especially, in the eastern and north-eastern parts of the lake have the tendency to impact on this fragility and susceptibility. The need to alleviate this phenomenon warranted the selection of this study site. Land cover mapping and change analysis, though, was done only for a section of the drainage basin for lack of multi-temporal imagery covering the entire area.

2.2. Pre-field Work

This phase was characterized by stratification of the study area, preparation of the sampling design, spatial data layers, interviewing schedules, field observation sheets and organisation of field equipment and logistics.

2.2.1. Sampling Design

The Lake Naivasha drainage basin was stratified based on the existing agro-ecological zones map that synthesized information on precipitation, temperature and altitude. This was aimed at achieving an objective basis for description of the land cover classes within the study area. Thereafter, random points were generated, using Hawths tools 3 ESRI extensions for ArcGIS, to derive the sampling units, which were to be visited in the field for documentation of the biophysical attributes. However, during the actual fieldwork it was impossible to implement this sampling strategy due to time and mobility constraints. As a result, most samples were collected by traversing the accessible areas (Appendix 6) and selecting suitable sampling units that were approximately 30 by 30 metres considering the spatial resolutions of the imagery available for land cover classification.

2.2.2 Spatial Data Coverage

Topographic sheets, published by the survey of Kenya, were geo-referenced and existing vector datasets, from the International Livestock Research Institute's database, (http://www.ilri.org/gis/), were re-projected to UTM zone 37 south (map projection) and WGS 84 (datum and ellipsoid) adopted for the study. The vector dataset comprised of agro-ecological zones, roads, towns, markets, administrative boundaries, water bodies, land use, soils, forests and villages. Unsupervised classification of the most recent image (ASTER 23.01.2007) was performed to aid in identification of land cover classes in the field. Unsupervised classification implies that neither additional data nor expert knowledge influenced the outcome of the classification. The pertinent datasets were uploaded onto the mobile GIS (Hp iPAQ) for use in the field. These data not only facilitated field navigation but also the interpretation of land covers on the satellite imagery during classification.

2.3 Data Collection

Four types of data were collected for different purposes. These were: remote sensing data, land cover field data, ancillary data and interview data. Details follow in the subsequent sub-sections.

2.3.1 Remotely Sensed Data

Geo-referenced, radiometrically calibrated and ortho-rectified ASTER, Landsat MSS and TM images for 1986, 1995 and 2007, were acquired from the United States Geological Survey, Centre for Earth Resources Observation and Science (USGS-EROS) and Global Land Cover Facility's (GLCF) website, http://glcf.umiacs.umd.edu/index.shtm. These images were selected based on cost, date of acquisition, spatial resolution, availability and the percent cloud cover (Table 1). As already mentioned in section 2.1, the available remote sensing data covered only parts of Lake Naivasha drainage basin. Bottomley (1998) and Lu *et al.* (2004) underscored the importance of image acquisition dates. This should either be on anniversary dates or within-window anniversary so as to avert variations in reflectance(s) caused by seasonal vegetation fluxes and solar angle differences. Such considerations ultimately improve the accuracy and the potential to discern land cover changes (Lunetta and Elvidge, 1999) by allowing comparison of images with almost similar vegetation conditions. SPOT vegetation ten daily synthesis data from www.vgt.vito.be, Quick Bird and IKONOS images, were also utilized in the field and during classification. Attempts to make use of aerial photos acquired in 1947 were thwarted by their late delivery.

Table 1: Characteristics of the remotely sensed data used in the study

Satellite sensor	**Spatial resolution**	**Spectral resolution**	**Date of acquisition**	**Source**
ASTER	15m	14 bands	01/23/2007	USGS
Landsat TM	30m	7 bands	01/27/1986	GLCF
Landsat TM	30m	7 bands	01/ 21/1995	GLCF
Quick Bird	2.6m	4 bands	06/02 /2003	Digital Globe
IKONOS	4m	4 bands	03/06 /2002, 9/10/2002	GeoEye
SPOT-VGT1	1km	324 layers	01/04/ 98 - 31/04/ 07	VITO

2.3.2 Ancillary Data

A range of reference data was collected to facilitate the research process. Sample vertical aerial photographs for 1992, 1996 and 2007 were obtained from the department of resource surveys and remote sensing (DRSRS, Kenya). They had an average scale of 1:30,000 and an areal coverage of 45 to 50 hectares on the ground. These photographs were used to aid interpretation of the older satellite imagery. Meteorological data, statistical abstracts from the central bureau of statistics and farm management handbook co-authored by GTZ and the ministry of agriculture, Kenya were also used for additional information on rainfall, crops and population.

2.3.3 Land Cover Field Data

Reliable training and validation data is prerequisite for meaningful land cover mapping. Field surveys were conducted between 11.09.2007 and 08.10.2007, which yielded a set of 430 sample points using the hand-held GARMIN 12X Global Positioning Systems (GPS) and a mobile GIS (Hp IPAQ). These points were, however, not equally distributed within each land cover (Appendix 6) due to the sampling strategy applied. The surveys aimed at: (i) determining the land use and cover types; (ii) associating the field data of specific land cover types with their image characteristics and; (iii) collecting sufficient field data for validation of the 2007 land cover map derived from ASTER image. At the sampling units, which were about 30 by 30 metres, visual estimates of the biophysical attributes (percent cover of shrubs, grass, herbs, trees, bare soils and water) were made and recorded in the field observation sheet (Appendix 1). The digital photographs of the sites were also taken. These data were later on entered into Microsoft Excel 2003 spreadsheet at the end of the field campaign.

2.3.3.1 Development of Land Cover Classification Scheme

The land cover data from the field survey were sorted out based on the bio-physical attributes and a preliminary, three-level land cover classification legend was developed for the study (Appendix 5). The nine (9) classes in level one (I) were used for classification as well as change analyses taking into consideration the selected classification method and the scale of Landsat TM image pixels (Table 3).

2.3.4 Interview Data

Data on the driving factors of land use in the Lake Naivasha drainage basin were gathered through semi-structured interviews with the farmers (land owners) and key informants. Local group officials such as the *Githabai* self-help group, friends of Kinangop, Water Resource Users Association (WRUA), the in-charge of World Wildlife Fund (WWF), Naivasha district and farmers in Murungaru, Ngeta and Mkungi locations were interviewed concerning land use history and the perceived processes driving land use in the area (Appendix 2). Five different types of seeds, i.e. maize, green grams, beans, ground nuts and peas, were used to aid interviewees to rank the determinant forces behind their use of land on a 5-point scale of importance. Maize stood for sustenance (livelihood), beans for climate, green grams for infrastructure, peas for household size and ground nuts for the market forces. Five seeds of each kind were given to a farmer and s/he was expected to place a maximum of five on each category of a driving force, which had been clearly marked on a card board, in regard to their importance. Five (5) meant that a driving factor was very important whereas one (1) meant that it was not important.

Adequate capture of the earth's complexity, by the remote sensors, is often constrained by their limited spatial, spectral, temporal and radiometric resolutions. This introduces errors that can compromise the data quality, hence, calling for their elimination (pre-processing) prior to analysis (Shaikh *et al.* 2005). Success in change analysis using multi-temporal imagery, in particular, depends on accurate radiometric and geometric pre-processing (Treitz and Rogan 2004). Since geometric and radiometric correction of the satellite data had already been conducted by the suppliers, the pre-processing operations performed in this study comprised of mosaicking the ASTER scenes and clipping out the study area from the mosaics. These were thereafter re-projected, using ERDAS imagine 9.1 software, to UTM zone 37 south (map projection) and WGS 84 (datum and ellipsoid). The geo-rectified ASTER images were later resampled to 30m, in order to simulate the coarser spatial resolution of Landsat TM images, using the nearest neighbour method. This method preserves the original pixel values, which is a vital consideration for change detection.

2.4 Image Pre-processing

In land cover change analysis, geometric correction guarantees accurate spatial orientation of the satellite images while radiometric data normalization suppresses the spectral differences emanating from detector disparity, variations in radiation incidence angle and sensor calibration among others (Lunetta and Elvidge 1999, Yang and Liu 2005). Thus, variations between multi-temporal dataset, which can cause systematic overestimation of change, are reduced and correct datasets obtained for change analysis. Atmospheric correction, which compensates for the variations in atmospheric depths between dates, was not performed due to limited resources but this was circumvented by post-classification change detection technique that was chosen. The unnecessary nature of atmospheric correction on classification with a single date image has been extended to post-classification change detection method (Song *et al.* 2001, Singh 1989). The method minimizes problems introduced by not only the use of different sensors but also varied atmospheric and phenological conditions between dates through production and comparison of independently classified maps (Shalaby and Tateishi 2007, Loveland *et al.* 1999).

2.5 Image Classification

In the first instance, the traditional pixel-based maximum likelihood classifier was used but yielded noisy results with poor accuracy. This could be ascribed to the heterogeneity of land cover types and spectral confusion of some, especially, shrub lands, croplands and woodlands. A suitable alternative was found in object-oriented approach, which has positively contributed to the classification of remote sensing imagery of high to medium spatial resolutions in a variety of studies (Blaschke *et al.* 2000). It partitions the image into meaningful homogenous areas (objects) by taking into account, not only, the spectral information inherent in it, but also, the spatial attributes such as shape, compactness, size, smoothness and other topological features (Im *et al.* 2007). The underlying assumption is that meaningful objects exist in a scene and their attributes bear information capable of discriminating them in classification. In contrast to pixel-based classification, individual objects form the basic unit in the entire process of sample selection and training of the classifier, classification, preparation of reference data and assessment of accuracy (Zhan *et.* al 2005).

The object-based approach to classification of the available satellite data, *per se*, was implemented in Definiens® developer (eCognition™) version 7.0 software, which was more appropriate relative to the new ENVI 4.4 feature extraction module, in regard to time consumption and editing capabilities. It uses a fuzzy rule base consisting of conditions combined by operators to classify image objects. Thus, prior definition of one- or multi-dimensional membership functions for the objects is essential (Baatz *et al.* 2004). The first step was creation of false colour composites using green, red and near-infra-red bands and execution of multi-resolution segmentation based on user-specified parameters in Table 2. The scale parameter was determined on *'trial and error'* basis until an optimal value was realized.

Table 2: Image segmentation parameters

Satellite Imagery	Level	Scale	Homogeneity criteria		Shape ratio	
			Colour	Shape	Compactness	smoothness
ASTER	1	10	0.8	0.2	0.3	0.7
Landsat TMs	1	5	0.8	0.2	0.3	0.7

This rendered the images into polygonal object primitives, with similar spectral and neighbourhood characteristics, that formed the basis of further analyses.

The training data was then uploaded as a thematic layer to facilitate declaration of sample objects for classification of 2007 ASTER image using the standard nearest neighbour algorithm that automatically generates multi-dimensional membership functions based on the sample objects. This dataset was derived randomly from two-thirds (2/3) of the sample data that had been collected from the field surveys. The remaining third (1/3) of the data were used to create training and test area (TTA) mask for assessing the quality of the extracted land cover map. Visual inspection and iterative manual editing of the observable confusion preceded appraisal of the map quality. Declaration of sample objects for classification of the previous satellite images was based on the extracted land cover map for 2007 (‘*backward classification*’), available reference materials (i.e. the sample vertical aerial photos, IKONOS and QuickBird images for 2001 and 2003 respectively, vector land cover map for Kenya produced by ILRI on the basis of 1980 Landsat data) and expert knowledge and expertise.

2.6 Accuracy Assessment

This is an important feature of land cover mapping that offers a guide to the map quality, reliability, implications to the users and an insight into the thematic uncertainties (Treitz and Rogan 2004). Geo-spatial data, inevitably, contain uncertainties owing to errors in space, value, time, consistency or correctness, variability, instability, conceptual ambiguity, over-abstraction and so forth (Zhan *et al.* 2005, Blaschke *et al.* 2000). In the context of per-object land cover classification, uncertainty could emanate either from the image, *per se*, its segmentation or classification. As already mentioned in the foregoing section, a TTA mask was externally created, using a third of the field samples data, for validation of the resultant land cover map from the classification of ASTER imagery captured on 23.01.07. In the validation process the algorithm compared the pixels in the classified map and the pixels within the TTA objects and determined the number of correctly and incorrectly classified pixels for each class. It then conveyed the measures of map quality in terms of kappa statistic, overall, producer and user accuracy using the conventional error (confusion) matrix (Table 4). The producer's accuracy (completeness) showed the percentage of reference pixels that had been explained by the extracted pixels; user's accuracy (correctness) indicated the percentage of pixels that had been correctly extracted and; kappa statistic (the measure of reproducibility) assessed the probability of chance agreement between the reference dataset and the classified land cover map. Zhan *et al.* (2005), however, expressed the need for per-object measures to go beyond the assessment of quality based primarily on location (pixels) and incorporate the diverse geometric aspects such as size, position and shape. Lack of existing land cover maps, of known quality, or aerial photos for the area, made it impossible to validate the land cover maps produced for 1986 and 1995 though, it is a crucial process in change analysis. Their validation would have permitted further assessment of change map accuracies by means of multiplying the accuracies of the independently classified maps (Yuan *et al.* 2005).

2.7 Data Analyses

2.7.1 Analysis of Land Cover Changes

This analysis involved two major steps. The first step established the individual units used for land cover change mapping while in the second step, the actual change detection was implemented.

2.7.1.1 Development of Mapping Units for Change Detection

To overcome the challenge posed by partial coverage of the study area by the multi-temporal satellite data, it was necessary to clip out the common area within this dataset. Further, within the common area, attempts were made to derive smaller units (*mapping units*) that would represent the missing portions. To achieve this, the research adopted an innovative approach that had been successfully applied for small-scale land use mapping on the basis of temporal Normalized Difference Vegetation Index (NDVI) characteristics (de bie's *et al.* n.d) to objectively derive these mapping units. Geo-referenced hyper-temporal SPOT data (324 ten-day composite NDVI images from 01.04.1998 to 31.03.2007) was classified repeatedly by unsupervised ISODATA (iterative self-organizing data analysis) clustering in ERDAS imagine 9.1 software. Each run had a specified number of clusters (classes), i.e. 5, 10, 11, 12, 13 and 14, a convergence threshold of 1 and a maximum of 10 iterations. A convergence threshold of 1 ensured attainment of maximum iteration in each run for better accuracy. Statistical divergence tests, that measure the distances between the generated signatures, were then conducted for each classification to establish the maximum signature separability among the classes. From the signature separability listings of each statistical divergence test, the minimum and the average values were entered in spreadsheet and a graph plotted (Appendix 4). The classification with 13 classes was selected for further analyses as it depicted a peak in average divergence statistical measure, hence, the one with the most distinct classes. The mean digital number (DN) values (i.e. {NDVI+0.1}/ 0.004) for each of its classes were extracted from the 324 image data layers and line graphs plotted showing the fluctuations in vegetative cover (and chlorophyll activity) from 01.04.1998 to 31.03.2007. The last step in derivation of the mapping units was grouping together the classes that depicted somewhat similar trends over the years thus reducing the classes from thirteen (13) to five (5). These formed the final mapping units used for the change detection. These were: **MU1** covering parts of Kinangop division; **MU2** covering parts of Ol Kalou division; **MU3** covering parts of Naivasha division and the lake and; **MU4** covering parts of Kipipiri division. The fifth unit, which was purely the lake, was included in **MU3**.

2.7.1.2. Change Detection

Post-classification comparison change detection algorithm was applied to determine the changes in land cover that had occurred, within each of the derived mapping units, in Lake Naivasha drainage basin over time. It is the most common approach used for monitoring land cover changes since it provides more useful information on the initial and final land cover types in a complete matrix of change direction (Campbell 2002, Fan *et al.* 2007, Fuller *et al.* 2003, Lu *et al.* 2004, Shalaby and Tateishi 2007, Singh 1999, Yang and Lo 2002, Yuan *et al.*2005). Further, it goes beyond simple change detection and quantifies the different rates and magnitude of changes. The degree of its success, however, depends on the reliability of the classified maps. The classified thematic maps for 2 different dates, e.g. 1986 and 1995, were loaded on to ERDAS 9.1 software and the change detection algorithm invoked. This produced change matrices from which the magnitude, rates and nature of land cover changes (internal conversions) were derived, as well as, change maps that exhibited their spatial distribution. The average (annual) rate of change between two periods was computed by a slightly modified formula used by Long *et al.* 2007, that is:

$$\Delta = \left\langle \frac{A2 - A1}{A1} \times 100 \right\rangle \div \langle T2 - T1 \rangle$$

Where:

Δ = Average annual rate of change (%)

$A1$= Amount of land cover type in time 1 ($T1$)

$A2$ = Amount of land cover type in time 2 ($T2$)

2.7.2 Analysis of the Driving Forces of Land Use

Rank-based Friedman's non-parametric analysis was conducted due to the correlated-sample nature of household survey and interviewing data. It is similar to repeated measures analysis of variance as it detects differences in treatments (variables) repeated on the same subjects at ordinal level (Zar 1996), that is, it facilitates two-way analysis of variance by ranks. Friedman's test makes no assumptions about data normality and homoscedasticity. It uses ranks in place of raw values to calculate the statistic and thus it is not as powerful as analysis of variance. It calculates the mean rank for each of the variables and, thereafter, indicates the differences in their mean ranks using the chi-square distribution at a given significance levels. The formula used for the computation of the test statistic (**F**) is shown below:

$$\mathbf{F} = \frac{12}{bk(k+1)} \sum_{i=1}^{k} R^2 - 3b(k+1)$$

Where:

b = the number of subjects (respondents) each represented by a row

R = the sum of the ranks given by the subjects in the columns

k = is the number of treatments (variables) ranked by the subjects

The null hypothesis (H_0) is rejected at a significance level (α) if F is greater than the chi-square distribution (χ^2) with (k-1) degrees of freedom, that is:

$$\mathbf{F} > \chi^2_{\alpha}(k-1)$$

The variables (*k*) in this specific research were the five (5) driving factors of land use ranked by the thirty (30) farmers (*b*) who were interviewed.

2.8 Data Presentation

Both the findings from field work, as well as, the result of their analyses were presented in the form of figures, i.e. thematic maps and bar charts, and tables.

3.0 RESULTS AND ANALYSES

This chapter presents the land cover maps resulting from classification of satellite images, assessment of map accuracy, analyses of the magnitude, rates, nature and geographic distribution of the land cover changes. The findings on some of the driving factors of land use in Lake Naivasha drainage basin are also presented.

3.1 Land Cover Classification

3.1.1 Land Cover Map

The three (3) thematic maps (Figures 5, 6 and 7) in this sub-section show the land cover types in Lake Naivasha drainage basin extracted from Landsat TM for 1986 and 1995 and ASTER for 2007. A total of ten (10) land cover types are displayed namely: cropland, cropland (horticulture), grassland, shrub land, built up land, woodland, bare land, water body, forest and moorland. The croplands were split into three sub-classes, i.e. horticulture, cultivated and ploughed croplands, during classification process due to their dissimilar spectral nature. The same case applied to grasslands, which appeared in two different tones on the satellite imagery. However, for change analysis, these have been merged.

Table 3: Description of land cover classes

Code	Land Cover	Description
10	Grasslands	These are areas dominated by grasses (0-0.2m) and herbs (0.2-2m)
20	Croplands	These are areas covered by growing crops, ploughed fields and horticultural farms
30	Forests	These are areas predominantly covered by tree (> 5m high) with closed canopies (> 40% cover).
40	Woodlands	These are areas dominated by scattered trees (> 5m high) with open canopies (< 40% cover).
50	Shrub lands	These are areas characterized by a high percentage of shrub cover (2 – 5m high)
60	Built-up	Areas with commercial or residential structures and/ or constructed materials.
70	Bare lands	These are either completely non-vegetated areas or areas with very low percent vegetation cover.
80	Water bodies	Areas covered by open waters, rivers and the lake.
90	Moorlands	Wetter areas, mostly, in the upper highlands and tropical alpine zones with low growing vegetation on acidic soils.

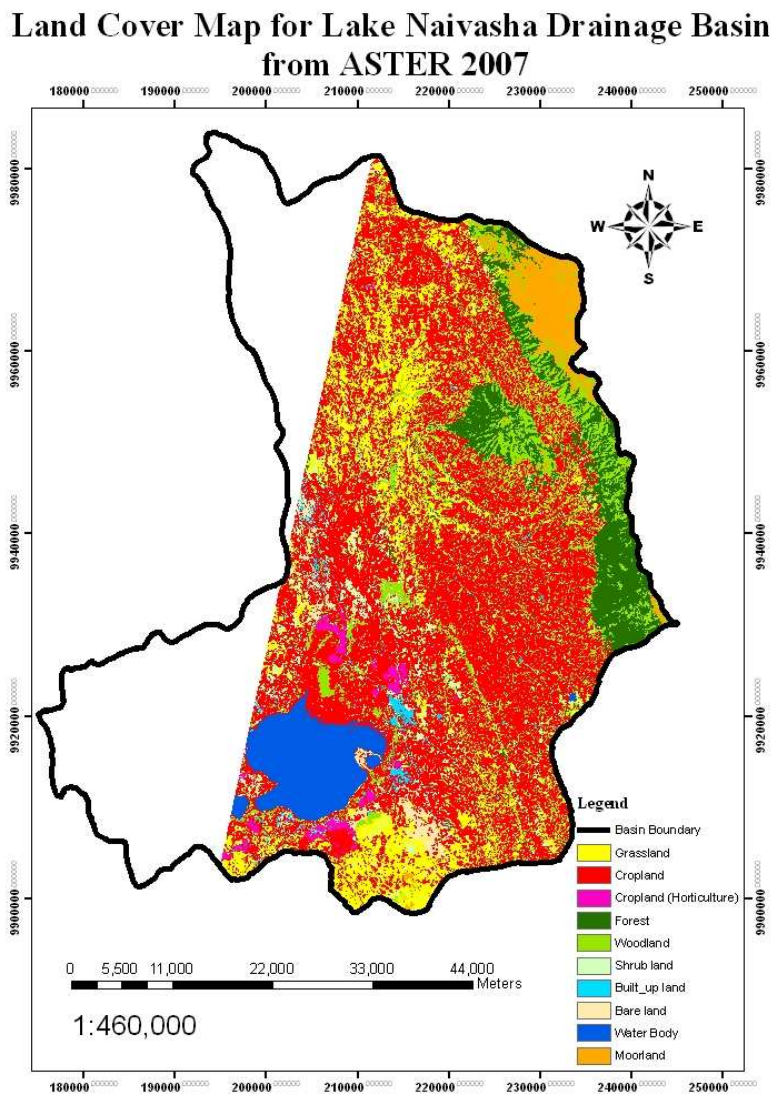


Figure 5: Land cover classification for 2007

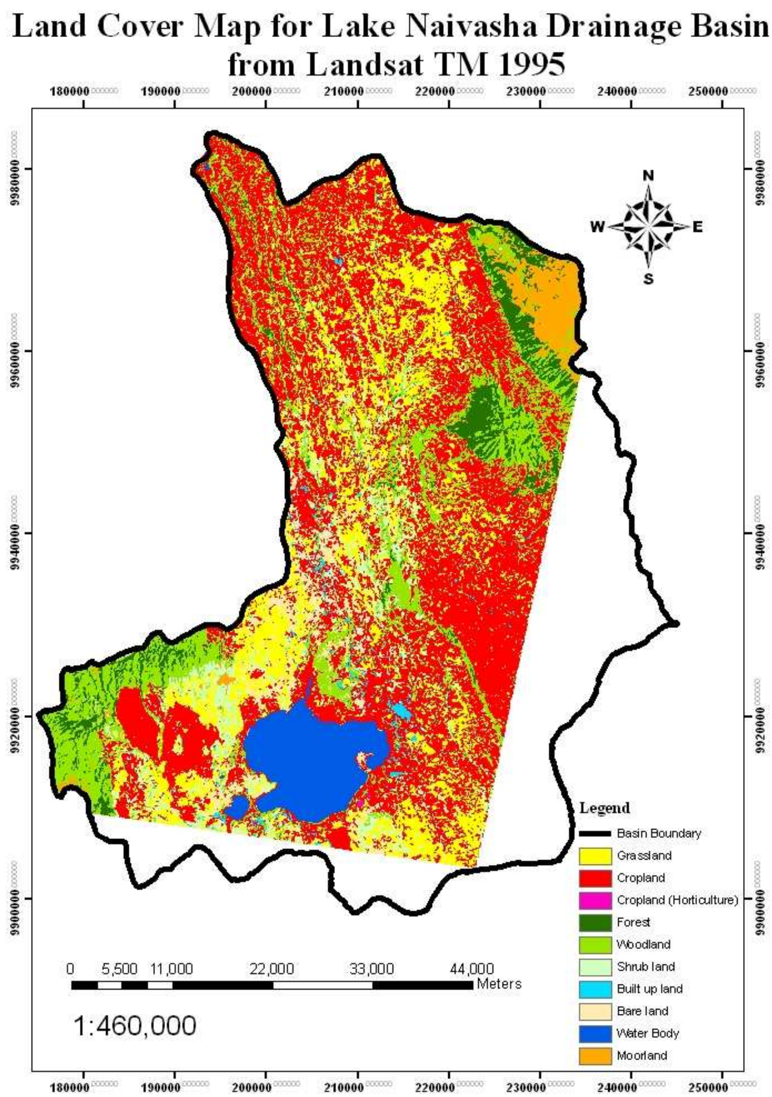


Figure 6: Land cover classification for 1995

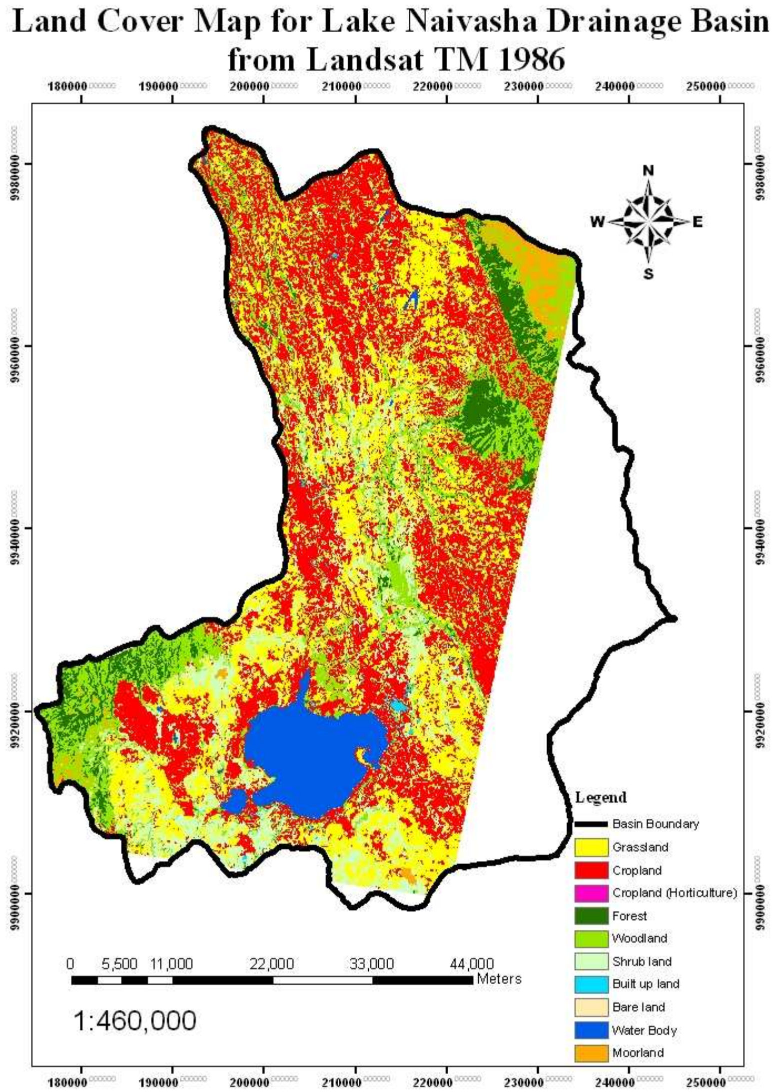


Figure 7: Land cover classification for 1986

Table 4: Accuracy assessment report for classification of ASTER (2007)

Table 4: Accuracy assessment report for the classification of ASTER image 2007

Cc=Cropland (Cultivated), G[I]&G[II]=Grassland, Cp=Cropland (ploughed), Ch=Cropland (horticulture), F=Forest, W=Woodland, Shrub land, Bt=Built-up land, B=Bare land, Wt=Water Bodies & M=Moorland

Error Matrix based on Test and Training Area (TTA) mask													
User/	Reference class												
	Cc	G [I]	G [II]	Cp	Ch	F	W	S	Bt	B	Wt	M	Totals
Cc	**5664**	131	27	18	0	62	535	362	2	0	2	0	6803
G [I]	7	**5047**	732	5	0	0	0	251	0	0	0	0	6042
G [II]	0	1123	**2334**	21	0	0	0	3	0	0	0	0	3481
Cp	0	289	0	**3281**	0	0	0	0	0	2	0	0	3572
Ch	0	0	0	0	**979**	0	0	0	0	0	0	0	979
F	0	0	0	0	0	**9391**	0	56	0	0	0	0	9447
W	28	14	0	7	0	201	**3811**	729	0	0	0	395	5185
S	53	175	0	0	0	0	330	**1312**	0	0	0	0	1870
Bt	0	0	0	0	0	0	0	0	**1330**	322	0	0	1652
B	0	2	0	0	0	0	0	0	7	**1370**	0	0	1379
Wt	0	0	0	0	0	0	0	0	0	0	**18865**	0	18865
M	0	0	0	0	0	0	0	0	0	0	0	**13465**	13465
Unclassified	0	0	0	0	6	0	0	0	2	0	3		11
Totals	5752	6781	3093	3332	985	9654	4676	2713	1341	1694	18870	13860	72751
Accuracy													
Producer	0.98	0.74	0.75	0.98	0.99	0.97	0.81	0.48	0.99	0.80	0.99	0.97	
User	0.83	0.83	0.67	0.91	1	0.99	0.73	0.70	0.80	0.99	1	1	
Kappa/ Class	0.98	0.72	0.74	0.98	0.99	0.96	0.80	0.47	0.99	0.80	0.99	0.96	
Overall	0.91												
Kappa	0.90												

NB: Grassland was split into two, and cropland into three, sub-classes in order to deal with the within-class variations.

3.1.2 Assessment of Land Cover Classification Accuracy

The statistical output from the comparison of an externally created TTA mask and the extracted land cover map from ASTER imagery for 2007 are summed up in Table 4. The first column shows the classes under evaluation (user's classes) whereas the other columns show the number of pixels covered by the TTA mask (reference data) for each class. The sums of the pixels for each class in the TTA mask are shown in the last row. The last column shows the sums of the classified pixels in each class on the extracted land cover map. The matrix, essentially gives an indication of the map quality in relation to the TTA mask. For example, in the forest category 9654 pixels contained in the TTA mask were forests. Out of these, 9301 were correctly classified as forest but 201 and 62 pixels were misclassified as woodlands and croplands (cultivated) respectively. Similarly, out of the 9447 pixels that were classified as forests in the generated land cover map, 52 pixels were confused with the shrubs. Shrub lands show the poorest results as it was mostly confused with the woodlands, croplands, grasses and forests. The overall accuracy achieved for this map is 91% while the kappa coefficient is 0.9. The latter statistic implies that 90% of the classification agreed with the reference data, leaving only 10% to chance. However, no remarks are made regarding the accuracies of the Land cover maps for 1986 and 1995 for lack of reference data to assess their quality.

3.2 Land Cover Change Analysis

3.2.1 Mapping Units Derived for Land Cover Change Detection

Figures 8 and 9 illustrate the outcome of the procedure described in sub-section 2.7.1.1 for delineating the individual units for land cover change mapping and analysis. Figure 8, shows on one side, the thirteen (13) classes resulting from the unsupervised classification of hyper-temporal SPOT-vegetation data by ISODATA clustering. The second part shows the five (5) classes arrived at by merging classes with somewhat similar temporal NDVI profiles (Appendix 4). Similarly, the first part of Figure 9 shows four mapping units when the smaller portions within the initial five larger classes are combined. The final part displays the four units defined for change analyses based on the available satellite data.

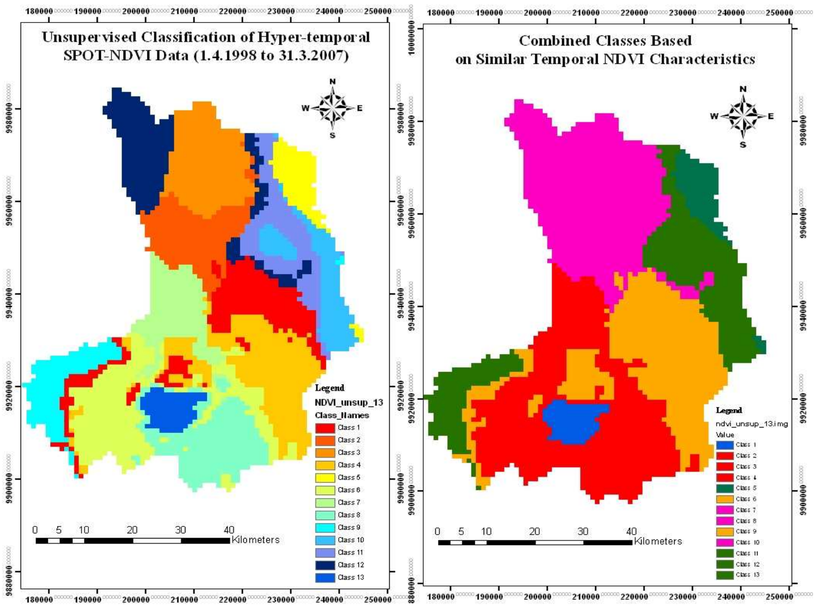


Figure 8: Unsupervised classification of SPOT-NDVI data and, the combined classes based on similar temporal NDVI behaviour

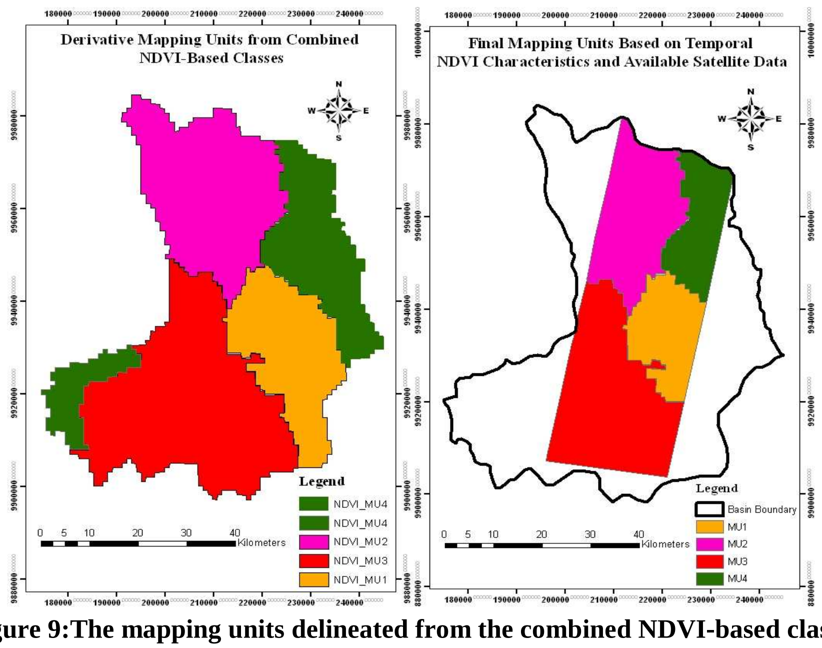


Figure 9:The mapping units delineated from the combined NDVI-based classes and, the final units based on the available satellite data

3.2.2 Magnitude and Rates of Land Cover Changes

The tables and figures in this sub-section provide quantitative information regarding the areal extent of each land cover type and the magnitude and rates of land cover changes within the four mapping units: **MU1** (Parts of Kinangop Division)**, MU2** (Parts of Ol Kalou Division)**, MU3** (Parts of Naivasha Division) and **MU4** (Parts of Kipipiri Division and Aberdares Mountain Ranges)**.** The areal extents are derived from the number of pixel counts within each class in a given land cover map and the spatial resolution of the imagery, while the rates of change are computed using the formula given in sub-section 2.7.1.2. A negative sign before a given value denotes a decrease in the rate and magnitude of change in the land cover type.

A. *Mapping Unit 1 (MU1)*

The results in Table 5 indicate that grasslands, forests, woodlands, and shrub lands declined steadily from 1986 through to 2007 at annual rates between 0 and 5%. In contrast, croplands and built up areas had notable increases with annual rates surpassing 5%, at least, in one of the two dates. The remaining land cover types had a mix of increases and decreases, in their cover proportions and rates of change, within the period.

Table 5: Areal, Magnitude and Rates of Land Cover Changes in MU1

Land Cover	**Area (Km^2)**			**Magnitude (Km^2)**			**Rate per annum (%)**		
	1986	**1995**	**2007**	**86-95**	**95-07**	**86-07**	**86-95**	**95-07**	**86-07**
Grasslands	69.8	41.3	34.0	-28.5	-7.3	-35.8	-4.5	-1.4	-2.4
Croplands	130.9	191.1	201.5	60.2	10.4	70.6	5.1	0.4	2.5
Forests	5.1	3.2	3.1	-1.9	-0.1	-2.0	-4.1	-0.2	-1.8
Woodlands	47.2	44.3	35.9	-2.9	-8.4	-11.3	-0.6	-1.5	-1.1
Shrub lands	35.4	19.4	16.2	-16	-3.2	-19.2	-5.0	-1.3	-2.5
Built up	1.3	1.4	3.0	0.1	1.6	1.7	0.8	9.5	6.2
Bare lands	8.1	0.6	1.1	-7.5	0.5	-7.0	-10.2	6.9	-4.1
Water	0.5	0.3	0.3	-0.2	0.0	-0.2	-4.4	0.0	-1.9
Moorlands	0.0	0.0	0.1	0.0	0.1	0.1	0.0	∞	∞

These findings are, also, graphically, represented in Figure 10:

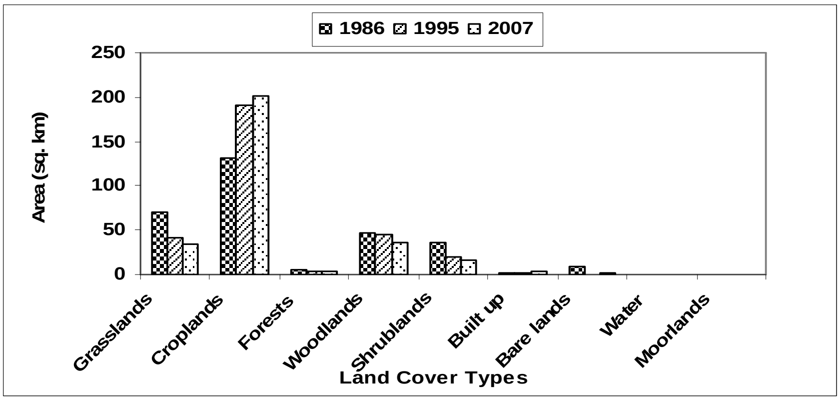


Figure 10: The relative land cover changes in MU1

B. Mapping Unit 2 (MU2)

Just like in MU1, Table 6 exhibits continual decline in grasslands from 1986 through to 2007. Croplands, on the other hand, expanded throughout this period and so were the built up areas. In addition, the forests and shrub lands experienced steady rates of decline while the remnant land cover classes, i.e. woodlands, water, bare lands and moorlands, experienced both increases and decreases in their cover proportions.

Table 6: Areal, Magnitude and Rates of Land Cover Changes in MU2

Land Cover	**Area (Km^2)**			**Magnitude (Km^2)**			**Rate per annum (%)**		
	1986	**1995**	**2007**	**86-95**	**95-07**	**86-07**	**86-95**	**95-07**	**86-07**
Grasslands	172.7	164.5	161.3	-8.2	-3.2	11.4	-0.5	-0.1	-0.3
Croplands	194.6	225.9	258.3	31.3	32.4	63.7	1.7	1.1	1.5
Forests	4.7	4.6	3.7	-0.1	-0.9	-1.0	-0.2	-1.6	-1.0
Woodlands	48.7	49.7	41.0	1.0	-8.7	-7.7	0.2	-1.4	-0.7
Shrub lands	49.4	36.8	13.1	-12.6	-23.7	-36.3	-2.8	-5.3	-3.4
Built up	1.4	2.0	2.8	0.6	0.8	1.4	4.7	3.3	4.7
Bare lands	14.9	3.8	6.5	-11.1	2.7	-8.4	-8.2	5.9	-2.6
Water	2.5	0.2	0.2	-2.3	0.0	-2.3	-10.2	0.0	-4.3
Moorlands	0.5	0.2	0.6	-0.3	0.4	0.1	-6.6	16.6	0.9

Figure 11 shows the dynamics in areal extent of the land cover types in this mapping unit between 1986 and 2007:

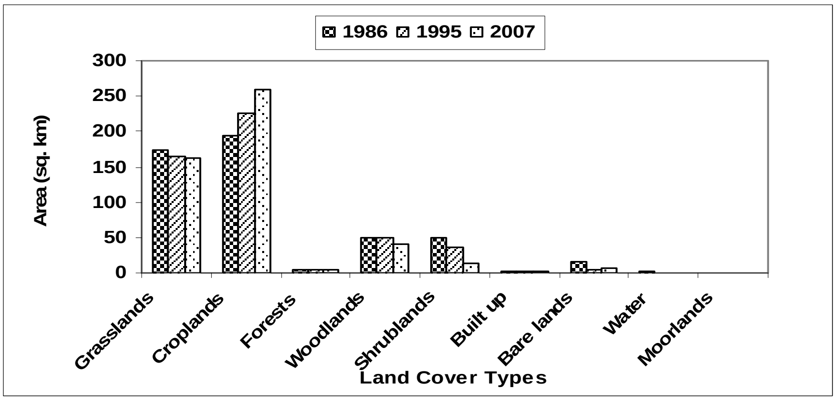


Figure 11: The relative land cover changes in MU2

C. Mapping Unit 3 (MU3)

It is quite evident from the negative rates and magnitude of changes in Table 7 that the grasslands, forests, woodlands, water bodies and shrub lands declined in MU3 between 1986 and 2007. The positive rates and magnitude of changes in croplands, moorlands and built up categories, however, indicates the gains they made. Bare lands display a combination of positive and negative changes within this period.

Table 7: Areal, Magnitude and Rates of Land Cover Changes in MU3

Land Cover	**Area (Km^2)**			**Magnitude (Km^2)**			**Rate per annum (%)**		
	1986	**1995**	**2007**	**86-95**	**95-07**	**86-07**	**86-95**	**95-07**	**86-07**
Grasslands	181.1	146.1	59.7	-35.0	-86.4	-121	-2.1	-4.9	-3.1
Croplands	240.9	258.7	380.3	17.8	121.6	139.4	0.8	3.9	3.2
Forests	0.8	0.3	0.3	-0.5	0.0	-0.5	-6.9	0.0	-2.9
Woodlands	42.5	40.8	30.9	-1.7	-9.9	-11.6	-0.4	-2.0	-1.2
Shrub lands	63.4	42.7	39.2	-20.7	-3.5	-24.2	-3.6	-0.6	-1.8
Built up	10.7	20.7	21.9	10.0	1.2	11.2	10.3	0.4	4.9
Bare lands	31.8	66.1	52.1	34.3	-14	20.3	11.9	-1.7	3.0
Water	143.2	138.5	129.4	-4.7	-9.1	-13.8	-0.3	-0.5	-0.4
Moorlands	0.0	0.1	0.2	0.1	0.1	0.2	∞	8.3	∞

These changes are, also, reflected in Figure 12:

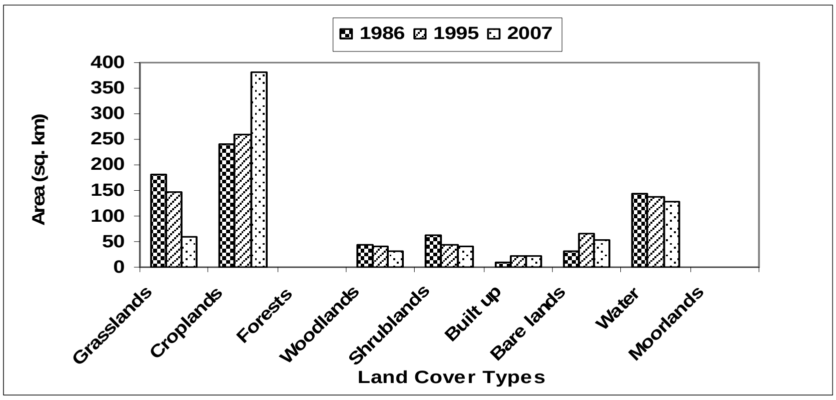


Figure 12: The relative land cover changes in MU3

D. Mapping Unit 4 (MU4)

Unlike in the other mapping units, the results in Table 8 suggest that the rates and magnitude of changes in grasslands were negative, only, between 1986 and 1995 and, thereafter, increased remarkably. The croplands, built up, bare lands and moorlands had positive changes all through whereas the changes in woodlands were negative. The remaining classes either, witnessed increases during the former period and decreases in the latter, or the converse of this.

Table 8: Areal, Magnitude and Rates of Land Cover Changes in MU4

Land Cover	Area (Km^2)			Magnitude (Km^2)			Rate per annum (%)		
	1986	1995	2007	86-95	95-07	86-07	86-95	95-07	86-07
Grasslands	5.1	2.0	9.7	-3.1	7.7	4.6	-6.7	32	4.2
Croplands	50.5	55.2	27.7	4.7	2.5	7.2	1.0	0.3	0.6
Forests	71.8	72.9	66.6	1.1	-6.3	-5.2	0.1	-0.7	-0.3
Woodlands	102.3	82.7	67.4	-19.6	-15.3	-34.9	-2.1	-1.5	-1.6
Shrub lands	2.8	1.4	2.5	-1.4	1.1	-0.3	-5.5	6.5	-0.5
Built up	0.2	0.2	0.3	0.0	0.1	0.1	0.0	4.1	2.3
Bare lands	0.0	0.0	0.3	0.0	0.3	0.3	0.0	∞	∞
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Moorlands	42.0	60.3	70.3	18.3	10.0	28.3	4.8	1.3	3.2

These trends are, further, depicted in Figure 13:

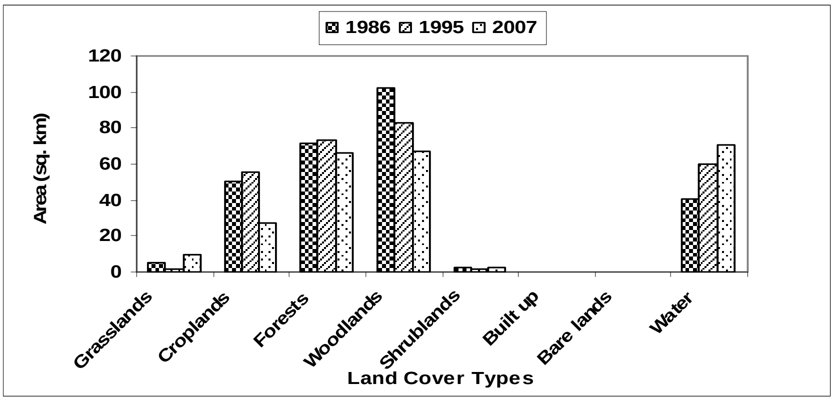


Figure 13: The relative land cover changes in MU4

3.2.3 Nature of Land Cover Changes

The patterns of transition from one land cover to another that have taken place in Lake Naivasha drainage basin from 1986 to 2007, within **MU1, MU2, MU3** and **MU4**, are presented in the following change matrices (tables). In these matrices, the unchanged pixels are located along the major diagonals and the total areas (in km^2), for the given years, occur on the final rows and columns.

A. Mapping Unit 1 (MU1)

From Table 9, it is apparent that croplands had the greatest increase (i.e. 60 km^2) among the land cover types between 1986 and 1995. It gained a great deal, especially, from grasslands (43.7 km^2) and other land cover types viz. forest (0.6 km^2), shrubs (14.2 km^2), woodlands (17.5 km^2) and bare lands (6.6 km^2). In similar fashion, the croplands were also replaced by other land cover types such as grasslands (16.2 km^2), woodlands (4.6 km^2) and built up (0.7 km^2), within this period. Though a huge area of grassland was converted to croplands in 1995, they also gained a bit from croplands (16.2 km^2), woodlands (1.7 km^2) and shrub lands (2.9 km^2).

Table 9: Nature of changes in MU1 from 1986 to 1995

1995	1986 G	C	F	Wd	S	Bt	B	Wt	M	Total
G	**18.9**	16.2	0.0	1.7	2.9	0.2	1.2	0.1	0.0	**41.3**
C	43.7	**107.1**	0.6	17.5	14.2	0.9	6.6	0.3	0.0	**191.0**
F	0.0	0.0	**1.5**	1.4	0.3	0.0	0.0	0.0	0.0	**3.2**
Wd	3.3	4.6	2.7	**23.6**	9.7	0.1	0.2	0.0	0.0	**44.2**
S	3.3	1.8	0.3	2.6	**8.1**	0.1	0.0	0.0	0.0	**16.2**
Bt	0.4	0.7	0.0	0.1	0.1	**0.0**	0.0	0.0	0.0	**1.4**
B	0.2	0.3	0.0	0.0	0.0	0.0	**0.0**	0.0	0.0	**0.6**
Wt	0.0	0.1	0.0	0.1	0.0	0.0	0.0	**0.1**	0.0	**0.3**
M	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.0**
Total	**69.8**	**130.9**	**5.1**	**47.2**	**35.4**	**1.3**	**8.1**	**0.5**	**0.0**	**298.3**

In Table 10, an upward trend in croplands and built up, between 1995 and 2007, in MU1, is revealed at the expense of grasslands, woodlands and forests. The shrub lands and bare lands, which were on the decline between 1986 and 1995 (Table 9) reversed the trend and experienced some moderate gains mainly from croplands (i.e. 8 km^2 and 0.9 km^2 respectively).

Table 10: Nature of changes in MU1 from 1995 to 2007

2007	1995 G	C	F	Wd	S	Bt	B	Wt	M	Total
G	**6.9**	16.5	0.2	6.1	4.2	0.1	0.0	0.0	0.0	**34.0**
C	29.0	**146.4**	0.6	16.5	7.4	1.0	0.5	0.1	0.0	**201.5**
F	0.1	0.6	**0.4**	1.9	0.1	0.0	0.0	0.0	0.0	**3.1**
Wd	2.6	16.2	1.7	**13.3**	1.8	0.2	0.0	0.0	0.0	**35.9**
S	2.1	8.0	0.3	6.3	**2.6**	0.1	0.0	0.0	0.0	**19.4**
Bt	0.4	2.3	0.0	0.2	0.1	**0.1**	0.0	0.0	0.0	**3.0**
B	0.1	0.9	0.0	0.1	0.0	0.0	**0.0**	0.0	0.0	**1.1**
Wt	0.0	0.2	0.0	0.0	0.0	0.0	0.0	**0.1**	0.0	**0.3**
M	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.1**
Total	**41.3**	**191.1**	**3.2**	**44.3**	**16.2**	**1.4**	**0.6**	**0.3**	**0.0**	**298.4**

B. Mapping Unit 2 (MU2)

Like in MU1, it is revealed in Table 11 that croplands had the largest gains (32.5 km^2) relative to the other land cover types between 1986 and 1995. Conversions, mainly from grasslands (67.3 km^2), woodlands (15.6 km^2), shrub lands (13.4 km^2) and bare lands (8.1 km^2) contributed the bulk of this increment. Despite loses to croplands, the woodlands also increased by a margin of 1 km^2 thanks to conversions from grasslands (6.7 km^2), croplands (7.6 km^2) and shrub lands (11.4 km^2). The overall effect of the conversions of bare lands, water, forests and shrub lands to the other land cover types is the evident decline in their trend.

Table 11: Nature of changes in MU2 from 1986 to 1995

	1986									
1995	**G**	**C**	**F**	**Wd**	**S**	**Bt**	**B**	**Wt**	**M**	**Total**
G	**85.0**	59.3	0.0	4.8	9.2	0.3	5.7	0.7	0.0	**165.1**
C	67.3	**119.9**	0.2	15.6	13.4	0.8	8.1	1.5	0.1	**227.1**
F	0.0	0.1	**2.0**	2.2	0.3	0.0	0.0	0.0	0.0	**4.6**
Wd	6.7	7.6	2.4	**21.1**	11.4	0.1	0.2	0.0	0.2	**49.7**
S	12.4	4.3	0.1	4.6	**14.8**	0.0	0.3	0.2	0.1	**36.9**
Bt	0.5	1.0	0.0	0.2	0.1	**0.1**	0.1	0.0	0.0	**2.0**
B	0.8	2.4	0.0	0.1	0.1	0.0	**0.5**	0.0	0.0	**3.8**
Wt	0.0	0.1	0.0	0.0	0.0	0.0	0.0	**0.1**	0.0	**0.2**
M	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	**0.0**	**0.2**
Total	**172.7**	**194.6**	**4.7**	**48.7**	**49.4**	**1.4**	**14.9**	**2.5**	**0.5**	**489.5**

Between 1995 and 2007, the statistics provided in Table 12 indicate that croplands maintained the same magnitude of increase (32.4 km^2) in MU2 as in the previous period. Transformations from grasslands (85.5 km^2), woodlands (16.6 km^2) and shrub lands (13.0 km^2) remained the primary factors responsible for this growth. The built up areas, bare lands and moorlands, also increased as water maintained *status quo*. In contrast, the woodlands, which had increased previously, lost 8.7 km^2 of their total cover as grasslands, forests and shrub lands followed suit.

Table 12: Nature of changes in MU2 from 1995 to 2007

	1995									
2007	**G**	**C**	**F**	**Wd**	**S**	**Bt**	**B**	**Wt**	**M**	**Total**
G	**67.0**	61.1	0.8	13.4	17.5	0.4	1.1	0.0	0.1	**161.3**
C	85.5	**139.0**	0.5	16.6	13.0	1.2	2.3	0.1	0.0	**258.3**
F	0.1	0.5	**1.1**	1.8	0.2	0.0	0.0	0.0	0.0	**3.7**
Wd	6.0	16.0	1.6	**14.2**	3.0	0.1	0.0	0.0	0.0	**41.0**
S	2.7	3.8	0.5	3.3	**2.7**	0.0	0.1	0.0	0.0	**13.1**
Bt	0.8	1.5	0.0	0.1	0.1	**0.1**	0.1	0.0	0.0	**2.8**
B	2.2	3.7	0.0	0.1	0.2	0.1	**0.2**	0.0	0.0	**6.5**
Wt	0.0	0.1	0.0	0.0	0.0	0.0	0.0	**0.1**	0.0	**0.2**
M	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	**0.0**	**0.6**
Total	**164.5**	**225.9**	**4.6**	**49.7**	**36.8**	**2.0**	**3.8**	**0.2**	**0.2**	**487.7**

C. *Mapping Unit 3 (MU3)*

Lake Naivasha, the principal water body, is situated within this unit. Its total surface area decreased by 4.7 km^2 between 1986 and 1995 as shown in Table

13. Some of the area under water was converted to croplands, forests, woodlands and shrubs and, similarly, some of the areas occupied by these land covers were converted back to water. Overall, cropland expanded by 18 km^2 through reciprocal loses and gains from the conversions between grasslands, woodlands, shrub lands, bare lands and water.

Table 13: Nature of changes in MU3 from 1986 to 1995

	1986									
1995	**G**	**C**	**F**	**Wd**	**S**	**Bt**	**B**	**Wt**	**M**	**Total**
G	**80.6**	40.8	0.0	2.3	16.7	0.8	4.9	0.1	0.0	**146.2**
C	66.8	**133.1**	0.1	13.9	16.1	5.0	17.1	6.7	0.0	**258.9**
F	0.0	0.0	**0.1**	0.1	0.0	0.0	0.0	0.1	0.0	**0.3**
Wd	3.3	9.8	0.2	**18.1**	7.1	0.8	0.8	0.7	0.0	**40.8**
S	14.2	4.4	0.2	3.1	**19.9**	0.4	0.5	0.1	0.0	**42.7**
Bt	2.2	10.3	0.0	2.2	1.5	**3.2**	1.2	0.0	0.0	**20.7**
B	14.1	40.6	0.0	1.8	2.0	0.4	**7.2**	0.0	0.0	**66.1**
Wt	0.0	1.8	0.2	0.9	0.1	0.0	0.0	**135.5**	0.0	**138.5**
M	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.1**
Total	**181.1**	**240.9**	**0.8**	**42.5**	**63.4**	**10.7**	**31.8**	**143.2**	**0.0**	**714.4**

It is evident from Table 14 that contraction of water bodies, mainly the lake, persisted between 1995 and 2007 with a huge area (7.4 km^2) being converted to croplands. However, croplands increased remarkably by 121.6 km^2. This constituted conversions, majorly from grasslands, woodlands, bare lands, shrub lands and water. The croplands were also replaced by the same land cover types. The other conversions within this mapping unit led to reductions in woodlands, bare lands and shrub lands as shown in the table.

Table 14: Nature of changes in MU3 from 1995 to 2007

	1995									
2007	**G**	**C**	**F**	**Wd**	**S**	**Bt**	**B**	**Wt**	**M**	**Total**
G	**30.3**	13.1	0.0	1.8	10.7	0.5	2.4	0.9	0.0	**59.7**
C	81.6	**188.3**	0.2	23.7	20.7	11.7	46.7	7.4	0.1	**380.3**
F	0.0	0.0	**0.0**	0.1	0.0	0.0	0.0	0.1	0.0	**0.3**
Wd	2.4	11.2	0.1	**11.4**	2.6	1.3	1.3	0.5	0.0	**30.9**
S	16.8	10.0	0.0	1.8	**7.1**	0.4	2.7	0.3	0.0	**39.2**
Bt	2.0	11.4	0.0	1.1	0.5	**4.9**	1.9	0.0	0.0	**21.9**
B	13.0	23.8	0.0	0.8	1.0	1.8	**11.1**	0.6	0.0	**52.1**
Wt	0.0	0.8	0.0	0.1	0.0	0.0	0.0	**128.5**	0.0	**129.4**
M	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	**0.2**
Total	**146.1**	**258.7**	**0.3**	**40.8**	**42.7**	**20.7**	**66.1**	**138.5**	**0.1**	**714.0**

D. Mapping Unit 4 (MU4)

In reference to Table 15, the moorlands, croplands and woodlands depict considerable changes. The woodlands decreased tremendously from 102.2 km^2 to 82.7 km^2 due to their replacement by the moorlands (26.7 km^2), forests (18.1 km^2) and croplands (16.2 km^2). Likewise, conversions from grasslands and woodlands added on to croplands as conversions from forests and woodlands added on to moorlands.

Table 15: Nature of changes in MU4 from 1986 to 1995

	1986									
1995	**G**	**C**	**F**	**Wd**	**S**	**Bt**	**B**	**Wt**	**M**	**Total**
G	**0.7**	1.0	0.0	0.2	0.0	0.0	0.0	0.0	0.1	**2.0**
C	3.5	**32.8**	1.1	16.2	1.5	0.1	0.0	0.0	0.0	**55.2**
F	0.0	0.5	**44.6**	18.1	0.1	0.0	0.0	0.0	9.8	**73.1**
Wd	0.6	15.7	18.9	**40.5**	1.1	0.0	0.0	0.0	5.9	**82.7**
S	0.1	0.3	0.1	0.4	**0.1**	0.0	0.0	0.0	0.2	**1.2**
Bt	0.0	0.1	0.0	0.1	0.0	**0.0**	0.0	0.0	0.0	**0.2**
B	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	0.0	0.0	**0.0**
Wt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	0.0	**0.0**
M	0.2	0.0	7.1	26.7	0.0	0.0	0.0	0.0	**26.0**	**60.1**
Total	5.1	50.5	71.8	102.2	2.8	0.2	0.0	0.0	42.0	**274.6**

In the second period (1995-2007), Table 16 shows sustained expansion of croplands and moorlands in MU4 while the woodlands continued to contract. The forests also decreased immensely from 72.9 km^2 to 66.6 km^2 due to their conversions to croplands (1.8 km^2), woodlands (16.5 km^2) and moorlands (11.0 km^2). Further, shrub lands gained some increases from croplands, grasses, forests and woodlands.

Table 16: Nature of changes in MU4 from 1995 to 2007

	1995									
2007	**G**	**C**	**F**	**Wd**	**S**	**Bt**	**B**	**Wt**	**M**	**Total**
G	**0.4**	4.6	0.5	3.9	0.1	0.0	0.0	0.0	0.2	**9.7**
C	1.2	**33.6**	1.8	20.3	0.6	0.1	0.0	0.0	0.1	**57.7**
F	0.0	1.2	**42.7**	20.3	0.1	0.0	0.0	0.0	2.2	**66.6**
Wd	0.3	14.1	16.5	**29.9**	0.5	0.1	0.0	0.0	6.0	**67.4**
S	0.1	1.1	0.4	0.9	**0.0**	0.0	0.0	0.0	0.0	**2.5**
Bt	0.0	0.2	0.0	0.1	0.0	**0.0**	0.0	0.0	0.0	**0.3**
B	0.0	0.2	0.0	0.1	0.0	0.0	**0.0**	0.0	0.0	**0.3**
Wt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	0.0	**0.0**
M	0.1	0.1	11.0	7.3	0.1	0.0	0.0	0.0	**51.8**	**70.3**
Total	**2.0**	**55.2**	**72.9**	**82.7**	**1.4**	**0.2**	**0.0**	**0.0**	**60.3**	**274.8**

3.2.4 Spatial Distribution of Land Cover Changes

The above change statistics indicates the changes that have occurred in a given land cover type in relation to the others. By creating a change map, the distribution of these changes in space over time is attained. Figures 14 to 17 show the status of land cover in the initial period (1986) and the subsequent years (1995 and 2007). All the conversions have been lumped into one class, '*combined changes*', while the unchanged areas retain their original colours and class names.

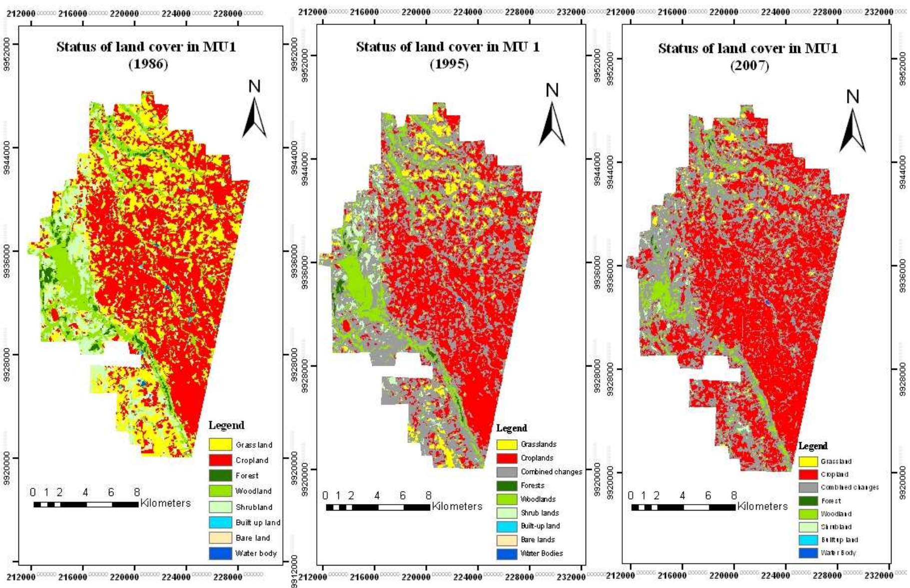


Figure 14: Land cover change maps for MU1 (1986 to 2007)

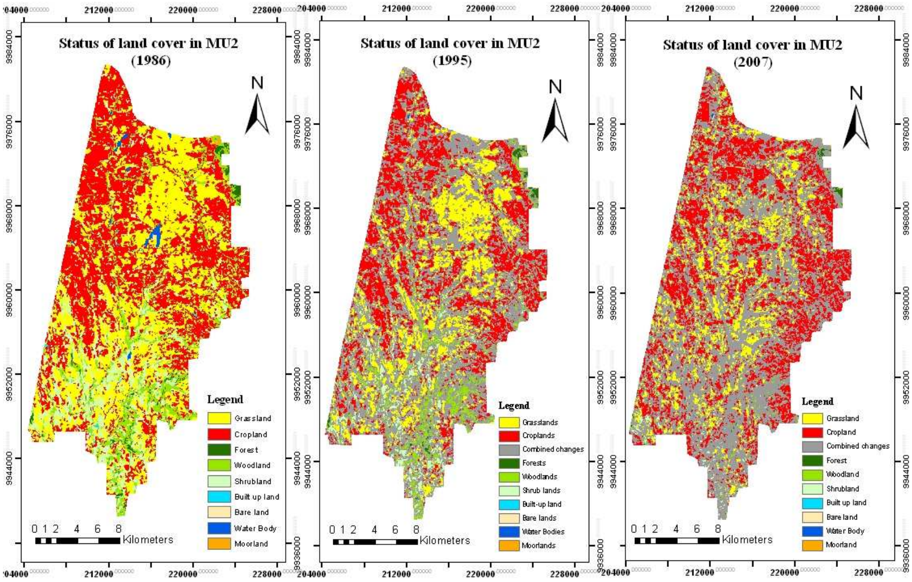


Figure 15: Land cover change maps for MU2 (1986 to 2007)

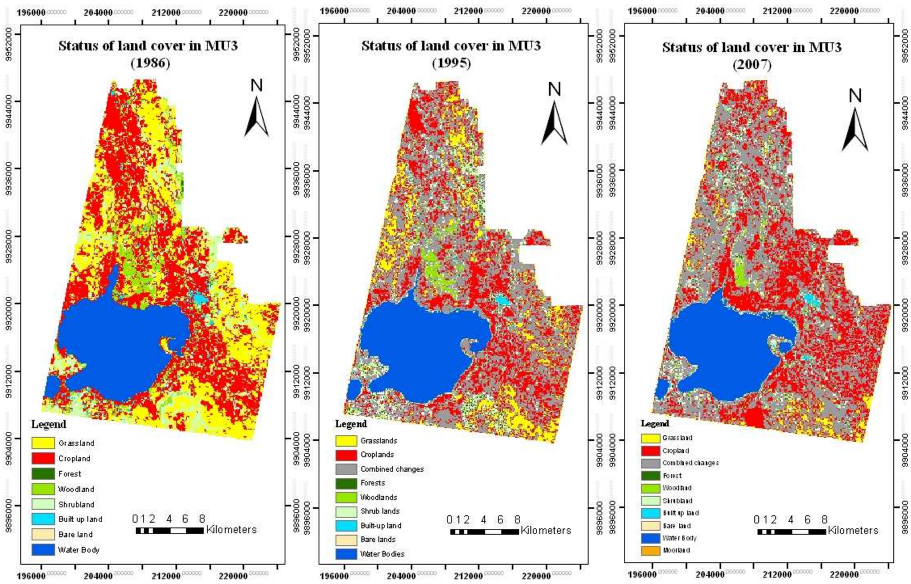


Figure 16: Land cover change maps for MU3 (1986 to 2007)

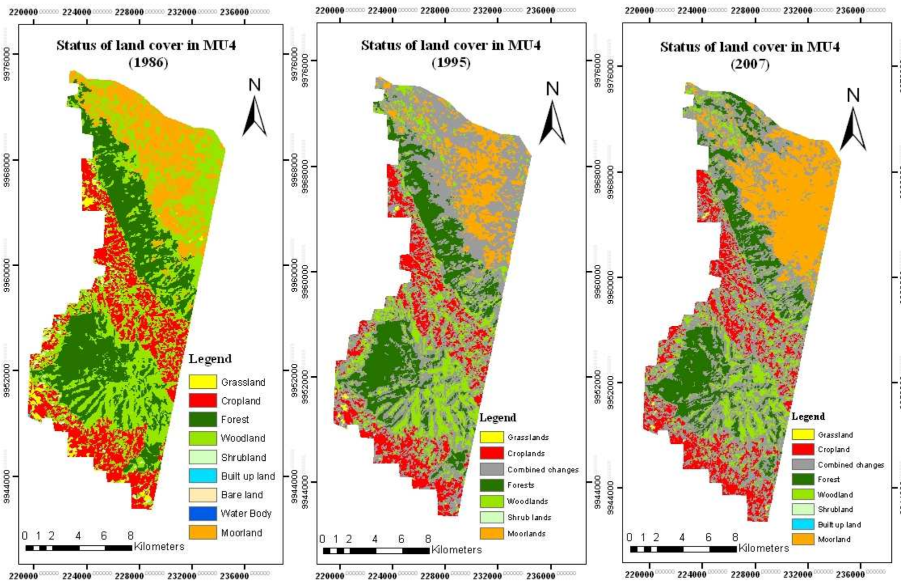


Figure 17: Land cover change maps for MU4 (1986 to 2007)

3.3 Driving Forces of Land Use in Lake Naivasha Drainage Basin

The responses obtained from the interviews captured some of the on-going interactions between the bio-physical, socio-economic, cultural and political processes in space and time. Land use history and the perceived land cover changes, however, precede the presentation of these processes in this section:

3.3.1 Land Use History

a) In the colonial era, the upper basin, particularly, Kinangop area was occupied by the European settlers (wazungu) who, mainly, grew apples, wheat, barley and pyrethrum for commercial purposes.

b) The wazungu also kept dairy cattle in this area, which was predominated by the Kikuyu grass (*Pennisetum clandestinum*) and had only a few trees.

c) Upon the independence of Kenya in 1963, this land was re-occupied by Kenyans, who were either resettled or offered land by the new government. Rearing of cattle for milk and cultivation of crops such as pyrethrum, potatoes, beans, peas, carrots, cabbages, maize (on small scale due to unfavourable frosty weather), wheat, fruits, Napier, Lucerne, onions among other crops, persisted. In late 1960s, the residents, also, began planting trees, mainly, the eucalyptus trees; a practice that has endured to the present age. The month of April is renowned for tree planting.

d) The farmlands were as large as 40 acres in 1964, shortly after independence, but presently, this had diminished to lows of 2 to 4 acres per household thanks to the sale and sub-divisions of land among the elder sons and unmarried daughters. This practice commenced in the late 1970s.

e) The lower basin, encompassing the lake and its environs, were formerly occupied by the Maasai communities who practiced nomadic pastoralism. In 1905, large scale mixed farming was introduced, upon the settlement of the wazungu, in the area.

3.3.2 Respondents' Perception of Land Cover Changes

In the upper parts of Lake Naivasha drainage basin there had been:

a) Preponderance of Kikuyu grass (*Pennisetum clandestinum*) with few trees due to the frosty weather conditions and low population in the area, both in the colonial times and shortly after independence.

b) Decline in grassland following the resettlement of Kenyans, who mainly cultivated crops, in the area.

c) Increase in the proportion of tree cover due to the culture of planting trees alongside the crop fields and homesteads.

d) Increasing residential settlements with the increasing sizes of households; approximately 380 farmers were resettled in the area, after independence but, their number amounted to about 12,000 farmers at the time of the survey.

e) Diminishing sizes of both cultivated and pasture lands due to the increasing household sizes.

f) Felling of trees for timber, settlement and cultivation in the forested areas such as the Aberdares, Ngeta etc, especially, in the 1980s.

In the lower parts of Lake Naivasha drainage basin there had been:

f) Development of unplanned human settlements in Naivasha town and its environs owing to the influx of people who came to work in the horticultural, geothermal production and tourism firms that flourished in the 1990s.

g) Conversion of former pastoral lands to large scale horticultural and mixed farms, which had become the backbone of Naivasha's economy and, at the same time, a source of conflict between the *Maasais* and the farm owners. Flower farms, for instance the New Holland Flowers in Wanjohi, Kipipiri division, had, also, emerged in the upper parts.

h) Overgrazing had been, and still was, a serious environmental issue, especially, in the riparian zones according to the in-charge of the WWF.

3.3.3 Processes Affecting Land Use leading to Land Cover Changes

Table 17 presents the trends of some events that had taken place in the upper basin (MU1&MU4) over time. These were observations made by members of the *Githabai* self-help group who were interviewed.

Table 17: Timeline of Events and Processes in Upper Basin (MU1&MU4)

Time	Events
1950's	-Large tracts of land, e.g. Kinangop covered by montane grass -Presence of wild life such as hyena, gazelles, zebras etc -Predominance of frosty climatic conditions -Practice of dairy farming and cultivation of pyrethrum, barley and wheat by the *Wazungus*
1960's	-Attainment of Kenya's independence and resettlement of Kenyans in the area -Persistence of crop cultivation (pyrethrum) and dairy farming -Commencement of eucalyptus tree planting -Farmlands as large as 40 (forty) acres on average size
1970's	-Incentive for cultivation of wheat and barley through financing and marketing by the Kenya Breweries company Limited. -Ready market for milk and vegetables surpluses provided by KCC and Pan African Board respectively. -Frosty climatic conditions continued to favour production of dairy cattle and sheep farming -Beginning of sub-divisions and sale of parcels of land.
1980's	-Severe drought that almost denuded vegetative cover. -The onset of tree felling in the Aberdares mountain ranges.
1990's	-Poor performance by KCC and its eventual collapse -Withdrawal of Pan African Board from the vegetable market -Collapse of the pyrethrum board of Kenya -Relenting of the initial severe frosty conditions in the area
2000's	-Severe drought that necessitated food relief. -Revival of KCC -Improvement of infrastructure -Reduction of tree felling in the Aberdares mountain ranges

3.3.3.1 Physical factors:

Climatic conditions: The frosty weather experienced in Kinangop area, the upper of the lake Naivasha drainage basin, notably during the months of February, July and September favoured the rearing of dairy cattle and sheep while hindered the cultivation of annual crops such as maize and beans. As such, maize grown in the area was primarily used as fodder for the dairy cattle. Similarly, semi-arid conditions that prevailed in the lower parts of Naivasha basin favoured ranching and keeping of drought-resistant animals such as goat, beef cattle and sheep. Severe droughts experienced countrywide in 1984 and 2000 also adversely affected land use and land cover. The farmers particularly commented that the drought experienced in 1984 denuded vast tracts of land in its wake.

3.3.3.2 Social factors:

Poverty: It was mentioned that some people let out their parcels of land to rich farmers for periods that ranged between 1 (one) and 3 (three) years. The rich farmers, subsequently, used agro-chemicals and mechanized farming techniques to cultivate crops such as wheat, and hence, degraded the croplands upon the expiry of the let-out date.

Population/ Household Size: The population in the area had risen since independence. This was evidenced by the large sizes of nuclear households that typically comprised of 5 to 10 members, in the upper parts of the Naivasha basin. This, majorly, accounted for the sub-divisions of land, which had been ongoing in the area since late 1970s. Consequently, the amount of land available for pasture and agriculture had been diminishing.

Table 18: Population of the administrative divisions within Naivasha basin

Year	Division	Province	Male	Female	Total	HHs
1979	Ol-Kalou	Central	28980	29638	**58618**	10482
	Kipipiri	Central	15515	16884	**32399**	5869
	Gilgil	Rift Valley	18733	16604	**35337**	8221
	Kinangop	Central	30029	31170	**61199**	10634
	Naivasha	Rift Valley	26600	23749	**50349**	12329
1989	Ol-Kalou	Central	28688	29058	**57746**	11083
	Kipipiri	Central	33960	36036	**69996**	13438
	Gilgil	Rift Valley	23336	21218	**44554**	10000
	Kinangop	Central	43295	44311	**87606**	15876
	Naivasha	Rift Valley	53651	51807	**105458**	26796
1999	Ol-Kalou	Central	51403	52652	**104055**	22329
	Kipipiri	Central	38162	40731	**78893**	16527
	Gilgil	Rift Valley	46247	45682	**91929**	22385
	Kinangop	Central	74306	77423	**151729**	32646
	Naivasha	Rift Valley	71937	69938	**141875**	42901

Data source: ILRI database, http://www.ilri.org/gis/

Land Ownership: Inheritance was the commonest form of land ownership implying that the family heads had to subdivide their parcels of land amongst their children, i.e. sons and/or unmarried daughters, upon attaining adulthood. The household respondents ascribed the decline in cropland sizes and pasture land and the increasing settlements since the 1970s, to this factor.

Environmental campaigns: The influence of land use by the local conservation was also evident in the responses. Friends of Kinangop, for instance, campaigned for the conservation of the kikuyu grass (*Pennisetum clandestinum*), which was a natural habitat for the Sharpe's long claw bird (*Macronyx sharpei*) whereas, the WWF fostered conservation of indigenous and exotic tree species, for instance, in Kitiri location and along the Mkungi River. Further, agricultural programs, such as the Agricultural Technology and Information Response Initiative (ATIRI), also, attempted to enlighten the local farmers regarding the appropriate type of crops for cultivation, as well as, optimal farm use. Githabai self-help group in Murungaru division, for instance, nurtured tree seedlings, which, in turn, were sold to the rest of the community.

3.3.3.3 Economic factors:

Market prices: The local people responded to economic opportunities and constraints as was evident in their land use patterns. Favourable prices in the market for products such as milk, potatoes, wheat and timber, inclined majority of the respondents to use their land for dairy farming, cultivation and tree plantation, especially, in the upper parts of the lake Naivasha drainage basin.

Market availability: According to the farmers interviewed, marketing channels such as the Pan African Board, Pyrethrum Board of Kenya, Kenya Cooperative Creameries (KCC) and companies like the Kenya Breweries Limited, which provided ready market for agricultural produce in the 1970s and 1980s, boosted the production of wheat, barley, milk and vegetables in the area. Their collapse in the 1990s precipitated a decline in production during this time. However, there was resurgence of dairy production following the revival of KCC, by the incumbent National Rainbow Coalition (NARC) government, in 2003.

Sustenance (Livelihood)**:** All the farmers interviewed and/ or households surveyed considered sustenance, particularly, feeding the children, as a fundamental cause for cultivation of their land. A better portion of the farm produce was consumed domestically and, only, the surplus taken to the market in order to augment family income.

3.3.3.4 Institutional factors:

Government interventions: Government-funded institutions, which offered help to the farmers, had had ramifications on land use in the Naivasha basin. The establishment, collapse and revival of KCC, for instance, affected dairy farming in the upper parts of the lake Naivasha drainage basin in the 1990s and 2000s. Likewise, the collapse of Pyrethrum Board of Kenya led to cessation of pyrethrum growing in the 1990s. This is because there was no longer ready market for the produce, which gave a chance to the middle men to exploit the farmers. Agricultural organizations like the Kenya Agricultural Research Institute, on the other hand, through projects such as ATIRI, endeavoured to fund and technically support farmer training sessions on sustainable utilization and management of farmland.

Resettlement*:* Upon the independence of Kenya, the incoming Kenya African National Union (KANU) government undertook to resettle landless Kenyans in the upper parts of the lake Naivasha drainage basin, and thereby, cultivation began in a land that was previously carpeted by the *Kikuyu* grass (*Pennisetum clandestinum*). Thus, the upper part was, dotted by multiple settlement schemes such as the Kahuru settlement scheme, Ol aragwai settlement scheme, Nandarasi settlement scheme, Kitiri settlement scheme, Mkungi settlement scheme to mention but a few.

Infrastructure: Though most farmers conceded that infrastructure, particularly, roads played an important role in determining land use decisions, they ranked it low among the drivers of land use that had been offered. The rationale behind this was that most of the roads traversing the area had for a long time been in poor state (until the installation of the incumbent NARC government in 2003) and as such did not influence their decisions much.

3.3.4 Statistical Analyses of the Driving Forces of Land Use

Table 19 shows a summarized version of data on the driving factors of land use in Lake Naivasha drainage basin; the complete set of data is found on appendix 3. Descriptive and Friedman test statistics derived from the data are also given:

Table 19: Summarized ratings of the drivers of land use

Rank-ratings → **Land Use Drivers ↓**	**1**	**2**	**3**	**4**	**5**	Total Responses
D1. Sustenance	0	5	7	12	6	30
D2. Market	0	0	6	18	6	30
D3. Household size	0	7	15	8	0	30
D4. Climate	0	0	5	13	12	30
D5. Infrastructure	0	16	9	0	5	30

(5) = very important, (4) = important, (3) = average, (2) = not so important, (1) = not important

Table 20: Descriptive statistics of the ratings of the drivers of land use

	Sustenance	**Market**	**HH size**	**Climate**	**Infrastr.**
Valid Cases (N)	30.00	30.00	30.00	30.00	30.00
Mean	3.63	4.00	3.03	4.23	2.80
Variance	1.00	0.41	0.52	0.53	1.20
Std. Deviation	1.00	0.64	0.72	0.73	1.10
Minimum	2.00	3.00	2.00	3.00	2.00
Maximum	5.00	5.00	4.00	5.00	5.00
Sum of Ranks	109	120	91	127	84

The results of the test for difference in the mean ranks of the driving factors of land use in the lake Naivasha drainage basin using Friedman's non-parametric repeated measures comparison are given below. The number of repeated measures was 5, i.e. the drivers of land use, and the number of subjects was 30, i.e. the interviewed farmers.

$$\mathbf{F} = \frac{12}{30(5)(6)}\{109^2 + 120^2 + 91^2 + 127^2 + 84^2\} - 3(30)(6)$$

$$\therefore \mathbf{F} = 229.96$$

$$\mathbf{F} = 229.96 > \chi^2_{(0.05)}(4) = 9.49$$

Table 21: Friedman's test statistic

Chi-square	Degrees of Freedom	Significance Level
9.49	4	0.05

Since the Friedman's test statistic (F) is greater than the chi-square's critical value (χ^2) at the significance level of 0.05, there is sufficient statistical evidence to conclude that the mean ranks of the five driving factors of land use in Naivasha basin are different. That is, the factors differ in their influence on the usage of land by the people who reside in the area. Therefore, the null hypothesis is rejected and the alternative one accepted:

H_0: The driving factors of land use have similar influence on land use in Lake Naivasha drainage basin
H_a: The driving factors, or at least one of them, have different influence on land use in Lake Naivasha drainage basin.

4 DISCUSSION

The fundamental output of this research are the thematic land cover maps for 1986, 1995 and 2007, change maps and statistics, as well as, the driving forces of land use in Lake Naivasha drainage basin. The following sections expatiate on these aspects of the output.

4.1 Land Cover and Change Mapping

The land cover classification of Landsat TM 1986, 1995 and ASTER 2007 images underpinned the fulfilment of the two research objectives. As such, it was imperative to employ per-object- rather than per-pixel- based algorithm, when attempts to use the latter yielded poor classification. This poor result emanated from the heterogeneity of land cover types in Lake Naivasha drainage basin, especially in high altitude areas (e.g. Kipipiri) and the spectral similarity between classes, mainly, croplands, bare lands and shrub lands. The fact that the timing of image capture and the fieldwork did not coincide could have also been a possible source of error. For instance, this meant that reference had to be made to crop calendars to aid in land cover identification at the time of image acquisition. A good accuracy in land use/ cover mapping is paramount since the standard overall accuracy is set at 80-85% (Treitz and Rogan 2004). The outcome of object-based classification of ASTER 2007 is therefore adequate as it has achieved an overall accuracy of 91% and a kappa statistic of 90% (Table 4). This means that only 10% of the classification is left to chance while the remaining 90% is in accord with the reference data. Though the accuracies of most classes increased, the user accuracy of 48%, producer accuracy of 78% and a kappa statistic of 47% attained in the shrub land class is not satisfactory. These statistics suggest that the possibility of end-users accurately locating shrubs on the ground using this map is less than 50%. This low accuracy is due to the spectral confusion that led to misclassification of shrub lands as woodlands or cultivated croplands. Refinement of such mapping quality can be done as additional *ground truth* information is gathered over time.

Assessment of the land cover maps for 1986 and 1995 is not reported for lack of reference data (land cover maps or aerial photos) for these dates. Obtaining sufficiently consistent data over consecutive years or seasons can, at times, be a challenge (Aspinall and Hill 2008), especially in Africa continent where information technology is limited. This notwithstanding, accuracy assessment remains an important feature in reflection of the suitability of land cover maps to the end users (Treitz and Rogan 2004). Inability to assess the accuracies of the 1986 and 1995 land cover maps implies that the possibility of land cover changes resulting from post-classification comparison portraying the differences in classification accuracy (Campbell 2002) cannot be overlooked. This also hampered the assessment of accuracies of the change maps derived from post-classification comparison of the land cover maps. This assessment, usually, proceeds by either multiplying the overall accuracies of the land cover maps or randomly selecting sample areas classified as change and no change and then determining whether they were correctly classified (Yuan *et al.* 2005). Accuracy check of the change maps is, normally, conducted because the error matrices do not describe the range and variation of accuracy across them. Moreover, it is not automatic that the classifications of Landsat TM 1986 and 1995 are as good as the ASTER 2007 classification because the difference in their spatial resolutions poses different classification challenges. The middle-size scale of Landsat pixel (i.e. 30m), for instance, causes a high degree of heterogeneity, especially in built-up land cover class due to mixing of small patches of bare land, building roofs, paved roads and vegetated gardens. This can affect classification accuracy and generate inflated estimates of the number of pixels that have genuinely changed (Campbell 2002).

The spatial and spectral resolutions of imagery also play a pivotal role in determining the level of detail at which land cover can be mapped. The broad spectral, and coarse spatial, resolutions of Landsat TM imagery are not suitable for mapping land cover at a finer level of detail (level II and III), that would have made use of supplementary information such as crop types or vegetation species generated by field surveys in the study area (Appendix 5).

With regard to land cover change mapping, the utility of hyper-temporal SPOT-NDVI data and post-classification technique have been demonstrated. Through analysis of the hyper-temporal SPOT-NDVI data, an innovative and objective means of delineating mapping units for change detection was realized. In this case, where image coverage for the whole of Lake Naivasha drainage basin was lacking, the mapping units are taken to be representative of the uncovered parts. Post-classification comparison, which has been successfully used for change detection by Yuan *et al.* (2005) and Shalaby and Tateishi (2007), did not just generate change maps (Figures 14 to 17) but also provided the *'from-to'* information (Campbell 2002). From these maps, the spatial distribution of the changes and nature of changes can be visualized whereas from the map attributes (i.e. the pixel counts per class), the areal extent, magnitude and rates of land cover changes can be computed. Therefore, the method adequately fulfils objective one (1) and contributes to answering the second, third and fourth research questions. From visual analysis of the land cover change maps shown in Figures 14 to 17, it is evident that the spatial occurrence of change is not just confined in one of the mapping but rather, change is distributed all over. This validates the null hypothesis that the distribution of most of the land cover changes has not been in the lower parts of the basin (i.e. MU3) and nullifies the alternative one.

4.2 Synthesis of the Magnitude, Rates and Nature of Land Cover Changes with the Driving Forces of Land Use

An important challenge in reporting land cover change is discrimination of the different dimensions of change (Aspinall and Hill 2008). In this study, the land cover changes have been reported in terms of the areal change (losses or gains in areal extent), transformations (the patterns of transition from land cover to another), dynamics (the rates in areal extent) and geographic distribution. In a nutshell, the main trends in land cover changes revealed by the change analyses results include: reduction in grasslands, forests, shrub lands and woodlands in the four mapping units (i.e. **MU1, MU2, MU3** and **MU4**), between 1986 and 2007; contraction of water bodies, particularly, Lake Naivasha in **MU3**; sustained increase of croplands and built-up areas throughout the period and; fluctuations in the remaining land cover types, i.e. bare lands and moorlands though, the moorlands exhibited a constant increase in **MU4**, where they abound on top of the Aberdares mountain ranges.

Some of the resultant trends in the rates, nature and magnitude of land cover changes are anticipated considering the rapid land use transformations within Lake Naivasha drainage basin mentioned by Mireri (2005) and Onywere (2005). These are also confirmed by responses elicited from the residents on the driving forces of land use. For instance, since sustenance (i.e. source of livelihood) came out explicitly as a major driving force of land use in Naivasha basin, it follows that the rising population (Table 18) would increase the demand for agricultural land. The culmination of this is expansion of croplands owing to conversions from other land cover types as represented in Tables 5 to 8, and reduction in farm sizes due to fragmentation. As such, the null hypothesis that cropland is not the land cover type that has been greatly converted to other land cover types, is accepted, while the alternative one is rejected. Further, the results from interviews with the farmers indicate that the process of forest clearance for crop farming, especially in **MU1** and **MU4**, began way back in the 1980s and only reduced in 2000. This means that any studies that might have been undertaken within this time would have demonstrated declining trends in forest cover. This conforms to Geist and Lambin's (2002) argument that agricultural activities and expansion, infrastructural extension and wood extraction were the proximate causes of change common to tropical deforestation. Agriculture, singularly, accounts for about 96% of deforestation cases in the tropics. Other efforts to measure and monitor land cover change that have yielded almost similar results include: studies by Imbernon (1999) in Embu district (part of the Kenyan highlands), which reported a significant increase of the annual croplands owing to population growth in the area and; studies by Shalaby and Tateishi (2007), which showed an increase in croplands and a decline in grasslands in the north-western coastal zone of Egypt where the majority of its population reside.

However, depending on the driving forces at work in a given environment, it is also common to encounter contrary results, in literature, whereby croplands are decreasing due to transformations to non-agricultural lands. Long *et al.* (2007) presented a scenario in China, where the cultivated lands within the coastal zones were being converted to non-agricultural lands following initiation of economic reforms in 1978. Likewise, Yuan *et al.* (2005) observed the growth of urban areas at the expense of agricultural land in Minnesota metropolitan area. This is a common phenomenon in the developed nations of the world where the rate of urbanization is relatively high.

Moreover, the decreasing rates and magnitude of change in grasslands as the croplands increase (Tables 5 to 8) could have been precipitated by the expanding household sizes (population) coupled with the collapse of KCC. The history of the area as told by the farmers, for example, indicated that Kinangop area (**MU1**) was predominated by large tracts of grasslands during the colonial, and immediate post-colonial era, but currently, it is small-holder croplands and tree lines that characterize the landscape. This links quite well with the subject of resettlement of indigenous people in **MU1** and **MU4** after independence, leading to both demographic and land use changes. The in-coming population enhanced crop farming as opposed to dairy faming (the former land use) but at the same time, the progressive rise in their numbers has decreased the cropland area per capita, hence, the smaller farms. This insight demonstrates the value of capturing historical developments in land cover change studies. Therefore, it is worthwhile to integrate environmental history with the quantitative remote sensing approaches of studying spatial patterns and temporal dynamics of land systems with a view to understanding the roles of multiple causes and processes of change (Aspinall and Hill 2008). Interview is one of the key tools for collecting this kind of data.

Other studies conducted within Lake Naivasha drainage basin (Onywere 2005 and Lamb *et al.* 2003) have also shed some light on the response of the residents to the mounting pressure for agricultural land. Some have resorted not only to clearing the woodlands and forests, but also the riparian vegetation in **MU3**. The shrub lands, known to have thrived as part of the outmoded shifting cultivation in most Kenyan communities (Imbernon 1999), are also disappearing and being replaced by croplands. All these occurrences offer a plausible rationale for the increasing rates and magnitudes of cropland changes as the results indicate in Table 7 and the, subsequent, decline in the land cover types contributing to these increases.

In addition, the encroachment of riparian zones in **MU3**, especially, by the large-scale horticultural farms and tourist industry that extracts water for use is a probable factor contributing to the dwindling waters of Lake Naivasha (Tables 7, 13 and 14). Horticultural development is the chief form of agricultural intensification in the tropical regions, which is propelled by underlying processes such as market availability, demographics and institutional regimes (Geist and Lambin 2002). For example, in the upper basin (**MU1 and MU4**) ready market and prices for vegetables are the main factors for their cultivation while horticultural practice in **MU3** is driven by the international flower and vegetable markets. That aside, climate, especially, fluctuations in annual temperature and precipitation remains the fundamental cause of the negative rates and magnitude of change of water in **MU3.** This is due to fact that, east African rainfall patterns are characterised by variations on annual and inter-annual time scales that are correlated to the phase of El-Nino/ southern oscillation phenomenon (Kiage *et al* 2007). The downward spiral of precipitation within this region has been recognized since 1960s and is more pronounced in the semi-arid environments such as Lake Naivasha and its environs. This fact notwithstanding, though, Kiage *et al.* (2007) found out in his studies that sedimentation, and not the fluctuations in annual rainfall trends, was responsible for reduction in total surface area of Lake Baringo, within the Baringo lowlands (Kenya), between 1986 and 2000.

Built up areas is yet another land cover type that has maintained an upward trend in its rates and magnitude of change, from 1986 through to 2007, in all the four mapping units (Tables 5 to 8). The logic behind this could lie in the assumption that, as the population in an area increases so does the human habitation centres. For instance, the rising population in Naivasha (**MU3**), owing to the influx of labour force to the horticultural farms, tourism and geothermal industries, has led to the emergence of residential settlements like Kihoto, Karagita and small trading centres. However, the conversion statistics displayed in Tables 9 to 16 strangely indicate that built up areas have been converted to croplands, grasslands or, in other instances, woodlands. With this regard, it is worth commenting that classification errors, which propagate through multiple dates, are known to cause such unusual land cover changes (Yuan *et al.* 2005). This fact cannot be ignored, especially, in this instance where the accuracies of the generated land cover maps for 1986 and 1995 have not been assessed. The unusual changes most likely relate to the errors of commission and omission in the classification of these Landsat TM images. The built up areas could not be adequately discriminated from the ploughed croplands and bare lands in the Landsat TM images in spite of using object-oriented classification. This partly explains the mutual conversions shown to have taken place between these classes in the tables. Campbell (2002) stated that the high percentage of mixed pixels in urban and built up lands (especially at the scale of Landsat image pixel) have a tendency to decrease classification accuracy thus producing misleading estimates of the pixel counts that have undergone change.

In their studies, Yang and Liu (2005) managed to suppress classification errors introduced by spectral confusion through adoption of spatial reclassification method in addition to hierarchical classification. The latter entails the use of image subsets organised hierarchically rather than whole scenes in a series of classification procedures. Spatial reclassification exerts GIS functions, auxiliary data and image interpretation procedures to rectify the wrongly labelled pixels. Image interpretation can be integrated in the digital classification process through on-screen digitizing, multiple zooming, area of interest facility, recoding and overlaying. Butt and Olson (2002) successfully classified the heterogeneous landscape on the eastern slopes of Mount Kenya by supplementing automatic classification with visual interpretation i.e. vector digitisation of polygon features. Further, Stefanov *et al.* (2001) recommended application of fuzzy classification algorithm to subdue spectral confusion between classes when processing satellite data. This algorithm ranks the possibility of a given pixel's membership to a defined class. In general, efforts to come up with sophisticated spatial analytical approaches that can handle the more complex structures caused by heterogeneous spectral signatures in land cover classification continues but, the breakthroughs so far include: artificial neural networks, fuzzy set theory, extraction and use of *a priori* probabilities or *a posteriori* processing, texture processing, frequency-based contextual approaches, knowledge-based algorithms and image segmentation (Treitz and Rogan 2004).

In all, though the results show that some land cover types experienced increasing rates and magnitudes of changes whereas in others the converse is true, the overall observation made is that the magnitude and the rates of land cover changes (whether increases or decreases) in Naivasha basin always exceeded zero, both in percentage (%) and spatial extent (km^2) (Tables 5 to 8). Therefore, the alternative hypothesis that the magnitude and the rate of land cover changes have been greater than zero (H_a: $\Delta > 0\%$) is accepted and the null hypothesis rejected.

4.3 Limitations of the Research

The research proceeded fairly well but not without hitches; a number of challenges were encountered in the process. These include:

a) Lack of multi-temporal satellite data that fully covered the Lake Naivasha drainage basin hence the resolve to sub-divide the common areas within the available satellite images into 4 units representative of the uncovered parts.
b) The timing of the available multi-temporal remote sensing dataset did not correspond with the timing of the fieldwork. The satellite images were acquired in January whereas the fieldwork was conducted in September. As such, difficulties in identification of some land cover types arising from phenological differences had to be dealt with.
c) Insufficiency of funds, time and vehicles that would have facilitated implementation of the predetermined stratified random sampling design. This resulted in collection of sample points that were not well distributed within the study area.
d) Inability to access reference data that would have allowed accuracy check of the generated land cover maps for 1986 and 1995, as well as the change maps.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the results obtained and their analyses, the following conclusions are drawn:

a) Both proximate and underlying processes drive land use in Lake Naivasha drainage basin leading to land cover changes. The underlying forces include: demographics (expansion of households), climate, market prices and availability and government interventions whereas sustenance (livelihood) is the identified proximate cause. These forces influence land use differently in the area as indicated by the Friedman's test.

b) The magnitude and the rates of land cover changes, whether increases or decreases, in Lake Naivasha drainage basin has always exceeded zero, both in percentage (%) and spatial extent (km^2).

c) The dominant nature of change occurring in Lake Naivasha drainage basin has been the conversion of grasslands to croplands leading to the increase of the latter.

d) The land cover changes are spread throughout Lake Naivasha drainage basin and not confined in one particular location.

e) The results on change estimates and patterns of change are major steps towards filling in of the information gap and creation of a database for monitoring land and water resources in Lake Naivasha drainage basin. This effort would facilitate decision making on mitigating the impacts of land use/ cover dynamics on these resources as well as provide a basis for future research.

f) The approach of using SPOT-NDVI data to delineate units for change detection and object-based classification performed quite well. Refinement of accuracies within individual class in classification of the heterogeneous landscape in Naivasha basin is still needed though.

5.2 Recommendations

In view of the conclusions drawn, the following suggestions are made:

a) A follow up research that would integrate older aerial photos with finer resolution satellite imagery in order to achieve mapping at detailed level, give a long-term impression of land cover changes and enhance the inventory of land resources in Naivasha basin for planning and monitoring.

b) Exploration of other classification approaches that might yield better results taking into consideration the complexity of land cover types within Lake Naivasha drainage basin.

c) Down-scaling of the research to the individual mapping unit level where an in-depth study of each unit is conducted at a time, with a view to capturing the dynamics of land cover changes within lowest level of administration.

REFERENCES

Aspinall, R.J. and Hill, M.J. (eds.) (2008) Land use change: science, policy and management, New York; CRC Press, Taylor and Francis Group

Aspinall, R.J. and Justice, C. (2004) A land use and land cover change science strategy summary of a workshop held at the Smithsonian institution Nov 19-21, 2003

Baatz, M., Benz, U., Dehghani, S. and Heynen, M. (2004) eCognition user guide 4 (Munich, Germany: Definiens Imagine GmbH).

Becht, R., Odada, E.O. and Higgins, S. (n.d) Lake Naivasha: experiences and lessons learned, *unpublished*

Blaschke, T., Lang, S., Lorup, E., Strobl, J. and Zeill, P. (2000) Object-oriented image processing in an integrated gis/remote sensing environment and perspectives for environmental applications [Online] Available: http://enviroinfo.isep.at/UI%20200/Blaschke_et_al_engl200700.el.hsp.pdf [Accessed 2007, December 13]

Bottomley, B.R. (1998) Mapping rural land use & land cover change, in carroll county, Arkansas utilizing multi-temporal Landsat thematic mapper satellite imagery 1984 – 1999, University of Arkansas, MSc thesis, *unpublished*

Butt, B. and Olson, J.M. (2002) An approach to dual land use and land cover interpretation of 2001satellite imagery of the eastern slopes of Mt. Kenya, LUCID Working paper series No. 16

Campbell. D.J., Lusch, D.P., Smucker, T. and Wangui, E.E. (2003) Root causes of land use change in the Loitoktok area, Kajiado district, Kenya LUCID Working paper series No.19

Campbell, J.B. (2002) Introduction to Remote Sensing London; Taylor & Francis

Carpenter, G.A., Gopal, S., Shock, B.M. and Woodcock, C.E. (2001) A neural network method for land use change classification, with application to the Nile river delta, BU/CNS Technical Report TR-2001-010

Civco, D.L., Hurd, J.D., Wilson, E.H., Song, M. and Zhang, Z. (2002) A comparison of land use and land cover change detection methods ASPRS-ACSM Annual Conference and FIG XXII Congress April 22-26, 2002

de Bie, C.A.J.M., Nidumolo, U.B., Smakhtin, V.U. and Venus, V. (n.d) Multi-temporal NDVI SPOT image analysis as an approach for small-scale land use mapping and legend construction *unpublished*

Elmqvist, B. (n.d) Land use assessment in the dry lands of Sudan using historical and recent high resolution satellite data, *unpublished*

Fan, F., Weng, Q. and Wang, Y. (2007) Land use and land cover change in guangzhou, china, from 1998 to 2003, based on Landsat TM /ETM+ imagery *Sensors* 7, 1323-1342

FAO. (1998) Wetland characterization and classification for sustainable agricultural development [Online] Available: http://www.fao.org/DOCREP/003/X6611E/X6611e00.htm#TopOfPage [Accessed 2007, September 2]

Foody, G.M. (2002) Status of land cover classification accuracy assessment *Remote Sensing of Environment* **80**:185– 201

Fuller, R.M., Smith,G.M. and Devereux, B.J. (2003) The characterization and measurement of land cover change through remote sensing: problems in operational applications? *International Journal of Applied Earth Observation and Geo-information* **4,** 243–253

Geist, H.J. and Lambin, E.F. (2002) Proximate causes and underlying driving forces of tropical deforestation *Bioscience* **52:** 143-149

Gregorio, A.D. and Jansen, L.J.M. (1998) Land cover classification system (LCCS): classification concepts and user manual, Rome, FAO

Hurskainen, P. & Pellikka, P. (2004) Change detection of informal settlements using multi-temporal aerial photographs – The case of Voi, south east-Kenya. *Proceedings of the 5th AARSE conference* (African Association of Remote Sensing of the Environment), 18-21 October, 2004, Nairobi Kenya

Im, J., Jensen, J. R. and Tullis, J. A.. (2007) 'Object-based change detection using correlation image analysis and image segmentation', *International Journal of Remote Sensing* 1 – 25

Imbernon, J. (1999) Pattern and development of land-use changes in the kenyan highlands since the 1950s *Agriculture Ecosystems and Environment* **76,** 67-73

Kenya Land Alliance. (2006) A survey into the management and use of wetlands in Kenya, *Land Update newsletter* **5** (1):3-5

Kiage, L.M., Liu, K.B., Walker, N.D., Lam, N. and Huh, O.K. (2007) Recent land-cover/use change associated with land degradation in the Lake Baringo catchment, Kenya, East Africa: Evidence from Landsat TM and ETM+, *International Journal of Remote Sensing* **28** (19) 4285–4309

Kundu, P.M., China, S.S., Chemelil, M.C. and Onyando, J.O. (n.d) Detecting and quantifying land cover and land use change in eastern Mau by remote sensing, *unpublished*

Lamb, H., Darbyshire, I. and Verschuren, D. (2003) Vegetation response to rainfall variation and human impact in central Kenya during the past 1100 years *The Holocene* **13** (2): 285–292

Lambin, E.F., Geist, H.J. and Lepers, E. (2003) Dynamics of land use and land cover change in tropical regions *Annual Review of Environment and Resources* **(28)** 205-41doi: 10.1146/annurev.energy.28.050302.105459

Lambin, E.F. *et al* (2001) The causes of land-use and land-cover change: moving beyond the myths *Global Environmental Change* **11**: 261–269

Long, H.G., Tang, G., Li, X. and Heilig, G.K. (2007) Socio-economic driving forces of land use change in Kunshan, the Yangtze river delta economic area of China *Journal of Environmental Management* **83** (3):351-364

Lu, D., Mausel, P., Brondizio, E. and Moran, E. (2004) Change detection techniques *International Journal of Remote Sensing* **25** (12):2365-2407

Lunetta, R.S. and Elvidge, C.D. (1999) Remote sensing change detection: environmental monitoring methods and applications London; Taylor & Francis Ltd

Mas, J. (1999) Monitoring land cover changes: a comparison of change detection techniques, *International Journal of Remote Sensing* **20** (1): 139-152

Mireri, C. (2005) Challenges facing the conservation of Lake Naivasha, Kenya, Topics of Integrated Watershed Management – Proceedings 89, FWU, Vol. 3

Mugisha, S. (2002) Patterns and root causes of land cover/ use in Uganda: an account of the past 100 years, LUCID Working Paper Series No. 14

Mwagore, D. (ed.) (2002). Land use in Kenya – the case of a national land use policy, *Land Reform*, vol.3 [Online] Available: http://www.oxfam.org.uk/landrights/KLAfull.pdf [Accessed 2007, August 24]

Onywere, S.M. (2005) Morphological structure and the anthropogenic dynamics in the Lake Naivasha drainage basin and its implications to water flows, Topics of Integrated Watershed Management – Proceedings, FWU, Vol. 3

Overmars, K.P. and Verburg, P.H. (2005) Analysis of land use drivers at the watershed and household level: linking two paradigms at the Philippine forest fringe *International Journal of Geographical Information Science* **19** (2):125–152

Read, J.M. and Lam, S-.N. (2002) Spatial methods for characterising land cover and detecting land cover changes for the tropics *International Journal of Remote Sensing* **23** (12): 2457-2474

Seto, K. C., Woodcock, C. E., Song, C., Huang, X., Lu, J. and Kaufmann, R. K. (2002) Monitoring land use change in the Pearl river delta using Landsat TM *International Journal of Remote Sensing* **23** (10):1985–2004

Shaikh, A.A., Gotoh, K. and Tachiiri, K. (2005) Multi-temporal analysis of land cover changes in Nagasaki city associated with natural disasters using satellite remote sensing *Journal of Natural Disaster Science* **27** (1): 9-15

Shalaby, A. and Tateishi, R. (2007) Remote sensing and GIS for mapping and monitoring land cover and land use changes in the north-western coastal zone of Egypt *Applied Geography* **27**(1): 28-41

Singh, A. (1989) Review article on digital change detection techniques using remotely-sensed data *International Journal of Remote Sensing* **10** (6):989-1003

Song, C., Curtis, E.W., Karen, C.S., Lenny, M.P. and Macomber S.A. (2001) Classification and change detection using Landsat TM data: when and how to correct atmospheric effects? *Remote Sensing of Environment* **75:** 230-144

Stefanov, W.L., Ramsey, M.S. and Christensen, P.R. (2001) Monitoring urban land cover change: an expert system approach to land cover classification of semi-arid to arid urban centers *Remote Sensing of Environment* **77:** 173-185

Treitz, P. and Rogan, J. (2004) Remote sensing for mapping and monitoring land cover and land use change- an introduction *Progress in Planning* **61:** 269-279

Weng, Q. (2002) Land use change analysis in the Zhujiang delta of China using satellite remote sensing, GIS and stochastic modelling *Journal of Environmental Management* **64**: 273–284

Wood, E.C., Tappana, G.G. and Hadj, A. (2004) Understanding the drivers of agricultural land use change in south-central Senegal *Journal of Arid Environments* **59**:565–582

Yang, X. and Liu, Z. (2005) Using satellite imagery and GIS for land use and land-cover change mapping in an estuarine watershed *International Journal of Remote Sensing* preview article

Yang, X. and Lo, C.P. (2002) Using a time series of satellite imagery to detect land use and land cover changes in the Atlanta, Georgia metropolitan area *International Journal of Remote Sensing* **23** (9) 1775-1798

Yuan, F., Sawaya, K.E., Loeffelholz, B.C. and Bauer, M.E. (2005) Land cover classification and change analysis of the twin cities (Minnesota) metropolitan area by multi-temporal Landsat remote sensing *Remote Sensing of Environment* **98:** 317-328

Zar, J.H. (1996) Bio-statistical analysis, Third edition, New Jersey; Prentice-Hall International Inc

Zhan, Q., Moleenar, M., Tempfli, K. and Shi, W. (2005) Quality assessment for geo-spatial objects derived from remotely sensed data *International Journal of Remote Sensing* **26** (14)**:** 2953-2974

APPENDICES

APPENDIX 1
Rélèvée (Field Observation) Sheet

<table>
<tr><td colspan="6">GENERAL DATA</td><td>Final classification</td></tr>
<tr><td>Observer's name:</td><td colspan="2">Date& time:</td><td>Sample ID:</td><td colspan="2">Sample plot size:
… (metres) by … (metres)
Sample plot shape:
…………………………….</td><td rowspan="2">Land cover
………………
Land use
………………</td></tr>
<tr><td>Location:
Division …………..
Ward ……………...
Place/ Area ...……..</td><td colspan="2">Position:
Lat. (X) ...….................
Long. (Y) …...............</td><td>Altitude (m):</td><td colspan="2">Photo taken:
…………. jpeg</td></tr>
<tr><td colspan="4">LANDSCAPE AND TERRAIN DATA</td><td colspan="3">LAND TENURE</td></tr>
<tr><td>Land form:
…………………….
Micro-relief
☐ Course ☐ Smooth
☐ Moderate</td><td colspan="2">Relief type:
☐ Flat ☐ Undulating
☐ Hilly ☐ Steep
☐ Mountainous
………………………</td><td>Slope (%):</td><td colspan="3">☐ Public ☐ Communal
☐ Private ☐ Leasehold/ rental
Other ……</td></tr>
<tr><td colspan="7">LAND COVER/ USE DATA</td></tr>
<tr><td colspan="2">Bio-Physical components</td><td>Percentage cover</td><td>Species composition</td><td>Dominant species.</td><td>Land use</td><td>Remarks</td></tr>
<tr><td colspan="2">1. Vegetation:
Trees: > 5m
Shrubs: 2 - 5m
Herbs: 0.2 - 2m
Grass: 0 - 0.2m</td><td>
…
…
…
…</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">2. Water (permanent pools):
☐ Lake
☐ River
☐ Swamp
Other(s) ……………………</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">3. Crops:
☐ Primary crop(s) …………..
☐ Secondary crop(s) ………..
☐ Tertiary crop(s) ………….
Other(s) e.g. woodlots ……..</td><td></td><td>
…
…
…
…</td><td></td><td></td><td>
☐ Cultivated
☐ Ploughed
☐ Fallow etc
…………….</td></tr>
<tr><td colspan="2">4. Bare soils</td><td></td><td>…</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">5. Settlements (Buildings)</td><td></td><td>…</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">6. Natural litter</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">7. Stones</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">8. Burning</td><td colspan="3"></td><td></td><td></td></tr>
<tr><td colspan="2">Other(s) ……………………..</td><td></td><td colspan="2"></td><td></td><td></td></tr>
</table>

APPENDIX 2

Household (farmer) Interviewing Schedule

1. What is the name of the land occupant (s) (individual or village)?
2. What is the location of the farmland (geographic /administrative)?
3. What is the size of the household?
4. When did s/he occupy the land?
5. How did s/he acquire the parcel of land?

   □ Inheritance □ Purchase □ Squatter □ Resettlement
   □ Other …
6. What was the size of the land and its cover type?
   a) At the time of occupation and;
   b) In the current period
7. How did s/he use the parcel of land immediately after its first occupation?
8. If the use was agriculture, further comment on:
   a) The primary, secondary & tertiary crops that were planted;
   b) The time they were planted;
   c) The farm inputs (i.e. seeds& fertilizers);
   d) The seasonal yields obtained from each crop;
   e) Any fluctuations in agricultural yields over time& their causes;
   f) Trends in market prices for the specific agricultural produce?
9. What are the factors that were considered before putting the parcel of land under the given land use when it was first occupied?

   □ Market prices and availability □ Sustenance □ Climate
   □ Household size (population) □ Infrastructure □ other …
10. Has here been consistency in the usage of the parcel of land since it was occupied?

    □ Yes □ No
11. If no, when were the times when land use was altered?
12. What are the factors that prompted the alterations in land use?

    □ Market prices and availability □ Sustenance □ Climate
    □ Household size (population) □ Infrastructure □ other …
13. Did the changes also alter the land cover types, in any way?

    □ Yes □ No
14. If yes, what did the land cover type shift to?
15. Is water a requirement in the use of land or in the household?

    □ Yes □ No
16. If yes, what is the source of the water?
17. Has it been a problem at any point in time?

    □ Yes □ No
18. If yes, at what time and what could the problem be attributed to?
19. What is the type of fuel used by the household?
20. If firewood, further comment on its source and its availability, both in the past and the present periods
21. In a nutshell, what are his/ her observations of the land cover/ use changes that have occurred in the area since the time s/he began residing in the area?

APPENDIX 3

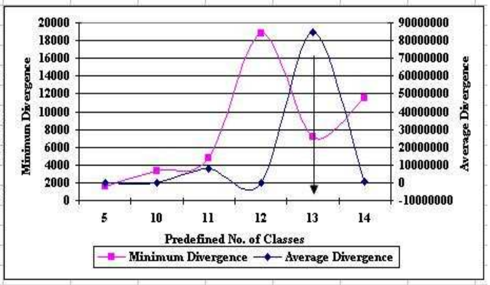
	Rank-ratings of the Drivers of Land Use				
Respondents	**D1**	**D2**	**D3**	**D4**	**D5**
A	2	3	2	5	2
B	2	3	2	5	2
C	2	3	4	3	5
D	4	5	3	3	2
E	3	3	3	5	2
F	3	3	2	4	5
G	5	4	2	4	3
H	3	4	3	5	5
I	4	3	4	4	3
J	2	4	3	4	2
K	3	4	2	4	2
L	3	5	3	4	2
M	4	4	3	4	2
N	4	4	2	4	2
O	4	4	3	5	2
P	4	5	3	4	2
Q	3	4	3	4	3
R	4	4	3	4	2
S	4	4	3	5	3
T	2	4	3	5	2
U	4	4	3	5	3
V	3	4	3	5	3
W	4	4	4	3	3
X	4	4	2	5	3
Y	5	5	4	5	3
Z	5	4	4	3	5
AA	5	4	3	4	5
BB	5	5	4	4	2
CC	4	5	4	3	2
DD	5	4	4	5	2
Sum of Ranks	**109**	**120**	**91**	**127**	**84**

APPENDIX 4

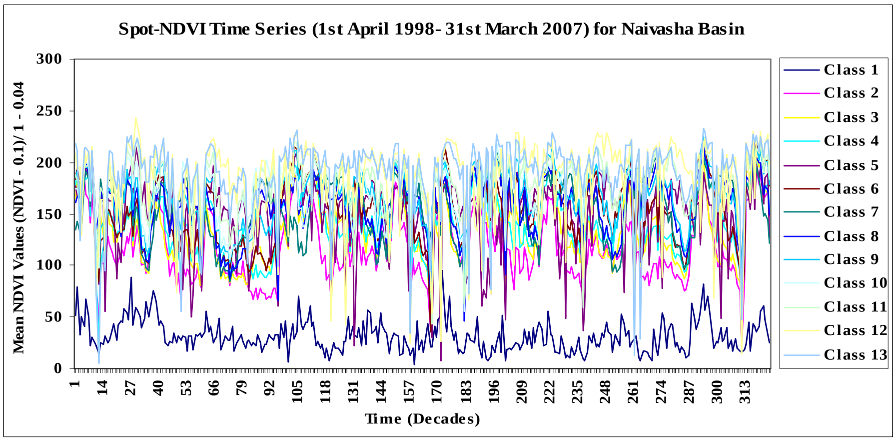
Divergence of unsupervised runs with xx Classes

	Divergence of unsupervised runs with xx Classes			
	(with 'use class probabilities' off)			
	xx	MIN	xx	AVG
	5	1653	5	4671
	10	3268	10	85100
	11	4749	11	7558299
	12	18790	12	55715
Selected	13	7160	13	84947131
	14	11461	14	637045

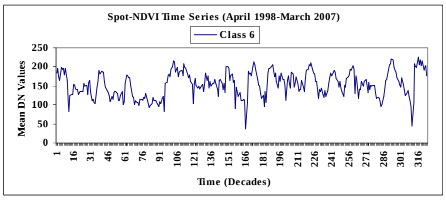
No. of iterations, 10
with do not classify zeros'
with convergence threshold of 1'

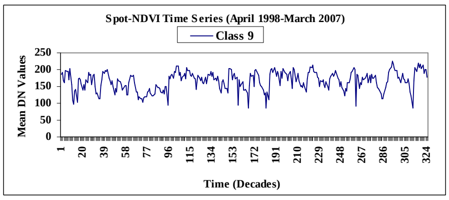


Average divergence for predefined classes with the arrow showing the classes with a peak in divergence

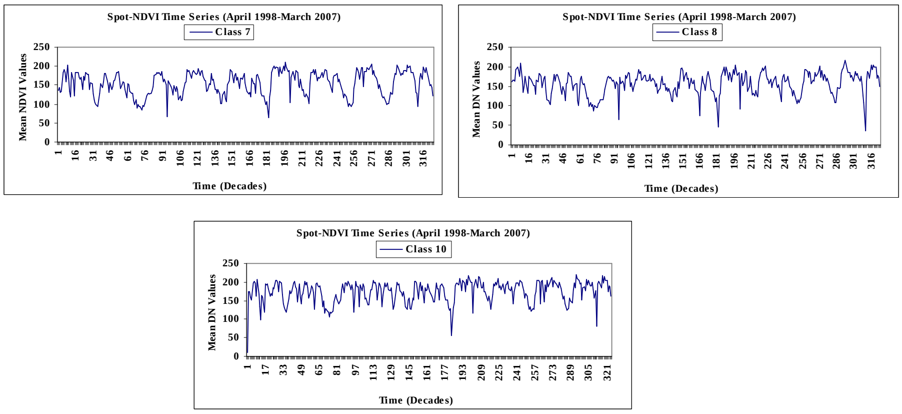


NDVI profiles of the 13 classes derived by unsupervised ISODATA clustering

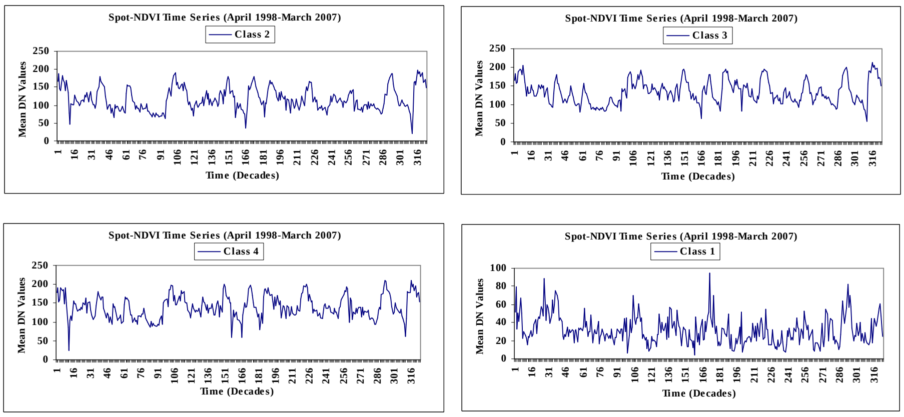




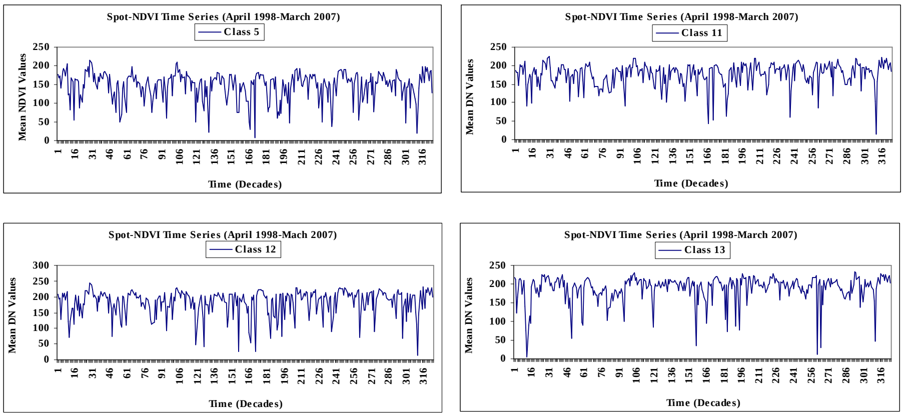
NDVI –based mapping unit one (MU1): combination of classes 6 and 9



NDVI-based mapping unit two (MU2): combination of classes 7, 8 and 10



NDVI-based mapping unit three (MU3): combination of classes 2, 3 and 4, and additional class 1 due to its situation within these classes.



NDVI-based mapping unit four (MU4): combination of classes 5, 11, 12 and 13

APPENDIX 5

APPENDIX 5: PRELIMINARY LEGEND FOR LAND COVER CLASSIFICATION

Code	Level I	Level II	Level III	Range of estimated percentage covers from samples							
				Soil	Grass	Shrub	Tree	Crop	Settl	Stones	Litter
10 11	Grassland	Tropical alpine- upper highlands montane grasslands	Kikuyu, Rye, Napier grasses	1-10	45-95	-	5-30	-	-	-	-
12		Lower highlands- upper midlands tropical savanna grasslands	-	5-10	30-95	2-45	5-30	-	-	-	-
20 21	Cropland	Cultivated croplands	Wheat, oats, pyrethrum, barley, cabbages, fodder maize, beans, potatoes	5-20	1-45	-	1-30	40-90	-	-	2-5
22		Ploughed and fallow croplands	-	≥80	-	-	-	-	-	-	<20
23		Large-scale horticultural croplands	Flowers, vegetables, peas	-	-	-	-	-	-	-	-
30 31	Forest	Evergreen tropical alpine -upper highlands broad-leaved forests	Bamboo forest; Eucalyptus, Blue gum	5-10	20-40	50	45-90	-	-	-	-
32		Evergreen tropical alpine -upper highlands narrow-leaved forests	Cypress, Pine	5-10	10-65	50	45-80	-	-	-	-
33		Evergreen mixed natural and planted forests	Eucalyptus, Bamboo, Pine, Cypress	-	-	-	-	-	-	-	-
40 41	Woodland	Lower highlands- upper midlands tropical savanna woodlands	Acacia (*xanthophloea, abyssinica* etc) and euphorbia	5-10	10-50	5-40	40-50	-	-	-	-
42		Tropical alpine- upper highlands mixed woodlands	Eucalyptus, Blue gum and Cypress plantations	5	5-35	10	60-80	-	-	-	-
50	Shrub land	Shrub lands, upper basin	*Grevillea robusta*	5-8	5-40	50-85	2-45	-	-	-	-
51		Shrub lands, lower basin	*Taconanthus camphoratus*	5-20	5-45	40-90	-	-	-	-	-
60 61	Built-up land	Medium -high intensity developed settlements	Big towns and trading centres	10-25	5-10	-	5	-	60-70	10-15	-
62		Low intensity developed settlements	Rural settlements, hospital buildings	-	-	-	5	-	30-70	-	-
70	Bare land	Exposed bare soils	-	50-90	5-15	10	15		-	-	-
80	Water Bodies	Marshlands	Marshes with papyrus reeds	-	-	-	-	-	-	-	-
81		Open water	Rivers, lakes, swamps	-	-	-	-	-	-	-	-
90	Moorland			-	-	-	-	-	-	-	-
100	Barren land	Outcrop rocks, quarries& litter	Saw dust piles, bldg stones	15-60	5-10	35	-	-	-	40-50	0-100

APPENDIX 6

Distribution of the Sample Points