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An Integrated Approach to Assessing Spread of Commercial Horticulture and Related Environmental Impacts on Watersheds : Cases in Central Highlands of Kenya

Faith Karegi Muriithi
Montclair State University

AN INTEGRATED APPROACH TO ASSESSING SPREAD OF COMMERCIAL HORTICULTURE AND RELATED ENVIRONMENTAL IMPACTS ON WATERSHEDS: CASES IN CENTRAL HIGHLANDS OF KENYA

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FAITH KAREGI MURIITHI

Montclair State University

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Dissertation Chair: Dr. Danlin Yu, PhD

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THE GRADUATE SCHOOL

DISSERTATION APPROVAL

We hereby approve the Dissertation

AN INTEGRATED APPROACH TO ASSESSING SPREAD OF COMMERCIAL HORTICULTURE AND RELATED ENVIRONMENTAL IMPACTS ON WATERSHEDS: CASES IN CENTRAL HIGHLANDS OF KENYA

of

Faith Karegi Muriithi

Candidate for the Degree:

Doctor of Philosophy

Dissertation Committee:

[redacted]

Dr. Danlin Yu
Dissertation Chair

[redacted]

Dr. Clement Alo

[redacted]

Dr. Jill Lipoti

[redacted]

Dr. Stefan Robila

Department of
Earth and Environmental Studies

Certified by:

[redacted]

Dr. Joan C. Ficke
Dean of The Graduate School

5/12/15

Date

ABSTRACT

AN INTEGRATED APPROACH TO ASSESSING SPREAD OF COMMERCIAL HORTICULTURE AND RELATED ENVIRONMENTAL IMPACTS ON WATERSHEDS: CASES IN CENTRAL HIGHLANDS OF KENYA

by Faith Karegi Muriithi

Intensive horticulture production has broad environmental implications due to the high dependency on natural resources. Numerous reports indicate positive socio-economic gains associated with the Kenyan horticulture sub-sector. Even so, few highlight the extent of the negative environmental impacts. We adopt a holistic approach that integrates deskwork, Geographical Information Systems (GIS), field study and remote sensing tools to evaluate the spread and growth of commercial horticulture, and the effects on: i) surface water quality, and ii) vegetation condition, in watersheds experiencing increased production within the central highlands.

The desk research utilized Google Earth archives and GIS data, to map greenhouse distribution, determining area under production and factors predicting choice of location. This was followed by a field study to sample and characterize surface water quality in select sub-watersheds with intensive horticulture, thereby highlighting potential pollutant source-processes. Twenty five years of remote sensing data were also analyzed to establish vegetation condition and responses to increased farming and human disturbances. This was followed by a detailed study to quantify land use and land cover changes, and finally a chapter illustrating trends in horticulture exports volumes.

Results from the desk research showed heterogeneous spread of farming, where area under production increased rapidly between 2000 and 2011. Population density, average slope, average rainfall and dams were significant predictors to farming location. Results from the field study show predominance of anthropogenic trace elements of cadmium, phosphate, and zinc in waters draining from regions with intensive large scale horticulture. The long-term vegetation study indicates spatially varying inter-annual NDVI, which continuously declined post 1990s in sub watersheds with increased farming. The study to quantify land transformation dynamics, indicate varying magnitudes of change with rates of change differing between land-uses, and between case studies, attributable to socio-economic drivers. We also find that horticultural exports had positive trends until 2008/2009, and 2010, where the effects of post-election violence and volcanic eruption are evident. Overall, the research has demonstrated the efficacy of integrated approaches in understanding implications intensified production on watershed resources. This knowledge is important in developing policies and regulatory frameworks that supports sustainable resource utilization and best management practices.

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DEDICATION

To my enduring mothers, Agnes Kanorio, and my mother in law Josephine Wangui and my sisters and brothers.

And

To my loving husband, Anthony and dear children Goretti, Martin and Rita.

TABLE OF CONTENTS

Content **Page**

Content **Page**

Content **Page**

Content **Page**

Content **Page**

Content **Page**

Content **Page**

Content **Page**

LIST OF APPENDICIES

LIST OF TABLES

Table **Page**

Table **Page**

LIST OF FIGURES

Figure **Page**

Figure **Page**

Figure **Page**

LIST OF ABBREVATIONS

AGR	Agriculture
AOIs	Areas of interest
ASALs	Arid and Semi-Arid Lands
AVHRR	Advanced Very High Resolution Radiometer
BAR	Bare bright soils
DA	Discriminant Analysis
DAR	Dark soil cover
DEM	Digital Elevation Model
DO	Dissolved oxygen
EC	Electro-conductivity
ENSO	El Niño Southern Oscillation
EVI	Enhanced Vegetation Index
FAO	Food and Agricultural Organization
FOR	Forest
FPEAK	Fresh Produce Exporters Association of Kenya
GCPs	Ground Control Points
GIMMS	Global Inventory Modeling and Mapping Studies
GIS	Geographical Information Sciences
GPS	Global Positioning System
HCDA	Horticultural Crops Development Authority
ICID	International Commission on Irrigation and Drainage
ILRI	International Livestock Research Institute
ITCZ	Inter-Tropical Convergence Zone
JICA	Japanese International Co-operation Agency
KFC	Kenya Flower Council
KMO	Kaiser-Meyer-Olkin
KNBS	Kenya National Bureau Statistics
L5 MSS	Landsat-5 MSS,
L5 TM	Landsat-5 TM
L7 +ETM	Landsat-7 +ETM
LAI	Leaf Area Index
LSHORT	Large scale horticulture
LULC	Land use-land cover
MAG	Mixed Agriculture
MISR	Multi-angle Imaging SpectroRadiometer
MoA	Ministry of Agriculture

MODIS	Moderate Resolution Imaging Spectroradiometer
MVC	Maximum Value Composite
NDVI	Normalized Difference Vegetation Index
NEMA	Natural environment management agency
NIH	National Institutes of Health
NRCS	Natural Resources Conservation Service
PCA	Principal Component Analysis
PCs	Principal Components
RMSE	Root Mean Square Error
SAVI	Soil Adjusted Vegetation Index
SET	Settlement/Urban use
SPOT	Satellite Pour l' Observation de la Terre
SPSS	Statistical Package for the Social Sciences
SSHORT	Small-scale horticulture
TDS	Total Dissolved Solids
USDA	United States Department Agriculture
UTM	Universal Transverse Mercator
WG	Woodlands and Shrubs
WRI	World Resources Institute

CHAPTER 1

INTRODUCTION

1. Introduction

Horticulture is fundamentally the intensive production of high value fresh produce such as cut-flowers, vegetables, fruits, bedding plants and ornamentals (Ulrich, 2014; Wainwright, Jordan, & Day, 2014). In Kenya, the practice is highly commercialized, with production targeting international and local/domestic markets. Cut-flowers such as roses, lilies, carnations, lisianthus, geraniums among *etc.,* are primarily produced for export markets. Production of cut-flowers is done under controlled greenhouse environment to enable a year-round production. The crops are planted directly in native sterilized soil beds, or in hydroponic systems that are fitted with drip lines for irrigation and fertilizer application. The global use of greenhouses in horticulture production increased dramatically during the 20th century (Wittwer & Castilla, 1995) with more than 500 000 ha of agricultural land covered with greenhouses (Bergstrand, 2010; Vox, et al., 2010). Greenhouse horticulture provides a controlled environment against weather occurrences, e.g., frost, strong winds, hail, torrential rains, which can severely affect crops. It also enables timely planting, monitoring and management of crops by controlling humidity, temperature and carbon dioxide levels (Vadiee & Martin, 2014), while protecting the crops from pest and diseases. In the tropics the production of vegetables, (e.g. runner-beans, snow peas, baby carrot, baby corn, and spinach) and fruits, (e.g. passion fruit, water melons, mangoes, strawberries, and avocadoes *etc.),* is widely done in open fields and plantations.

Agriculture accounts for about 24% of Kenya's GDP (Kibe, 2011), supporting an estimated 75% of the population that depend on farming. Coffee, tea and tobacco are the traditional cash crops. However, years of poor prices in the late 1980s - early 1990s (Ponte, 2001) prompted farmers to diversify towards fast growing high value horticulture produce. There has been a remarkable growth in the horticulture sub-sector, leading to sustained improved economic returns (23% GDP) (Kibe, 2011), social employment and enhanced per capita income to working households. An estimated 7 million people are employed directly or indirectly in the sub-sector (Ngugi, 2013). Direct employment include daily farm tasks, such as harvesting, grading, packing, pest control etc., while indirect employment is involved in sales, transportation and branding processes (Ngugi, 2013). Commercial production is carried out by both small-scale farmers (accounting for a larger share of the locally consumed produce (96%)); and the large-scale companies (contributing about 4 % of the exported volume) (GoK, 2010; Kibe, 2011; Namu, 2007). Small-scale producers play a significant role in the sub-sector amid challenges such as high cost of inputs, limited access to extension services, unreliable weather, and limited access to direct markets. The large-scale commercial firms' accounts for a small percentage share of the sub-sector yet, dominate the international cut-flower market (Dolan, Opondo, & Smith, 2003; Kibe, 2011; Ulrich, 2014).

Horticultural production has a high return per unit of cultivated land area compared to other agricultural field crops (Vadiee & Martin, 2014; Vox et al., 2010). However, unintended costs (externalities) related to the intensity of production and waste generated from the practice have relatively greater impact on the environment public health and rural communities (Aeschbacher, Liniger, & Weingartner, 2005; Jongeneel, Polman, & van der Ham, 2014; Ulrich et al., 2012; Vox et al., 2010; Wainwright et al., 2014). Literature shows that energy consumption in heating and lighting of greenhouse horticulture is extremely high (Bergstrand, 2010; Vadiee & Martin, 2014). Close to 65-85% of total greenhouse energy demand in Europe, and USA, is attributed to heating commercial greenhouses (Runkle & Both, 2011) besides concerns of carbon dioxide emissions (Carlsson-Kanyama, 1998). In Canada, increased horticultural effluents to the environment became a concern, necessitating standards of compliance to regulate the horticulture industry (Canada, 2001). Similar concerns in Sweden impelled regulatory measures that prohibit greenhouse wastewater disposal into drains, watercourses, or groundwater (Alsanius et al., 2011) to protect the environment. In Netherlands, concentration and expansion of greenhouse horticulture in specific areas was linked to high emissions of pesticides and nutrients, prompting measures towards zero nutrient and pesticide emissions into water systems by 2027 (Boy, 2013). These lines of evidence show that, globally, intensive horticulture has major negative impacts, which remain a global concern given the steady increase in land covered by greenhouse horticulture (Vox et al., 2010). On the other hand, positive impacts stemming from such production system cannot be ignored. For instance Dutch agricultural sector (primarily horticulture based) achieved major developments milestones since 1950s that included: declining real prices for agricultural products; an increase in the scale of farms; substantial growth in labor; and land productivity, and a shift towards less land based forms of production (Bruchem et al., 2008). These example demonstrate that there are positive impact of horticulture production and agriculture generally, and therefore a need for sustainable frameworks that can reduce the unintended side-effects that may be imposed on the environment and human health (Boy, 2013; Pretty et al., 2000; Tegtmeier & Duffy, 2004).

In sub-Saharan Africa, numerous nations have successfully engaged in commercial horticulture e.g., South Africa (Noluthando & Eloff, 2012), Tanzania (Toroka, 2010), Zambia and Zimbabwe (Barrientos, Dolan, & Tallontire, 2003). However, concerns of potential environmental impacts stemming from the sub-sector have been minimally highlighted. The resulting economic benefits following the rapid success of the sub-sector may have fairly outweighed efforts to mandate viable regulations (GIZ, 2012). Such failure to account for ecosystems' goods and services (the environmental externalities) used in production when calculating returns is a large loop hole contributing to resource over-use (Clevo, 2000). Until recently, environmental costs incurred in cleaning polluted waters (Tegtmeier & Duffy, 2004) and soils through remediation were minimally recognized as items that needed to be included in production cost estimation. On a local-regional scale, it becomes clear that watersheds experiencing intense and increased production may be more likely to deteriorate over years, and bouncing back to their productive status could be fairly unlikely. Currently, there lacks a national horticultural policy that can guide the growth and sustainability of the horticulture sub-sector (MoA), resulting to overcrowding of farms in specific regions of central Kenya.

There are lines of evidence highlighting broad environmental and occupational concerns, whose research inquiry can potentially improve our knowledge, bridge existing gaps and also provide possible ways to address the issues. A number of previous studies indicate rapid exploitation and degradation of natural resources (land and water) linked to intensive horticulture (Kiteme & Wiesmann, 2008; Kithiia & Ongwenyi, 1997; Owiti & Oswe, 2007; Wainwright et al., 2014). Increased use of nutrients and generation of pollution from fertilizer and pesticides enhance leaching of harmful pollutants into water systems (Bres, 2009; Kreuger et al., 2010). Since the late 1990s, Kenya's demand for pesticides has been increasing, a trend attributable to horticulture farming (Saoke, 2005). Close to 7,000 metric tons of pesticides are imported annually to meet the growing demand. Studies by Kithiia, (2012) and Owiti & Oswe, (2007) show that the magnitude of horticulture production is linked to declining water quality, primarily due to nitrogen and phosphorus runoff, pesticides, soil enhancements and untreated pit latrine waste from unplanned settlements (Murage et al., 2000). Besides, the intense dependency on surface water for irrigation is proving to be unmanageable, due to decreasing water levels in streams (Aeschbacher et al., 2005; Ulrich et al., 2012). This is widely attributed to the changing rainfall patterns and drought events in the country that affect hydrology cycles; and excessive abstraction of water in the rivers around Mount Kenya and Nyandarua foot areas which greatly affects downstream water users (Gichuki, 1998; Mutiga, et al., 2010). While these studies reported impact on water quantity, there is no work indicating impact of increased commercial horticulture in the sub-watersheds on surface water quality characteristics in the study areas. Previous studies carried out in Lake Naivasha (horticulture hotspot region) (Balana, Yatich, & Mäkelä, 2011; Owiti & Oswe, 2007) showed a link between declining biodiversity, and impaired water quality of the fresh water lake. This was interpreted as related to release of agricultural effluents (agrochemicals and fertilizers) that threaten the lake's ecosystem (Kamau, et al., 2007). Njogu, et al., (2011) found high levels of heavy metals of nickel, zinc, lead, copper and cadmium in sediment samples from River Malewa, attributed to horticultural effluents from surrounding flower farms and urban towns proximate to Lake Naivasha. Their study also reported traces of organo-chlorine pesticides, and heavy metal traces in the fish species sampled from river Malewa. The fish had high zinc concentration in the order *C. spectacularlus* followed by *C. carpio, O. leucostictus* and *M. salmoidies.* A need therefore arises to continuously monitor water flow (quantity) and quality, particularly in those regions already showing increased reliance on irrigation for farming.

Elevated disturbances and loss of vegetation cover in the watersheds, and continuous cultivation of fields deny the soils sufficient period to recuperate after crop removal. This heightens the rate of water erosion of the top soils during rain events, and the transportation of sediments, and diverse pollutants into aquatic systems. Vegetation cover can help reduce runoff into aquatic systems, by filtering sediments and suspended materials. Interestingly, regions with vibrant commercial horticulture also experience enhanced land-use and land-cover (LULC) transformation (Maitima et al., 2009), due to increased settlement, cultivation (Olson et al., 2003), and population growth (Tiffen, 2003).

Land transformation is an important local driver that contributes to land degradation and greenhouse gas emissions. As a result, monitoring land cover to detect disturbances, changes in land use and trends in environmental condition has become crucial in environmental management. It is an ideal approach for watershed studies, where vegetation behavior over long term period can be evaluated, providing insight into the nature and extent of probable disturbances. Previous work show that Kenya's Mau Forest underwent major transformation after 1995 (Baldyga, Miller, Driese, & Gichaba, 2008) where vast forests were lost through deforestation to farming. It still remains unclear how fast the conversions are occurring, and whether the rates of conversion differ between sub-watersheds. Quantifying land cover and land use dynamics using satellite data has been used as a useful means of studying sub-watershed land use dynamics over time, generating statistics that inform policy decisions (Pielke et al., 2007). This approach is used in this study to provide LULC maps and quantative information on land transformation in horticulture prone regions. Drivers of land transformation are complex and region dependent (Kasperson, Kasperson, & Turner, 1996), requiring specific tailored studies to investigate degree and rate of changes. The one fits all approach in designing solutions may not suffice in all cases, necessitating area based studies.

Moreover, the spatial distribution of horticulture farming is highly skewed, with farming concentrated in agriculturally productive sub-watersheds within Naivasha, Kiambu, and Mount Kenya in Central Kenya. Consequently, the environmental impact and burden on resources is disproportionate across the watersheds, which heightens concerns of intensive horticulture production in Kenya. Watersheds provide resources that are shared among a growing human population, expanding cities, wildlife, plant species, and microorganisms. Unsustainable means of exploiting resources for commercial horticulture production may lead enhanced to resource degradation. There is a need to develop accurate spatial maps that portray the spread and areal dynamics of horticulture in Kenya, especially area under greenhouse cultivation which is unavailable in public records.

The current study uses publicly available datasets (desktop work), field data, and remote sensing data for sub-watersheds within central highlands of Kenya to explore the above highlighted concerns with broad goals to inform existing research gaps. The central highland region was initially inhabited by the British colonial government. Once the colonialists left, the formerly low populated ranches were fragmented into smaller plots for agro-pastoralism. People resettled from overpopulated areas, and small scale farms and large scale horticulture farms emerged (Mutiga et al., 2010). The region has six diverse agro-ecological zones that show a varied physical environment of an almost equatorial type of climate in upper-lands and semi-arid and arid environments in the lowlands (Kareri, 2010).This presents a mixed status in terms of rainfall, soil characteristics, vegetation and temperature range, conditions that facilitate diverse farming including subsistence to export oriented commercial farms, and extensive large-scale farms to very intensive small scale farms and livestock keeping (van de Steeg, Verburg, Baltenweck, & Staal, 2010). Studies show population build up, intensified irrigation use, increased water demand (Murage et al., 2000; Notter, et al., 2007) and elevated conflicts in resources use (Kiteme & Wiesmann, 2008) in regions with increased commercial horticulture. However, there is no literature known to us that has explored whether these factors are significantly associated with the growth of commercial farming.

This study therefore aims to contribute to an understanding of the current spatial extent and dynamics of commercial horticulture and its environmental impact on sub-watersheds in Kenya. The research uses an integrated approach to address four major topics that are considered important in assessing spatial dynamics of horticulture production and impact on natural resources (land, water) employed in production. The specific questions addressed are:

1) What is the current spatial distribution of greenhouse horticulture in central Kenya? What is the area under green-house cultivation? What are the significant predicting factors to such farming?
2) What can surface streams and rivers tell us regarding water quality and quantity characteristics in highly clustered large scale production areas as compared to small scale production yet intensive production areas?
3) Can the extensive record of remote sensing data on vegetation condition (NDVI) show early warning signs of environmental stress in vegetation within sub-watersheds experiencing increasing production activities? How does the Normalized Difference Vegetation Index in hot spot sub-watersheds compare prior to and post horticulture periods? Are there any quantative differences or similarities in trends over time?
4) How is increased horticulture farming impacting land use and cover dynamics in hot spot production areas? What are the rates and quantities of land cover and land use changes (LULC) in areas of intensive commercial horticulture farming (hot spot areas)?

5) How did the 2008/2009 post-election violence and the 2010 Icelandic volcano eruption affect horticulture exports?

1.1 Research Objectives

The first objective of the study was to map/explore the spatial distribution patterns and dynamics of the area under greenhouse cultivation using Google Earth archives alongside static data obtained from various portals. In this objective, the study aimed at generating precise spatial maps showing where greenhouse horticulture is occurring within the sub-watersheds in central Kenya. The roles of selected topo-edaphic, infrastructure and demographics factors that might influence current location within sub-watersheds were also examined. This was necessary in order to determine their significance as predictor factors of farm location choice. Greenhouse commercial horticulture started more than two decades ago and has evolved into a significant sub-sector to the national economy but so far no studies detail growth dynamics. The detailed methods to meet these objectives are further discussed in chapter 2.

The second objective of the study sought to understand the environment impact of horticulture production practices on stream and river water quality in select sub-watersheds in Laikipia and Meru, regions with increased commercial horticulture production. The basis to this objective is that: "*as integrators of the effects of land use practices within their catchments, streams and rivers can help in the diagnosis of the environmental health of the landscapes that they drain (Dallas and Day, 1993)".* To achieve the above objective, the specific aims were: (1) to identify prevailing surface water quality by examining variation of 14 physico-chemical indicators of water quality, and (2) to categorize measured surface water quality parameters into land use types highlighting potential pollutant source-processes. A field study was carried out in July and August 2013, to sample surface water quality at 38 sites selected across the five main land types in Laikipia and Meru. These included forest (FOR), urban (URB), mixed subsistence agriculture (MAG), small scale intensive horticulture (SSHORT) and large scale intensive horticulture (LSHORT). A detailed methodology is highlighted in chapter 3 of this work.

The third objective of the study was to assess the long term vegetation condition in sub-watersheds mapped with increasing intensive horticulture production activities using GIMMS AVHRR NDVI data. Historical records of remote sensing data from 1981 to 2006 were utilized to allow an examination of potential early warning signs of environmental stress in vegetation, particularly in sub-watersheds experiencing increased production activities. The study evaluated: i) inter-annual variability in averaged Normalized Difference Vegetation Index (NDVI), ii) trends in average annual NDVI before and after 1990 -the presumed onset of rapid horticulture and iii) relationship between the average annual NDVI and large-scale commercial farms, population density, and mean annual rainfall in sub-watersheds. A combination of geospatial techniques (GIS, remote sensing) used to achieve the objectives are elaborated in chapter 4.

The fourth objective of the study was to quantify land use and land cover (LULC) changes and rate of change between 1984 and 2009/2010, identifying areas with increased change using Landsat (5 MSS, TM & 7 +ETM) multi-temporal data in classification and change detection analysis. Following the image processing, a supervised classification of the 1984 image scenes and the 2009/2010 scenes was carried out using the maximum likelihood decision rule. Classified images were validated to access goodness of classification using reference points derived from archived Google Earth images. A detailed description of the methods used to achieve the above objectives is highlighted in chapter 5.

The fifth objective of the study aimed to provide an overview of the performance of the sub-sector in terms of trends of exported volumes considering increasing environmental changes and natural events on farming, and socio-political unrests in the country. These events affect the sustainability of the sub-sector and therefore need for changes. Horticultural export data (from 1995 to 2013) for cut-flowers, vegetables and fruits, was obtained from Horticultural Crops Development Authority (HCDA), compiled and analyzed. The performance of the three export clusters was examined to highlight trends and seasonal variations in export volume in the last ~2 decades. A further description of the methods is provided in chapter 6.

1.2 Organization of thesis

The above-mentioned research objectives were accomplished and the research findings are organized in the form of various chapters in this dissertation. Each chapter details one broad objective with sub-objectives as follows:

- Chapter 2 entitled "Spatial Distribution of Greenhouse Commercial Horticulture in Kenya and the Role of Demographic, Infrastructure and Topo-Edaphic Factors” explored the spatial patterns and dynamics of the area under greenhouse cultivation. This was an area not explored before. Google Earth archives alongside data from various portals provided an opportunity to study those farms' spatial distribution. This study also examined and reported the role of selected topo-edaphic, infrastructure and demographics factors likely to influence current location within sub-watersheds in central highlands of Kenya.

- Chapter 3 entitled "Understanding the impact of intensive horticulture land-use practices on surface water quality in Central Kenya" seeks to understand the impact of increased production practices on stream and river water quality in Laikipia and Meru, regions identified as production hotspots. This study's specific aims attempted to (1) to identify prevailing surface water quality by examining variation of 14 physico-chemical indicators of water quality, and (2) to categorize measured surface water quality parameters into land use types highlighting potential pollutant source-processes. This study also reported results of water samples tested during field work that was conducted in July-August of 2013.
- Chapter 4 entitled "Vegetation response to intensive commercial horticulture and environmental changes within watersheds in Central highlands, Kenya, using AVHRR NDVI data" applies long term data records to evaluate likely changes in vegetation status in study area. Climate conditions for world horticultural regions are projected to change, making such farming extremely difficult and costly to the environment. To understand the scope of impact on vegetation, the study evaluated: i) inter-annual variability in averaged Normalized Difference

Vegetation Index (NDVI), ii) trends in average annual NDVI before and after 1990 -the presumed onset of rapid horticulture and iii) relationship between the average annual NDVI and large-scale commercial farms, population density, and mean annual rainfall in sub-watersheds. The Advanced Very High Resolution Radiometer (AVHRR) Global Inventory Modeling and Monitoring Studies (GIMMS NDVI data from 1982 to 2006 were used in this chapter.

- Chapter 5 entitled "LULC transformation in semi-arid to arid sub-watersheds of Laikipia and Athi River basin as influenced by expanding intensive large-scale horticulture, and revealed by Landsat data", quantified change and rate of change in land use and land cover (LULC) between 1984 and 2009/2010 in the watersheds with intensive commercial horticulture and increased human settlement using Landsat 5 MSS, TM and Landsat 7 +ETM multi-temporal data in classification and change detection analysis.
- Chapter 6 entitled "Coupled Effects on Kenyan Horticulture following the 2008/2009 Post-election Violence, and the 2010 Volcanic eruption of Eyjafjallajökull", evaluates the impacts of two events, 1) the 2008 post-election violence in Kenya, and 2) the 2010 Icelandic volcanic eruption on the Kenyan horticultural exports. Long-term annual and monthly trends in export volume for cut–flower, vegetables and fruits (export cluster), over a 19 year period are examined to establish impacts of both events on horticulture exports. The performance of the three export clusters are examined, highlighting underlying seasonal variations in export volume in the last ~2 decades.

Appendices A, B, contain detailed field images for Chapters 2 and 3. Appendices C and D contain data tables for chapter 4 and 6, respectively. Appendix E is the preface for the journal articles published from chapter 2 and chapter 6, in ISPRS International Journal of Geo-Information 2014, 3(1), 274-296, and Natural Hazards (2014), 76(2), 1205-1218 respectively.

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CHAPTER 2

Spatial Distribution of Greenhouse Commercial Horticulture in Kenya and the Role of Demographic, Infrastructure and Topo-Edaphic Factors

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Abstract

In this chapter, Google Earth image archives alongside data from various portals were used to study the spatial distribution of greenhouse commercial farms. The roles of selected topo-edaphic, infrastructure and demographics factors that might influence current greenhouse locations within sub-watersheds were also examined. Results revealed a non-uniform spread with two high clusters; one in the semi-arid sub-watersheds 3AB shared by Kajiado and Machakos districts and the other was in sub-humid sub-watersheds 3BA shared by Kiambu and Nairobi districts. Multivariate linear regression analysis identified four statistically significant parameters; population density ($p < 0.01$), number of dams ($p < 0.01$), average rainfall ($p < 0.01$) and average slope ($p < 0.05$) in predicting the number of greenhouse farms. Soil attributes were not significantly related to greenhouse farming. This was attributed to the use of soilless media in place of natural soils. The results from this chapter also show that greenhouse commercial horticulture is heterogeneous, and rapidly expanding beyond the central highlands towards marginal semi-arid zones in Kenya. These findings are applicable in policy and decision making processes that can aid the horticulture sector's progress in a

sustainable manner.

Keywords: Sub-watersheds, greenhouse, commercial horticulture, spatial patterns

2. Introduction

Proliferation of large-scale intensive commercial horticulture, i.e., the production of high value fresh cut flowers, vegetables and fruits has attracted several Sub Saharan African economies in quest for unconventional export commodities (Dever, 2007; Dolan & Humphrey, 2004). The decline of traditional cash crops (coffee, tea and tobacco) due to changes in market demands, low return prices (Gemech & Struthers, 2007; Ponte, 2001) and decreasing land resources for plantation farming (Mehta & Chavas, 2008) affected their production in Kenya. The horticulture sub sector has since been the fastest growing industry within the agricultural sector, scoring a yearly average growth of 15% to 20% in the last decade (MoA). Approximately 4.5 million people are directly employed in production, processing, and marketing activities, while 3.5 million people benefit indirectly through trade and numerous other activities. Several reasons have promoted horticulture growth. These include a high demand for fresh produce at the international European markets (Regmi, 2001), better trade terms and liberalization of economies, need for diversification (van Vliet, Reenberg, & Rasmussen, 2013; Weinberger & Lumpkin, 2007), growing health and dietary awareness linked to fresh produce (Gehlar & Regmi, 2005) and the desire of having year round availability of fresh produce. Other countries such as South Africa (Noluthando & Eloff, 2012) and Tanzania (Toroka, 2010) have successfully exploited the niche and often realized increased foreign income, creation of jobs for skilled and semi-skilled workers, and improved livelihoods for the urban and rural workers.

Success of the Kenyan horticultural sector is well documented (Dolan & Humphrey, 2004; Toroka, 2010). Many studies attribute the continued progress to the strategic location of the country on the equator, which endows Kenya with good climatic conditions (Thoen, Jaffee, & Dolan, 2000; Weinberger & Lumpkin, 2007). Additionally, availability of cheap labor (Weatherspoon & Reardon, 2003), widened market access, frequent and reliable freights from Jomo Kenyatta International Airport and minimal governmental interference have also contributed to the success (Dolan, 2002).

Recent studies show a general trend towards fewer and larger horticultural greenhouse growers (Dehnen-Schmutz, Holdenrieder, Jeger, & Pautasso, 2010), as evident in Kenya. Greenhouse horticulture production is intensive, occurring under a controlled environment which enables a year-round all season production. Crops are planted directly in native sterilized soils, under greenhouse field conditions, because of several reasons: (1) greenhouses offer a controlled environment against unexpected weather occurrences, e.g., frost, strong winds, hail, torrential rains, which can severely affect crops; (2) they also enable a timely planting, monitoring and management of crops, by controlling for humidity and carbon dioxide levels, which enable flower formation by the projected harvest dates; and (3), they offer protection from pest and diseases which are common in tropical climates. The sterilization of soil kills pathogens and nematodes which are a nuisance to crops like roses. Roses are commonly grown in Kenya on raised beds (~60 cm) (Figure A1) because the rose bushes (from where the flower stem sprouts), can last ~7 years under good management. The raised beds enhance deep root penetration and stability. However, other flower crops like Carnations, Statice, Alstroemeria, Lilies, Hypericum and Lisianthus (also commonly grown in Kenya) (KFC), do not require raised beds, but are directly planted in the ground under greenhouses (A1, A2). Large amounts of land resources, water, labor, machinery, agrochemicals and technological skills are utilized through complex strategic planning. Small scale farmers play a minimal role, often contracted by larger companies.

The success of the industry with such an intensive nature of production has enormous impacts on the environment (Aeschbacher, Liniger, & Weingartner, 2005; Ulrich et al., 2012). Yet such impact is not equally distributed since production is concentrated in specific sub-watersheds. Watersheds provide resources that are shared between a growing human population, expanding cities, wildlife, plant species, and microorganisms. A threshold of resource use can be quickly reached if unsustainable means are applied in exploiting resources for commercial production needs. Furthermore, particular agricultural management practices can affect soil structure, composition and microorganism communities (Sieverding, 1990). Fungal communities are affected by excessive soil fertilization, tillage (Oehl et al., 2003), and soil pretreatments with effects observed on spores and mycelia densities in temperate and tropical agro-ecosystems (Mohammad, Hamad, & Malkawi, 2003). The magnitude of production horticultural activities is also linked to declining water quality at Lake Naivasha (Owiti & Oswe, 2007), due to nitrogen and phosphorus runoff, pesticides, soil enhancements and untreated pit latrine waste from settlements.

Failure to account for ecosystems' goods and services (the environmental externalities) used in production when calculating returns is a large loop-hole contributing to resource over-use (Clevo, 2000). Until recently, environmental costs incurred in cleaning polluted waters (Tegtmeier & Duffy, 2004) and soils through remediation were minimally recognized as items that needed to be included in production cost estimation. It becomes clear that watersheds experiencing intense and increased production activities are likely to deteriorate over years, and bouncing back to their productive status is fairly unlikely.

Currently, there is no national horticultural policy to guide the growth and sustainability of the horticulture sector (MoA). This failure has resulted in overcrowding of farms in specific regions of central Kenya, which in turn necessitates a need to explore current spatial patterns and production dynamics, in order to generate information useful in forming a sustainable export culture. The current mainstream description of main horticulture production areas in Kenya is presented in a very general manner. It is stated that, "The main production areas are around Lake Naivasha, Mt. Kenya, Nairobi, Thika, Kiambu, Athi River, Kitale, Nakuru, Kericho, Nyandarua, Trans Nzoia, Uasin Gichu and Eastern Kenya",(KFC). Such a description lacks precise geolocation that can be rectified by a distribution map based on point locations of actual locality of greenhouses. Our preliminary cartographic endeavor suggests greenhouse production is concentrated in a few sub watersheds within these broader administrative districts.

This work is the first in a series of studies seeking to establish the spatial extent of greenhouse horticulture production in Kenya, understand important factors influencing choice of location, and evaluate the environmental impacts of increased production activities on sub-watersheds.

The study's objectives were (i) to determine current spatial distribution of green-housed commercial horticulture production and derive their acreage under cultivation within sub-watersheds in the central highland of Kenya; and (ii) to evaluate significance of topo-edaphic factors (i.e., soil pH, cation exchange capacity (cec), average bedrock, exchangeable sodium (exNa), exchangeable potassium(exK), average slope, rainfall and river density); infrastructure (road density and dams); and demography (population density) as factors determining location of farms.

2. 1 Materials and Methods

2.1.1 Study Area

The study area covered 88 sub-watersheds in central highland of Kenya, confined within: 34°55'51.88"E, 0°55'10.51"N (upper-left); 38°07'09.91"E, 2°23'03.73"S (lower-right) and an area of 81,607.26 km^2 (Figure 2-1A). The study region was found to have various greenhouse horticultural activities during the study period (2000–2011). Four lakes are found in the area (i.e., Lake Naivasha, Nakuru, Baringo and Elementaita) (Figure 2-1A). The region has six diverse agro-ecological zones that show a varied physical environment of an almost equatorial type of climate in upper-lands and semi-arid and arid environments in the lowlands (Kareri, 2010). The upper-lands occur in the upper northwest region of the study area and are generally humid to sub humid, often presenting thick forest vegetation. The lowlands show strong gradients in terms of average rainfall, temperature, and vegetation characteristics. Due to the mixed status, a variety of conditions exist that facilitate diverse farming. These include subsistence to export oriented commercial farms, and extensive large scale farms to very intensive small scale farms and livestock keeping (van de Steeg, Verburg, Baltenweck, & Staal, 2010).

Rainfall is highly variable in the study area, occurring in two seasons, April–May (long rains) and October–November (short rains). Around the Aberdare Mountains the average annual rainfall is about 1350 mm/year (Figure 2-1B). However, this reduces substantially to ~600 mm/year advancing near Lake Naivasha. Another interesting feature to the east of the area is Mt. Kenya which stands at 5199 m above sea level (Figure 2-1B). The mountain causes a strong shadow effect that highly influences climate conditions of the adjoining plateau land to more of a semi-arid to arid region, with rainfall of ~450 to 750 mm/year (Notter, 2003). Due to low average annual rainfall, vegetation to the eastern and southern (760 mm/year) regions is dominated by woody vegetation of Acacia and *Themeda* grass cover that mainly occur in savanna environments (Dougall & Glover, 1964).

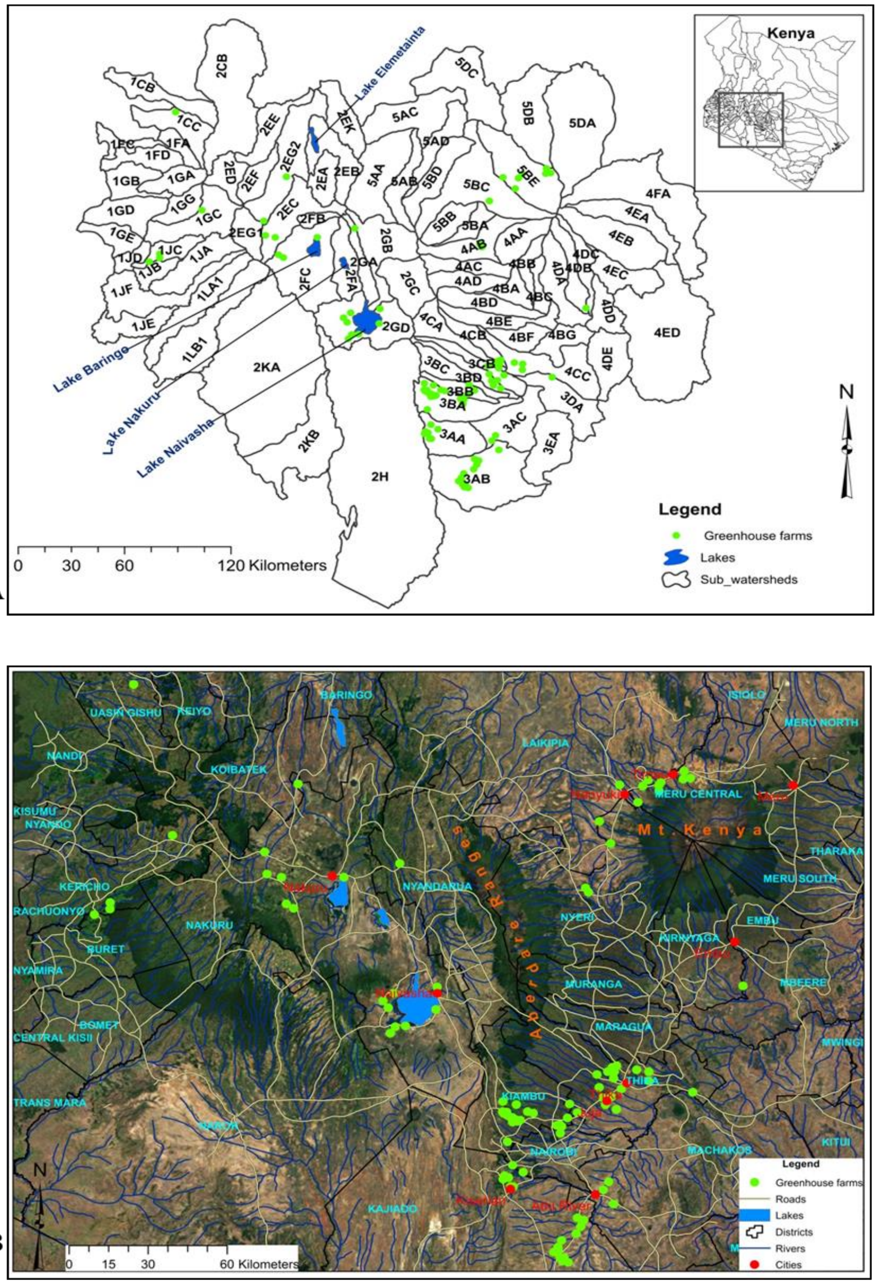

Figure 2-1: Study area. (**A**) Map of Kenya (right), and inset (left) is the study area showing sub-watersheds in the central highlands considered in the study. (**B**) Major towns, rivers, lakes and mountain features—Mt. Kenya and the Aberdare ranges.

C

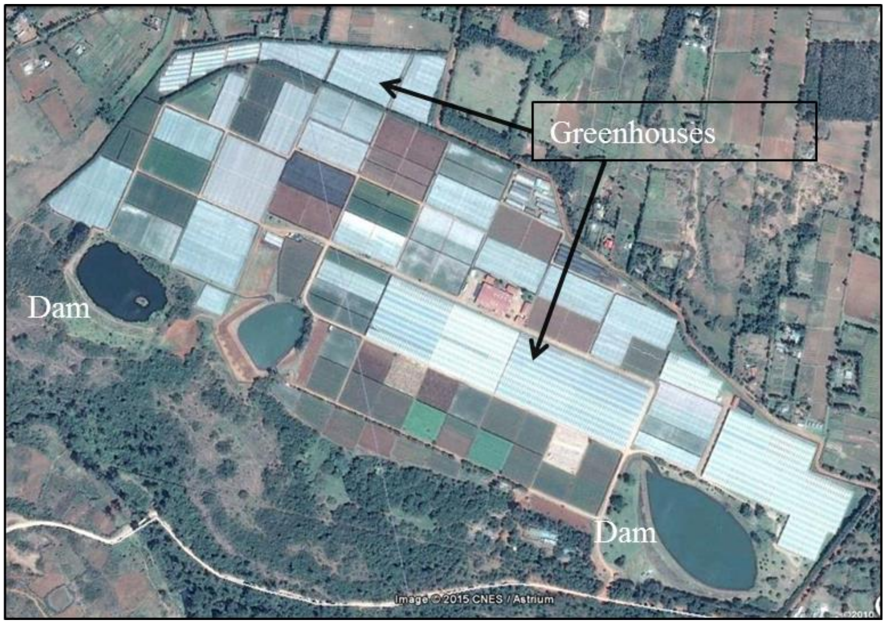

Figure 2-1: (**C)** A Google Earth image of a greenhouses and dams.

Temperature varies dramatically with altitude, attaining mean maximum and minimum temperatures of ~25 °C and 15 °C, respectively. Soils are predominantly fertile, deep (>160 cm) rich in clay and well drained, derived from mixed volcanic rocks. However, severe land degradation is widespread due to topsoil erosion attributed to continuous cultivation (Murage et al., 2000). The upper zones are densely populated while drier areas exhibit sparse population.

2.1.2. Data Acquisition and Processing

This study attempts to predict spatial extent of greenhouse farms in sub-watersheds using eleven potential explanatory variables that are grouped to include topo-edaphic variables of soil pH, cation exchange capacity (cec), average bedrock, exchangeable sodium (exNa), exchangeable potassium (exK), average slope, rainfall and river density;

infrastructure (road density and dams); and demography (population density). The crops are grown directly in the soil, under the greenhouses, and an incorporation of soil parameters in the model was considered meaningful. We describe data acquisition and preparation for each variable.

The sub-watershed data layer was created by the World Research Institute (WRI) from the 1992 Kenya National Water Master Plan, and is publically available (WRI, http://www.wri.org). Each sub watersheds is assigned a unique code composed of a number and two letters e.g., 5AB. The number represents one of the five river basins in Kenya, i.e., Lake Victoria (1); Rift valley and inland lakes (2); Athi River and coast (3); Tana River (4) and Ewaso Ng'iro (5) in which the sub-watershed resides. The first letter (in this case A) represents the sub catchment, while the second letter (in this case B) represents the major river branch in the particular sub-catchment. Given that a sub catchment may have more than one major river branch, the second letters can continue progressively to as many as there are major river branches in the sub basin, for example, 5AA, 5AB, 5AC, 5AD, 4BA, 4BB, *etc.*

To determine current spatial distribution of green-housed commercial horticulture production and derive their area under cultivation within sub-watersheds, the geographic coordinates of the centroid point locations with greenhouses were identified, alongside the corresponding greenhouse images from Google Earth®. Google Earth uses the WGS84 (World Geodetic System 1984) and a terrain data derived from the Shuttle Radar Topographical Mission (3-arcsecond, ~90 m resolution at the equator) with a nominal accuracy of between 6 m and 8 m (Farr et al., 2007; Philip et al., 2013). The increase in the use of Google Earth imageries in deriving area measurement e.g., mapping the area under urban agriculture (Taylor & Lovell, 2012); deriving the area of stone walled enclosures (Sadr & Rodier, 2012), and development of microscale meteorology models (Wang, Huynh, & Williamson, 2013) may be an indication of its acceptance in the geospatial community as a means of making areal measurements with an acceptable level of accuracy relative to the scale of the project.

Both historical (2000–2003) and current imageries (2010–2011) were used (Figure 2-1C). The background imagery for Google Earth is a Landsat mosaic of 30 m resolution satellite images. However, where available, images of higher spatial resolution (1 m to 4 m) from commercial satellite programs such as DigitalGlobe and GeoEye are added and can be viewed when zoomed in. The clarity of individual images (Figure 2-1C) allowed for an accurate determination of greenhouse structure outlines and derivation of polygon area, by zooming in to a satisfactorily extent before taking measurements. From the images, the total area around the individual greenhouses at each identified farm locations was calculated. Historical imagery enabled identification of previous area under greenhouse production (if any) existed in that point. It also helped to establish probable year when the farm started. Images were carefully labeled with the dates of acquisition.

ImageJ, an image processing and analysis software developed by the United States National Institute of Health (NIH) (Rasband, 2013) was used to derive the area under production from the saved images. ImageJ is widely used across disciplines due to its flexibility, and the ability to automate tasks using simple macros and plug in extensions. The measurement tool was calibrated before area calculation was performed. Calibrating the image indicates to the software what an image pixel represents in real world in terms of size and distance, to enable conversion of image pixels to distance measurements (SERC). Features of known distance are used in calibration, and in our study, a known distance of 100 m from a greenhouse was used. The area selection tool was then used to determine polygon area around individual greenhouses in sq. km.

Derived data on the area under greenhouses were then entered as attributes to the farms in a sub-watershed GIS layer. Sub-watersheds were used as the basic study units since this is a good balance between data collection and production of meaningful results and feedback, which would best serve watershed management plans in the future.
To evaluate the significance of topo-edaphic, infrastructure and demographic factors determining location of farms, various data layers of exploratory variables that potentially influence farm locations for greenhouse production and hence location suitability were obtained for each sub-watershed. The variables were based on literature and expert knowledge of the dominant factors influencing the choice of location (Farr et al., 2007; Genhua et al., 2008; Murage et al., 2000; Philip et al., 2013; Ritzema et al., 2008; Ross, 2002; Sadr & Rodier, 2012; Tavakkoli et al., 2010; Taylor & Lovell, 2012).

Data layers of administrative boundaries (Districts), river and stream network, roads network, population and agro-ecological zones were available from (ILRI), http://www.ilri.org).

Generally, the soil physical and chemical characteristics are important in determining its productivity and ability to support crop growth and development.

The soil parameters were derived from an Arc Info coverage of soil physical and chemical properties of Kenyan soils carried out by the Kenya soil survey in 1982 (Sombroek, Braun, & van der Pouw, 1982), and revised in 1997. It is publically available as a data layer from International Livestock Research Institute (ILRI, http://www.ilri.org). These data are the latest available at such scale and detail, and were recently used to characterize subsistence farming by different households in central Kenya (van de Steeg et al., 2010).

Soil pH is a measure of the soil acidity or alkalinity as measured in a soil “water” solution, and considered a proxy of the active pH that affects plant growth (van de Steeg et al., 2010). The average cation exchange capacity (cec) measured in me/100g of the soil was used to give an estimate of the soil’s ability to attract, retain, and exchange cationic elements. The exchangeable potassium (exK) me/100g, was considered important since potassium controls the stomata movements facilitating a plant’s efficiency in water use. It assists in recycling of nutrients to feed roots, leaves and fruits thereby promoting plant life (Tittonell et al., 2010). It is also a key element besides nitrogen and phosphorus. The amount of exchangeable sodium (exNa), measured in me/100g, is an important factor determining a soil’s suitability for supporting plants (Tittonell et al., 2010) as it strongly influences water infiltration and soil aeration. Furthermore, soils of arid and semi-arid areas contain large quantities of sodium (Na), and irrigation agriculture in such areas is often a source of soluble salts even if excellent quality water is used (Tavakkoli et al., 2010). Excesses of exNa (>2.5%) becomes toxic to the plant, and affects plant growth since it adversely alters the physical and chemical conditions of the soil (i.e., soil permeability, dispersion (Ritzema et al., 2008) and water permeability). Besides, sodium competes with calcium, magnesium, and potassium for uptake by plant roots prompting deficiencies of other cations.

The depth of average bedrock influences drainage of the site, water flow pattern and other hydro-geological functions (NRCS) that might influence the decision to establish a greenhouse. In addition, it can offer a solid foundation for greenhouse construction.

The average slope was derived from a 250 m Digital Elevation Model (DEM) grid (WRI, 2012). Slope influence drainage of an area (Freer et al., 2002; Kazemi, Dumenil, & Fenton, 1990) and the applicability of heavy farm equipment mainly utilized in large scale farming. It is an important parameter considered in installation of drip irrigation systems in greenhouses. While the use of a coarse-resolution DEM may affect the obtained slope values, it was a readily available dataset and compatible with our model. Furthermore, by deriving the average slope, the impact of likely high frequency noise introduced by the coarse DEM is reduced.

Average annual rainfall distribution (in millimeters) for sub-watersheds was derived from data compiled by the Japanese International Co-operation Agency (JICA) under the National Water Master Plan, Kenya (WRI). This data was applied in the model because, rainfall is a major source of river and groundwater recharge, which occurs at the higher altitudes of Mt. Kenya and the Aberdare regions. Reduced rainfall affects river flow, which may directly impact irrigation and the area under production. River density, commonly known as drainage (total length of all the streams and rivers in a drainage basin divided by the total drainage area) was derived using the streams and river network data layer. It is a measure of how well a watershed is drained by rivers and stream channels.

Road density and number of dams were considered as two infrastructure exploratory variables. Road density was estimated for each sub-watershed by dividing the sum of all roads (km) in sub-watersheds by the area of sub-watersheds (sq. km). The number of dams within 500 m to identified farms was counted from images and entered as an attribute to the farms in the same GIS layer.

The census data follows administrative boundaries (i.e., districts and sub-locations). Sub-locations are administrative units ranked lower in hierarchy than districts and locations. The census population data in Kenya were obtained at this level, and aggregated to the district level. The 2009 census data obtained from Kenya National Bureau of Statistics (KNBS, 2009) were joined to the district layer and population numbers for each sub-watershed extracted using ArcGIS®. Population density, representing a demographic exploratory variable, was derived by dividing the total population per sub-watershed by area of the sub-watershed.

Following the processing, the 11 exploratory variables were then used in a multivariate linear regression model to predict spatial location of observed greenhouse farms. The counted number of greenhouses and number of dams in the study area were logarithmically transformed to base ten. Such transformation is recommended to enable data normality (Osborne, 2002) since greenhouses and dams were not evenly observed across all sub-watersheds. This was to enable applicability of ANOVA analysis, before which the Shapiro-walk test was done to check for data normality after the transformation.

The test was statistically significant ($p < 0.01$) attesting data normality. A stepwise linear regression model (Montgomery, Peck, & Vining, 2006) was used to relate the occurrence of greenhouses in the different sub-watersheds to all 11 potential explanatory variables. This approach was chosen since it assesses the contribution of individual variables to overall model fitness, and assists in choosing to exclude or include variables accordingly.

2.2 Results

2.2.1 Spatial Distribution and Area under Greenhouse Commercial Horticulture

The distribution of farms varied greatly in the sub-watersheds (Figure 2-2A). Our findings indicate that 24 out of the 84 sub-watersheds had greenhouse horticulture farms during the study period. Clustering, defined as geographic concentrations of interconnected companies and institutions in a particular field (English & Jafee, 2004) was observed in the Athi River area. This was in sub-watershed 3AB shared between Kajiado and Machakos districts, which have semi-arid type of climate. An increased number of farms were also observed in sub-watershed 3BA that is shared by Kiambu and Nairobi districts, which are considered sub-humid to semi-arid areas. Other notable but moderately clustered sub-watersheds were 2GD which encompasses Lake Naivasha and Nakuru region, 3BB which covers Kiambu district, and 5BE that is shared by Meru Central and Laikipia Districts.

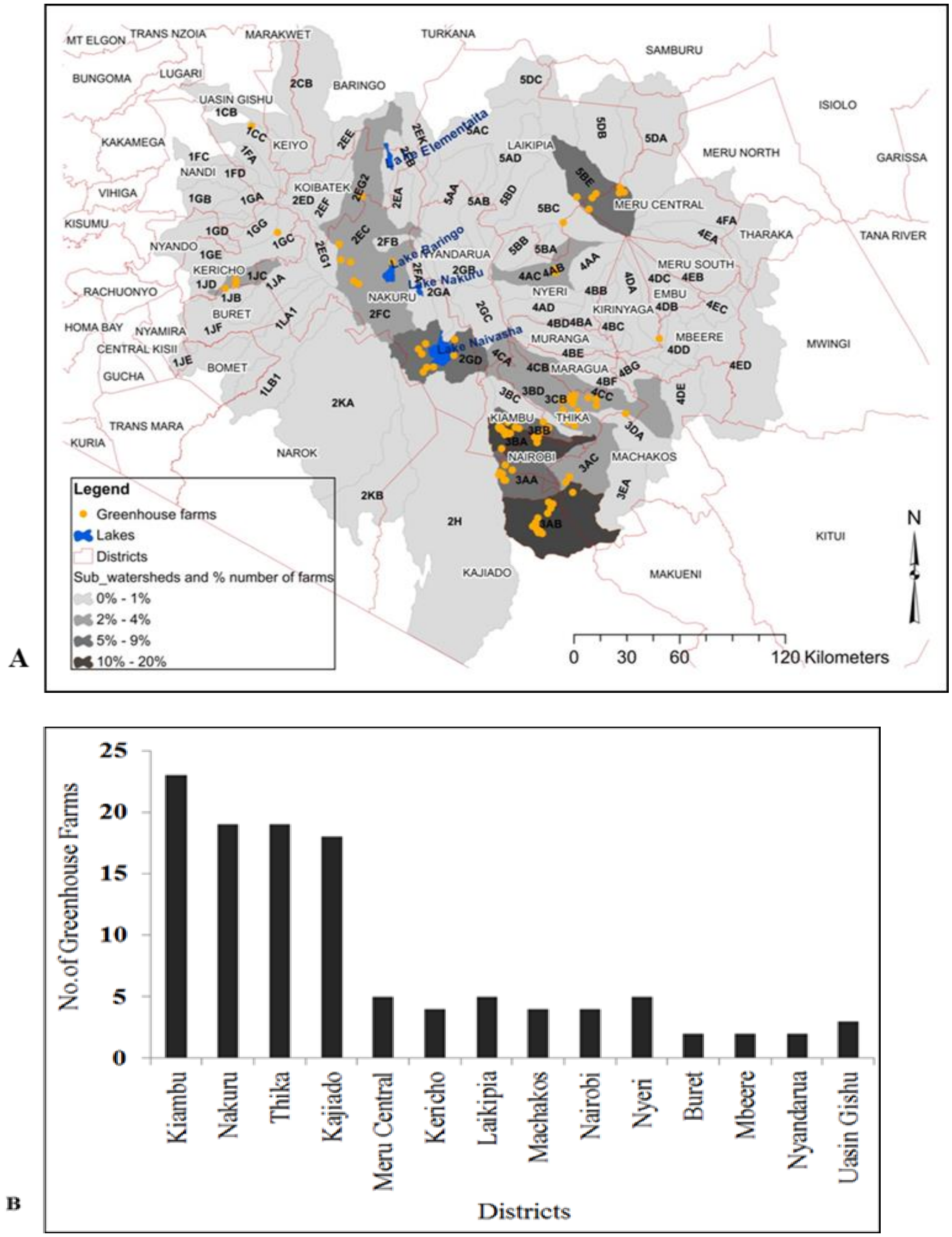

Figure 2-2: (A) Spatial distribution of greenhouse commercial horticulture in the central highlands of Kenya within sub-watersheds in 2000–2011, (B) Within districts.

Further examination of the spatial spread across the districts indicates that Kiambu, Nakuru, Thika and Kajiado, had more than 15 large scale commercial greenhouse farms each, while Laikipia, Meru Central and Kericho districts had 5 farms or less, individually (Figure 2-2B). Our observation is supported by (Hornberger et al., 2007) who report that production for export is concentrated in about two dozen, large-scale farms, accounting for 75% of the industry and 10%–15% by contracted small scale farmers.

Table 2-1. Total land area under greenhouse cultivation, and number of greenhouses in 2000–2003 and 2010–2011 in the study area.

Area under Greenhouses (sq. km)	**No. of Farms 2000–2003**	**No. of Farms 2010–2011**
0	30 **	4 *
0.01–0.02	10	16
0.02–0.04	13	21
0.04–0.06	14	11
0.06–0.08	13	10
0.08–0.10	9	14
0.10–0.12	2	9
0.12–0.14	2	5
0.14–0.16	2	3
0.16–0.18	0	3
0.18–0.20	0	2
0.20–0.22	1	2
>0.4	0	1
Total Farms	66	97

* In 2011, four farms that initially had greenhouses but were currently not greenhouses, or were converted to other uses and so are assigned zero sq. km. ** Farms not existing in 2000–2003 but established in 2010–2011 are assigned a zero area under greenhouses for the 2000–2003. This reduces the number of current observed farms to 97. Total land area and number of farms under greenhouse cultivation increased in the period 2000–2011 (Table 2-1).

In 2000–2003, 66 farms covering and estimated area of 3.76 sq. km were identified. This number increased in 2010–2011, to 97 greenhouse farms covering 6.83 sq. km, which was a 3.07 sq. km. increase from previous period (2000–2003). An additional 31 greenhouses were identified in 2010–2011, which greatly increased the area under production between the periods. This observation agrees with a noted increase in real Gross Domestic Product annual growth from ~0.6% in 2002 to 6% in 2006 (Hornberger et al., 2007).

The majority of the greenhouse farms in 2010–2011 were approximately 0.01–0.12 sq. km (83.5%). 15 greenhouses had 0.12–0.22 sq. km (15.4%), and 1 farm had >0.40 sq. km (0.01%) under production. A notable increase in number of greenhouses occurred in 2010–2011 (31), which corresponded to an increase in area under production. What, then, are the possible conditions that drive such spatial distribution? Our multivariate regression might shed light in this regard.

Table 2-2. Multivariate linear step-wise regression model results. Coefficient of determination $r^2 = 0.88$, ($p < 0.01$, t = 154.69) showing significant variables of dams ($p < 0.01$), population density ($p < 0.01$), average rainfall ($p < 0.01$) and average slope ($p < 0.05$), in predicting greenhouse farms.

Model Summary					Anova		Unstandardized Coefficients		
Model	**Adjusted R.sq.**	**df**	**F**	**sig.**	**Model**		**B**	**T**	**Sig.**
1	0.84	83	449.82	0.01	1	(Constant)	0.127	2.826	0.006
						Dams	0.642	21.209	0.01
2	0.86	83	449.82	0.01	2	(Constant)	0.013	0.249	0.80
						Dams	0.613	20.899	0.01
						POPden09	0.001	3.664	0.01
3	0.88	83	194.9	0.01	3	(Constant)	0.37	2.711	0.01
						Dams	0.598	20.862	0.01
						POPden09	0.01	4.537	0.01
						AvgRainfall	0.01	−2.813	0.01
4	0.88	83	154.69	0.01	4	(Constant)	0.535	3.513	0.01
						Dams	0.595	21.254	0.01
						POPden09	0.01	4.112	0.01
						AvgRainfall	0.01	−2.713	0.01
						AvgSlope	−0.059	−2.232	0.028

2.2.2 Significance of Topo-Edaphic, Demographic and Infrastructure Factors in Predicting Farm Locations

The multivariate linear stepwise regression model results (Table 2-2) show that not all 11 variables were significant predictors of greenhouse locations. In fact, the final model identifies only number of dams, population density (2009), average precipitation and average slope are significantly related with the occurrence of greenhouse farms. The final model has an $r^2 = 0.88$, indicating that 88% variation in the observed spatial location of greenhouse farms in sub-watersheds was explained by these four variables. The statistically significant F value suggests a linear relationship between the transformed occurrence of greenhouse farms and the four explanatory variables. The other seven variables are not found to be significantly related with observed number of greenhouse farms.

Our finding indicates the many soil parameters were not important factors influencing occurrence of greenhouse farms, which at the first glance, might be quite unanticipated. Considering the primary purpose of greenhouse farms, which is to seek the highest possible profit, such finding, however, does not seem to be unreasonable. We deduce that the variation of soil condition in our study area is not great enough to influence farm establishers for their locational decision. This is especially true due to increased use of soil amendments and soilless technologies in horticulture greenhouse farming. Instead, other factors that are more related with economic gains, such as population density, availability of water and slope factors, stand out as the most significant and alarming to decision makers who need to understand the current horticulture practice is not sustainable in the long run.

2.3 Discussion

2.3.1 Spatial Distribution of Greenhouse Commercial Horticulture

Based on our analysis, the spatial spread of greenhouse farms varied greatly from 2000 to 2011, occurring primarily in 24 sub-watersheds out of the 84 considered in central highlands. Production is heterogeneous across the study area, creating hot spots which have successfully sustained horticulture production in Kenya, at least in the last decade. Dense clusters were found in the Athi River (3AB), Kiambu and outskirts of Nairobi (3AA), alongside moderate clusters that surround Lake Naivasha and Nakuru region (3BB), Meru Central and Laikipia districts (5BE) (Figure 2-2A and B). A minimal number of farms were observed in other sub-watersheds. Our finding is important because it helps clarify the standing assumption that production of horticultural commodities in Kenya occurs in many locations and is favored by good climatic conditions. We found fewer districts (Figure 2-2B) than those provided by Kenya Flower Council as regions of commercial horticulture farming, particularly cut flowers. The highly heterogeneous spread of greenhouses (Figure 2-2A) in sub-watersheds is likely related to availability of capital environmental resources that are employed in production of fresh horticultural produce. Increased demand for fresh produce at the international and domestic markets requires an all year round production which is met provided continuous resource availability.

One key characteristic of horticulture farming is intense water usage (Aeschbacher et al., 2005). On the contrary, since water resources are unevenly distributed across and within sub-watersheds, we observe a limited number of farms in relatively arid areas and increased clustering in more humid regions where water is readily available (i.e., around Lake Naivasha). Greenhouse clustering can be an efficient use of land resources particularly in areas with high urbanization pressure (Veerle, Dessein, & Lauwers, 2008). From an environmental resource management perspective, such skewed patterns may result in imbalance in resource sharing, over-exploitation and faster degradation of sub-watersheds. This necessitates spatial planning and coordination of policy levels across institutions and various stakeholders. Our analysis is highly suggestive of a strong role played by combined production factors in explaining observed greenhouse concentration in specific sub-watersheds. Sub-watersheds with suitable soil characteristics but lacking in significant primary factors are possibly unsuitable as greenhouse sites. Presence of a diverse climate and vegetation gradients across sub-watersheds (Notter, 2003) further strengthens our observation that different factors may be influencing location of choice. For example, observed increases in greenhouses in Athi River (3AB), which is a semi-arid, low rainfall area and previously sparsely populated is likely due to the proximity of Jomo Kenyatta International Airport that readily provides a means of transport.

2.3.2. Changes in Area under Greenhouse Cultivation

A remarkable increase in number of greenhouses, and a corresponding increase in area under production (Table 2-1) were identified. Study analysis shows growth in production area from ~ 3.76 sq km to ~6.83 sq. km between 2000–2003 and 2010–2011 respectively. This observation agrees with a noted increase in real Gross Domestic Product annual growth estimated at 0.6% in 2002 and to 6% in 2006 attributed to growth of the horticulture sector (Hornberger et al., 2007). Our calculated area shows the majority of all counted greenhouses (83%) occupied an area between 0.01–0.12 sq. km, while 15.4% had between 0.12–0.22 sq. km and one farm had more than 0.4 sq. km under greenhouses. In recent years, studies show that greenhouses are generally occupying more space (Korthals, Willem, & van Rij, 2013). For instance in Canada, Spain, Great Britain and the Netherlands, new greenhouses occupy between 0.03 sq. km and 0.3 sq. km (Badgery-Parker, 2001). Meanwhile, a range is observed from 0.001 to 0.1 sq. km in Flanders (Rogge, Nevens, & Gulinck, 2008).

Greenhouses provide a controlled environment for crop production, and application of technological advances. A couple of reasons may explain the observed growth dynamics. In the years following the decline of coffee prices and revenues (Ponte, 2002), the majority of farmers sought alternative high value export commodities. Fresh produce commodities such as cut flowers, vegetables, fruits, and nuts provided this avenue. Diversification to high value produce was further strengthened by better trade terms such as the African Growth and Opportunity Agreement, increased produce demand at international market, and widened market access. Moreover, minimal government intervention in regulating the horticulture sector, unlike traditional cash crops, encouraged farmers to consider broader intensified production. The use of greenhouses to control for climate, pests invasion and weather effects on produce further enabled this type of production. The magnitude of area under production (Table 2-1) may seem small but considering the intensity of production per unit area, the value is interesting. Our finding can relate to a study by (Korthals et al., 2013) indicating a growth in greenhouse farms occupying 0.03 sq. km. It is rational to think that the ability to expand units of production highly depends on the investor's potential, more so because agricultural intensification requires labor and capital to enable the increased inputs necessary to raise the value of output per hectare (Carswell, 1997). Generally, the observed changes in area under production seem necessary and have supported horticulture sector growth atop traditional export commodities, and the economy (FPEAK; HCDA). However, rapid expansion of the sector has implications for resource utilization and sustainable management of watersheds resources, necessitating further evaluation of environmental impacts of increased production.

2.3.3 Role of Different Factors in Determining Spatial Location of Greenhouse Farms

2.3.3.1. Significant Predictors

Our multivariate regression analysis shows four significant factors related to location of greenhouses. These are average slope ($p < 0.05$, $t = -2.23$), average rainfall ($p < 0.01$, $t = -2.713$), number of dams ($p < 0.01$, $t = 21.25$) and population density ($p < 0.01$, $t = 4.11$) (Table 2-2). Our results show an average slope of 2.9% across the study area, with steepest slope at 6.8%, and lowest point at 0.77%.

The average slope considered in current study as a topography variable has significant effect on crop yield (Kazemi et al., 1990), and can affect mobility (Joly et al., 2013) and utilization of farm machinery in large scale farm operations. An increase in slope is shown to negatively affect corn yield reducing it by 0.79 bu./acre for each 1% increase in slope gradient (Kazemi et al., 1990). Their work supports our results, which show a significant negative relationship between the average slope and greenhouse farms.

Similar claims are discussed by (Corbeels, Shiferaw, & Haile, 2000) who indicate that farmers recognize importance of slope in choice of farmland. The negative directionality of effect indicates decreasing number of greenhouses with an increase in average slope, implying that less step gradients are more favorable since they allow ease in use of farm machinery, while sustaining crop yield. A study carried out in the Gikuuri catchment in central Kenya (Okoba & Sterk, 2006) indicated flat to gentle slope (2%–15%) in the region, described by (USDA, 1954) as having slight hindrance to the use of heavy farm machinery. Large scale commercial horticulture chiefly use heavy machinery whose ability to work can be limited on steep slopes. This consequently reduces efficiency of mechanization while increasing cost of farm operations. In addition, the level of difficulty and cost in erecting greenhouses and fitting drip line systems is likely to increase at steeper grounds (Kazemi et al., 1990).

Results also show a significant negative relationship between numbers of greenhouse farms and average annual rainfall (Table 2-2). The majority of greenhouses are observed within zones receiving ~ 950 mm/year. Rainfall as a primary source of irrigation water (FAO, 1978) characterizes the long term quantity of water available for hydrological and agricultural purposes (Kennen et al., 2008). Study findings show an average increase in annual rainfall towards humid agro-ecological zones as the number of greenhouses declined. While rainfall availability may influence choice of a location for greenhouse farming, other climate factors, e.g., temperature and vegetation cover that change along rainfall gradient may hinder preference of a location for greenhouse farms. This relates to observed increase in area and number of farms in sub-humid to semi-arid and arid regions of the study area. More clustering is observed in semi-arid to sub-humid regions, where rainfall is moderate. This has implications for dry land horticultural farming particularly since rainfall variability in Kenya is shown to relate to ongoing drought and famine. Variability in rainfall is perpetuated by a changing climate, and shifting rain seasons as a result of El Niño North Atlantic Oscillation activity (Funk, 2010). This may limit future spread and area under greenhouse production to specific areas creating an increased demand for water. Increasing rainfall variability may have an effect on the degree of water abstraction for farming purposes.

Based on our analysis, the number of dams is shown to be significantly ($p < 0.01$) related with greenhouse farming. Studies show increases in water abstraction via dams as farmers try to reduce shocks due to rainfall decline. Increased water abstraction for irrigation by large-scale commercial horticulture in Laikipia (5BE) was reported in (Kiteme & Wiesmann, 2008).This could elucidate findings of increased area under production as facilitated by availability of dam water. Presence of dams can increase the area under irrigation and sites of farming while enhancing productivity by increasing multi-cropping and the cultivation of water-intensive cash crops (Singh, 2000). A report by the

International Commission on Irrigation and Drainage (ICID, 2000) finds that dam construction significantly increases agricultural production and yield besides enabling farmers to substitute towards water-intensive crops. However, irrigated marginal lands in Spain are largely degrading due to increased extensive agriculture and population expansion is noted in (Alados et al., 2011). We identify an urgent need to seek alternative sustainable sources of water, and investigations on water harvesting technologies that can benefit the sector to avoid resource exhaustion.

Population density was statistically significant ($p < 0.01$) (Table 2-2.) in predicting greenhouse farms in our study area. Our findings agree with (McCulloch & Ota, 2002) highlighting that commercial horticulture is labor intensive, often employing masses of workers. Currently, the sector employs close to 4 million people directly (FPEAK) in the processes of production, produce processing e.g., cleaning, sorting, grading, labeling, packing and post-harvest tasks, which require substantial skilled and semi-skilled labor. This is met through seasonal hire, contract or fulltime jobs afforded by the farms. It explains why population density as a production factor is highly significant in horticulture, and particularly this region of the world where advances in technological applications are still developing. Furthermore, scarcity of labor in commercial horticulture can be a limiting factor to production (McCulloch & Ota, 2002). Substantial employment afforded by horticulture attracts job-seekers, prompting growth of unplanned settlements. Neighboring towns expand (Gockowski & Ndoumbé, 2004) and businesses grow to meet public demand for basic household items and services. However, rampant increase in population has implications for resource use, often resulting in conflict between the stakeholders (Aeschbacher et al., 2005; van Vliet et al., 2013). Land fragmentation to build rental shelter structures is noted as a current common scenario that results in declining land productivity and increased discharge of human waste into river system affecting water quality (Mohammad et al., 2003). We identify a strong need for long term sustainable solutions to control overcrowding in sub-watersheds experiencing increased production.

2.3.3.2 Non Significant Factors: Soil Characteristics, River Density, Road Density and Depth of Bedrock

We find that neither soil parameters, river density, road density nor the average depth of the bedrock was statistically significant in predicting spatial extent of greenhouse farms. However, from our knowledge and reviewed literature, these variables may influence site selection for agricultural activities (Ritzema et al., 2008; Tittonell et al., 2010; Van de Steeg et al., 2010). Here below, we highlight the importance of each factor, speculating why our analysis results show non-significant relationships.

Soil characteristics considered at the sub-watershed scale offer a convenient means to organize field measurements, enabling an assessment of the role played by each in predicting greenhouse farming. Soil attributes, for example soil moisture, are highly variable in time and particularly at the watershed scale (Maher et al., 2008). Even so, obtaining continuous field data to assess a vast area is challenging. Our approach used a static soil data layer (ILRI), found useful to gain a general idea and baseline understanding of importance of soil parameters in predicting greenhouse farming. Our results show minimal non-significant relationship between observed greenhouses and considered soil parameters. Despite our finding, the relative importance of soil characteristics cannot be overlooked. A study by (Murage et al., 2000) indicate that soils in the study area have formed as a result of volcanic activity of the Rift Valley. They are fertile, deep, well drained clays that support diverse agricultural activities. We attempt to explain our finding based on available literature and knowledge of horticulture farming. Increasing use of superior soilless media (Maher et al., 2008) e.g., peat, moss, that has better physical properties compared to soil could lend ordinary soil parameters less influential in siting greenhouses. Soilless media is preferred because it is free of disease, pest and weeds contamination, is relatively inexpensive and environmentally friendly providing an overall less cost of production. It also allows easy adjustment of plant nutrients, depending on crop needs. Nevertheless, not all farmers use soilless substrate. Increased availability of fertilizers and soil dressers provide cheaper alternatives for investors to manipulate soils elements to desirable status irrespective of soil status of a location. Farmers view soil fertility as a dynamic process that integrates a soil's chemical and physical characteristics, agricultural necessities, and factors in the surrounding environment (Desbiez et al., 2004). More importantly, farmers are influential in the process of increasing soil fertility or degrading soil (Ambouta et al., 1998).

Road infrastructure enhances a region's suitability for not only horticulture but also numerous other commercial activities. Fresh horticultural products are highly perishable requiring readily available means of transportation to the market. In the absence of a good road network post-harvest losses (Kereth et al., 2013) can occur which constrain production and inability of investors to recover investment costs. Even though large scale companies have refrigerated trucks to transport produce, the costs attached to such transportation can be efficiently reduced in the presence of a good road network. Farm proximity to roads network could offer faster access to the airport.

However, growing concern indicates that traffic pollution (Petit, Christine, & Elisabeth, 2011) poses a threat of produce contamination, particularly on farms clustered in proximity to roads (Wang et al., 2000). These may explain the poor ability of road density in predicting spatial spread of greenhouses. It is not farfetched to reason that in effort to avoid such risks farms choose to concentrate in interior rural areas where a dense road network is absent. Farms in the interior areas of sub-watersheds face a challenge in transporting commodities to the airport for international markets. Night transportation with less traffic congestion seems a convenient alternative.

This spells a need to increase road amenities in productive areas, but in a sustainable way. A note of concern is that our approach to use road density as a key variable could be adjusted to consider distance of farms from main roads or road quality as the variable influencing location choice. The role of road infrastructure in fueling greenhouse horticulture must be established in order to improve our understanding of spatial spread of horticulture and its impacts on environmental resources.

Our assumption that regions with denser river and streams network would likely attract more greenhouses was not supported by our findings. Results show a weak non-significant prediction, a probable indication that presence of dense network of rivers, may not necessarily assure quantity and quality of irrigation water, or its reliability, which is desirable in continuous intensive greenhouse farming.

2.3.3.3 Suitability of Google Earth and Downloaded Data

Google Earth provides a powerful tool for viewing global imagery with integrated GIS data and well organized tools, maps and graphics, e.g., borders, place labels, roads, ability to zoom in/out, viewing historical archived data among other tools (Sadr & Rodier, 2012; Wang et al., 2013). In our assessment, its use as a tool to generate acreage under greenhouses in Kenya is especially suitable for studies in areas with limited access to aerial imagery. To the best of our judgment, the background Landsat imagery of medium spatial resolution in Google Earth, alongside other images from DigitalGlobe and GeoEye satellites with minimal cloud coverage enabled candid spatial assessment of trends in horticultural greenhouses in Kenya. The clarity of greenhouses, as displayed in Google Earth allowed precise area measurement, around the features of interest.

On the contrary, available archived Google Earth data for the region were limited to 2000–2003. Images of greenhouses, within this period were therefore grouped as the starting period. While greenhouse horticulture in Kenya dates back to the 1990s, Google Earth, may be limited in assessing trends in area under greenhouses or the number of farms during that time. Other archives of remote or aerial data would be required. Interestingly, the soaring number of Google Earth data usage in scientific work, and across disciplines, indicates its growing applicability.

The soil dataset used in our study was recently used by (van de Steeg et al., 2010). This evidence prompted its use in our model, and found it of suitable representation of the general soil characteristics in the area. Furthermore, obtaining extensive and detailed soil data is difficult, because recent soil studies are localized, and the data generated are limited to specific local scales of sampling that answers specific research questions. There is need for current, broader scale soil datasets that can be used by the wider research community.

The use of administrative boundaries, the census data (2009), and the sub-watershed data layers in a GIS environment enabled the extraction of population information that was employed in the regression model.

Other data layers of rivers and streams, rainfall, the road network, and the DEM have been compiled by the International Livestock Research Institute group, and are available in public domain. These data were considered suitable for the purpose of our study, and have been used in numerous studies and regional reports.

Though the coarse resolution 250 m DEM (WRI) used in the study could affect the accuracy of derived slope values, we assume that measures taken, e.g., averaging the slope would minimize likely errors. For the purpose of the study, and in our best judgment, the static data layers provided useful information, not easily gathered for remote study areas in developing countries.

2.4 Conclusion

In the current study, we examined spatial distributions patterns and the significance of selected demographic, infrastructure and topo-edaphic factors in influencing observed greenhouse location in 84 sub-watersheds using available datasets and Google Earth archives. To the best of our knowledge, the current work is the first attempt to map the spread and dynamics of greenhouse horticulture production at sub-watersheds level in Kenya. Sub-watersheds are chosen as study units since, as a unit, they balance well between data collection and production of meaningful results and feedback that would serve overall best watershed management plans in the future. The study focused on the central highlands of Kenya due to its diverse agro-ecological (humid to very dry arid areas) and sharp rainfall gradients that prevail between the uplands and lowlands.

Results indicate a non-uniform spread occurring as high clusters in a few sub watersheds and low clusters in other. An increase in number of greenhouses and area under cultivation is evident between 2000–2011, possibly due to better trade terms, wider international market, diversification and increased fresh produce demand. We also find four statistically significant factors: population density, the average rainfall, average slope and dams that accurately predicted the observed spatial spread across area of study. While mainstream literature notes that the country has good climatic condition and soils, the ability of these factors to solely explain the observed patterns is debatable. Mapped distribution highly suggests dependency of greenhouse locations on multiple factor combinations rather than a single factor in selecting sites for production.

Mapping greenhouse distribution and deriving the area under cultivation in Kenya using accessible, online tools such as Google Earth is novel, since these data are currently unavailable, neither documented among other publically available export statistics. Having established the extent of distribution, the next goal would be to investigate environmental impacts of such farming on sub-watersheds, examining highly vulnerable regions.

Derived quantitative data on production area is useful in modeling environmental impacts of agricultural practices such as the application of pesticides and fertilizers, irrigation and product transport. The results are also applicable in decision making and priority management such that permitting regulations governing intensity of commercial farming in a given area, considering other ecosystem stressors are emphasized. Sub-watersheds vary greatly in size, endowed resource, number of stakeholders sharing resources, *etc.* These are factors for consideration when stipulating where to allow permits; where to increase amenities and prioritization of infrastructural development; provision of better sanitation, *etc.* A potential shortcoming of the approach used is that all mapped greenhouses accounted for are assumed to carry out commercial horticulture production. From experience working in this sector, only flowers were found in greenhouses. The findings are more or less region specific since climatic conditions and infrastructure driving export farming can vary diversely.

The study extends knowledge on spatial patterns of greenhouse farming and clarifies the significance of chosen key parameters in influencing choice of greenhouse sites.

Further studies can explore land use dynamics in hot spots zones as they can give an indication of watershed resource status and level of sustainability in greenhouse farming.

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CHAPTER 3

Understanding the impact of intensive horticulture land-use practices on surface water quality in Central Kenya

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Abstract

After establishing the spread and dynamics of greenhouse commercial horticulture, and the role of multi-variables in predicting location of farming in chapter 2, this chapter, sought to understand the impact of increased production practices on stream and river water quality in Laikipia and Meru, regions identified as production hotspots. Two specific aims were pursued: (1) to identify prevailing surface water quality by examining variation of 14 physico-chemical indicators of water quality, and (2) to categorize measured surface water quality parameters into land use types highlighting potential pollutant source-processes. A field study was carried out in July and August 2013, to collect surface water samples from 38 stations in 14 rivers draining 4 sub-watersheds in the two regions. The multivariate data were analyzed using principal component analysis (PCA) and discriminant analysis (DA). PCA results provided four principal components that explained 70% of the observed total variability of water quality. The results also indicated a prevalence of cadmium, phosphate, and zinc, which are heavy metal traces, linked to rigorous use of phosphate fertilizers and copper based agrochemicals. The DA provided four discriminant functions, and significantly ($p < 0.05$) separated water quality indicators into five land use types (89.5% correct assignment), enabling association of land use with observed water quality. The concentrations of dissolved solids, electro-conductivity and salinity spiked at locations downstream of intensive small scale and large scale horticulture. Nitrate was prevalent in mixed agriculture (MAG) likely due to the use of manure. The findings from this chapter are critical to formulating ecologically-sound watershed management and pollution abatement plans**.**

Keywords: Water quality, PCA, DA, Laikipia, Meru, fertilizers, land-use

3. Introduction

Surface streams and rivers are important sources of fresh water for domestic, industrial and irrigation purposes in Kenya. The rapid rise of commercial horticulture (Dever, 2007; Dolan & Humphrey, 2004; Thoen, Jaffee, & Dolan, 2000; Ulrich, 2014; Weinberger & Lumpkin, 2007), has impaired water quality affecting the physico-chemical properties of surface waters (Kibichii et al., 2007; Nyakundi, 2012; Owiti & Oswe, 2007). Horticultural pollutants transported in runoff, or through leaching into surface streams contribute to declining water quality that limit stream integrity and usefulness. The management of horticultural pollutants in watersheds with diverse land-uses (Wan et al., 2014; West et al., 2010; Zhu, 2008) is a complex process, and often faced with the difficulty to separate effluents from different land processes and land use types. In addition, horticultural effluents are high in nitrogen and phosphorus, pesticide residues and soil enhancements (Owiti & Oswe, 2007), which degrade water quality; making it unhealthy for human use, while also exposing the aquatic communities to habitation stress.

Since the late 1990s, Kenya's demand for pesticides has been increasing, a trend attributable to horticulture farming (Saoke, 2005). Close to 7,000 metric tons of pesticides are imported annually to meet the growing demand. Recently, Kithiia (2012) found high levels of pollutants and heavy metals (lead, mercury and copper) in Nairobi River and its tributaries. They highlighted a need to review the existing land use policy in the country in order to limit encroachment of unplanned land-use activities into important watershed areas. Horticultural vegetable farmers use a wide variety of pesticides, including herbicides (e.g., linurex 50 wp, diurex 80wp), insecticides (e.g., diazol 60EC, methomex 90S) and fungicides (e.g., Folicur EW and dithane M45)(Nyakundi, 2012). Their work (Nyakundi, 2012), is among a limited few recent studies documenting the prevalent use and mismanagement of pesticides in horticulture farming. Consequently, the extent of pollution and dominance of organic and inorganic elements in surface streams and rivers draining horticultural watersheds surrounding Mount Kenya region is poorly understood. Previous work on Lake Naivasha, which is surrounded by intensive horticulture, suggests that the practice has detrimental effects on the lake's fresh water quality and quantity (Owiti & Oswe, 2007). On the foot zones of Mount Kenya, where horticulture is rapidly expanding, Liniger et al. (2005) identified a decline in surface flow and increase in water abstraction by the farmers. Nevertheless, the study did not report water quality conditions despite a desire to create a long term sustainable water monitoring institution within the basin. Agrochemicals and fertilizers applied on agricultural lands are recognized as a main source of pollution to water systems, and are therefore a threat to the environment and human health (Nziguheba & Smolders, 2008).

Regular use of pesticides to ensure “pure” undefiled fresh produce free of insect marks promotes increased applications of agrochemicals, which may vary in degree of persistence in the environment. Long term continued exposure to aquatic creatures even when the environmental concentrations are not acutely toxic is not sustainable and can become critical (Magnusson et al., 2013).

As often in practice, however, intensification of agriculture is often accompanied by the use of additional agrochemicals, a common approach to maximize production per unit land area (Arunakumara, Walpola, & Yoon, 2013). Water contamination by heavy metals due to intensified agriculture, rapid urbanization and industrialization, is of global concern (Singh, 2011a). Commonly used basal and top dressing fertilizers in intensive horticulture have phosphorite base, which is high in heavy metals of environmental concern such as cadmium, uranium, and arsenic (Otero at al., 2005). The long term application of phosphorus (P) fertilizers contributes to cadmium build up in soils (Lugon-Moulin et al., 2006) and global surveys of metals in P-fertilizers corroborate the finding (Nziguheba & Smolders, 2008). Also, other metals such as zinc and lead have shown positive correlations with increasing P concentrations in soils. Once in the soil, metals may accumulate, or even enter the food chain through hyper-accumulating plants. They may also enter the surface streams through leaching and erosion processes. The use of contaminated surface waters for irrigation purposes propagates the pollution effect onto land as well (Chanda, 2011). Depending on regional application of agrochemicals and more so the P fertilizers, the inputs of trace metals and metalloids into the agricultural soils, and surface water may differ spatially.

In this work, sub-watersheds with intensive small-scale (SSHORT) and large-scale commercial horticulture (LSHORT) are considered in an effort to examine underlying characteristics in water quality. Clustering of intensive farming in specific sub-watersheds (Justus & Yu, 2014), accompanied by growing changes in land-use and land cover patterns pose pollution risks to surface waters. In many cases, the water obtained from these streams is not screened for contaminants before use, which poses a public health concern. In this study, we intend to: (1) evaluate prevailing surface water quality by examining physico-chemical parameters variations in samples and, (2) categorize measured surface water quality parameters into land use types highlighting potential pollutant source-processes.

Water quality monitoring studies commonly assess water quality indicators such as: phosphate, nitrate, potassium, zinc, copper, cadmium, iron, sulfide, dissolved oxygen, pH, salinity, electrical conductivity, total dissolved substances and water temperature. These indicators are critical for sustaining aquatic life, plants, human, and animals (Arrigo, 2011; Bhardwaj, 2010; Tong & Chen, 2002; Vega et al.,1998). Some of these parameters occur as rare earth elements and so their occurrence in surface waters has been applied as tracers of anthropogenic processes in environmental studies (Otero et al., 2005).

To design better water resource management strategies, there is an urgent need for comprehensive water quality monitoring across the diverse land use platform in Kenya. Information of elemental composition in surface waters will help facilitate efficient policy decisions. However, diverse land use systems within sub-watershed present a complex situation when tracking source-processes, necessitating an application of combined methods of analyzing field data.

In this study, we adopt the commonly used principal components analysis (PCA) and discriminant analysis (DA) techniques to analyze water quality data. These techniques not only facilitate the analysis and interpretation of intricate water quality data (Bhardwaj, 2010; Olsen, 2012; Selle, Schwientek, & Lischeid, 2013) but also allow in-depth understanding of the prevailing surface water quality and the detection of source processes influencing water systems.

Such information is critical in watershed management (Shrestha & Kazama, 2007;Singh et al., 2004; Varol et al., 2012). An initial exploratory evaluation of the raw surface water quality data is considered, followed by data processing with PCA, and a determination of source-process relationship using DA.

Following this introduction section, we will discuss the study area and methodology in detail. Results from data analysis will be presented in the third section. The fourth section presents a discussion of these results, and we conclude the research with a summary and proposals for future research.

3.1 Materials and Methods

3.1.1 Study Area: rivers in the sub-watersheds

This research focuses on the major rivers in Laikipia and Meru central regions, which are major horticultural producing zones in Central Kenya. In Laikipia, export-oriented horticultural farming is mainly carried out by large scale farms and few small cale farmers. Intensive horticulture farming in Meru is carried out by small scale farmers on contractual basis. The two regions are geographically separated by Mt. Kenya forest (Figure 3-1), an important source of fresh water. Major rivers in Laikipia include: Likii, Nanyuki, Naromoru, and Burguret, which form tributaries to the Ewaso Nyiro River. In Meru, the major rivers are Kathita, and Mutonga, which provide water for irrigation as well as human use. Because of a strong shadow effect of Mt. Kenya, the adjoining Laikipia plateau is actually a semi-arid region, with a bimodal rainfall of ~ 450 to 750 mm/year (Notter, 2003). Due to the low average annual rainfall, the dominant vegetation is Acacia and *Themeda* grass, which is of typical savanna environments (Dougall & Glover, 1964). Meru is on the northeast slopes of Mt. Kenya, where the vegetation changes dramatically to thick mixed forest due to more annual rainfall varying between 1200 and 1500 mm (Shisanyan et al., 2009). The mean annual temperature is ~ 20 °C, and the soils are predominantly fertile, and well drained, even though there is land degradation attributed to continuous cultivation (Murage et al., 2000).

Surface waters in the area form a radial drainage pattern, characteristic to volcanic mountains of a relatively young drainage network (Notter, 2003). In the upper zones of Mt. Kenya, the rivers are fed by glacial and snow melt. As the river flow through the thick forest cover, they form dense networks of deeply incised tributaries, which find ways into the foot-zones of the mountain, resulting to meanders with ephemeral tributaries. The headwaters are generally cold, but the temperature increases as they exit the forest. The transitional zones are experiencing increased anthropogenic perturbations (Figure 3- 1) in form of land clearing on forest edges mainly for farming practices, and settlements. The mid-waters in Laikipia flow through dense horticultural production zones characterized by greenhouses, and open crop fields as well as urban areas with increased human settlements. The prevailing mix of land-uses is a concern to mid-waters quality mainly due to nutrient loaded horticultural effluents and municipal waste discharges. The lower reaches of rivers in Laikipia have low river flow due to over use of head and mid-waters. Towards Meru, the rivers flow to Tana and Ura, and later to the Indian Ocean. Like Laikipia, forest clearing to create farming land is common along the forest edges. These practices affect the quality and flow of surface waters in the study area.

Generally five main land-use practices exist in the study area: irrigation dependent all season large-scale intensive horticulture (LSHORT) (in greenhouses and also open field); all season small scale intensive horticulture (SSHORT) – mainly vegetables for export- sub-contracted farmers by large exporting companies; mixed agriculture (MAG) farming of subsistence and cash crops that depends on the prevailing rainfall; urban uses (including residential settlement, small industries/auto businesses, car washes, mechanical); and forest. The mix of land-uses and diverse waste effluents present a complex environmental management challenge to water resources managers.

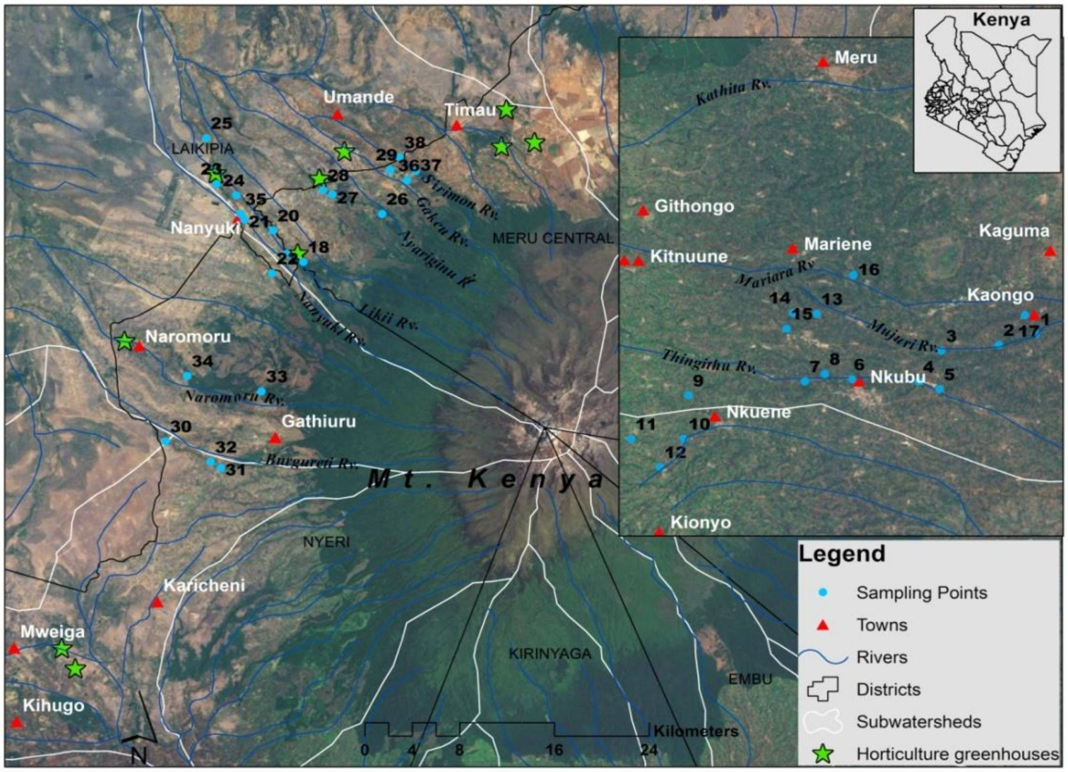

Figure 3-1: Study area map showing sub-watersheds around Mt. Kenya, surface water sampling points and towns. To the West is Laikipia which represents a growing cluster of large scale commercial horticulture; and to the East is Meru, consisting of a mix of subsistence farming and intensive small-scale contracted horticulture farmers.

3.1.1.1 Field Sampling

3.1.1.2 Sites

38 sampling sites were established across five land-use types common in the region. Twenty one (21) sites were in Laikipia sub-watersheds, and 17 sites in Meru central sub-watersheds. The site selection was based on prior knowledge of the area and land use types, accessibility of rivers to conduct sampling, and also proximity to greenhouses farming (particularly in Laikipia where greenhouses are utilized). The sites

in Laikipia were located on 6 main rivers i.e., Nanyuki, Likii, Burgureti, Naromoru, Nyariginu, Sirimon and Gakeu (See Table 3-1). Sampling sites in Meru were located on 8 rivers i.e., Mujuri, Thinghithu, Mariara, Njoe, Kithinu, Gitauga, Gatauga and Kiuna Ndegwa. Samples were representative of the site conditions under the different land use to enable accurate assessment of the study area with a minimum number of samples.

Table 3-1. Sampled sites (Site ID) and the respective rivers

Site ID	Name	Site ID	Name
Site 1	Mujuri Rv. (downstream)	Site 20	Likii Rv. near Likii high sch.
Site 2	Mujuri Rv. (midstream)	Site 21	Nanyuki Rv.below Bucaneer
Site 3	Mujuri Rv. (upstream)	Site 22	Nanyuki Rv. Mt.Kenya Safariclub (upstream)
Site 4	Thingithu Rv.(downstream; quary)	Site 23	Nanyuki Rv.(downstream)
Site 5	Thingithu Rv. at Mujwa bridge	Site 24	Likii Rv. near Likii (downstream)
Site 6	Thingithu Rv. at Nkubu bridge	Site 25	Likii and Nanyuki Rv. (downstream)
Site 7	Kiuna Ndegwa Rv. (downstream)	Site 26	Nyariginu Rv. (upstream)
Site 8	Thingithu Rv. (upstream)	Site 27	Nyariginu Rv. (midstream)
Site 9	Kiuna Ndegwa Rv. (upstream)	Site 28	Nyariginu Rv. (midstream)
Site 10	Kithinu Rv. (downstream)	Site 29	Gakeu stream (downstream)
Site 11	Kithinu (upstream)	Site 30	Narumoru Rv. (downstream)
Site 12	Kirimba Rv. (midstream)	Site 31	Narumoru Rv. (upstream)
Site 13	Gitauga Rv. (midstream)	Site 32	Narumoru Rv. (midstream)
Site 14	Gakuri Rv. (midstream)	Site 33	Burguret Rv. (upstream)
Site 15	Gatauga Rv. (midstream)	Site 34	Burguret Rv. (downstream)
Site 16	Mariara below bridge (midstream)	Site 35	Nanyuki Rv. (midstream)
Site 17	Njoe Rv. (downstream)	Site 36	Kaleu Rv. (upstream)
Site 18	Likii Rv. (upstream)	Site 37	Sirimon Rv. (upstream)
Site 19	Likii Rv. (midstream)	Site 38	Sirimon Rv. (downstream)

3.1.1.3 Field Measurement and Analysis

Water samples were collected during the months of July and August 2013. Data for 14 commonly used physico-chemical water quality indicators (Arrigo et al., 2011; Eyre & Pepperell, 1999; Susanna et al., 2002; Vega et al., 1998; Wang, 2001), i.e., phosphate, nitrate, potassium, zinc, copper, cadmium, iron, sulphide, dissolved oxygen, pH, salinity, electric-conductivity, total dissolved substances and water temperature were collected.

No rainfall events occurred during the sampling period and all samples were obtained between 9:00 AM – 11:00AM, to avoid increased temperatures' influence over the parameters. GPS locations of all sites were recorded, and field notes taken documenting the surrounding river/stream habitat characteristics, bank conditions and other general observations that could be useful in result interpretation.

At each site, a grab sample was collected by directly filling a 1 gallon sample bottle at various vertical depths at the center of the channel where water was well mixed. In deeper waters, sampling was done by lowering a weighted bottled on a rope or steel rod into the stream. Measurements of water pH, water temperature (C^o), salinity (ppm), TDS (ppm), and electric-conductivity (EC- µS/cm) were determined *in situ* by dipping an EXTECH EC500 meter into subsample. For dissolved oxygen evaluation, sub-samples from the main grab sample were obtained and treated on site, and then later analyzed alongside other parameters.

Field analytical procedures outlined for the SMART3 colorimeter, an EPA-accepted multisensory field instrument, were followed (the specific methods and codes are cited in parentheses): Copper (Bicinchoninic Acid - CODE 3640); Sulphide (Methylene Blue- CODE 3654-020; Dissolved Oxygen (Winkler colorimetric- CODE 3688); Cadmium (Pan- CODE 4017-01); Nitrate (Zinc Reduction- CODE 3689); Zinc (Zincon- CODE 3667); Iron (Bipyridyl- CODE 3648); Phosphate (Ascorbic Acid Reduction- CODE 3653); and Potassium (tetraphenylboron- CODE 3639) (Geotech Smart3 Colorimenter Manual, 2011). Samples collected were assumed representative of the water quality, not contaminated or altered from improper handling, to ensure strict standards of sampling procedures and guidelines set by EPA.

3.1.2 Statistical Analysis of water quality data

3.1.2.1 Principal Component Analysis (PCA)

PCA detects similarities and differences in water quality, while pinpointing fewer important parameters that explain a high variability in samples. The technique is therefore useful in describing water quality with multiple variables. The generated principal components (PC) are uncorrelated new variables, obtained by multiplying the original correlated variables with the eigenvector loadings. The principal component (PCs) can be expressed as:

$$z_{ij} = a_{i1}x_{1j} + a_{i2}x_{2j} + a_{i3}x_{3j} + \ldots + a_{im}x_{mj} \qquad (1)$$

where;

z is the component score,

a is the component loading,

x is the measured value of variable,

i is the component number,

j is the sample number and *m* is the total number of variables.

As a common practice, PCs with eigenvalues greater than 1 were retained since they explained highest total variability in water quality. Biplots of the resulting scores and loading were also constructed. Biplots are considered a standard tool to present multivariate data, providing a meaningful investigation of the data structure. The arrangement and display of rays (loadings) is based on the overall correlation matrix (Reimann, 2008). Our use of biplots was mainly to enhance a profound understanding of system processes, while visualizing the pattern of spread and concentration of elements in water (Filzmoser, Hron, & Reimann, 2010). Compared to bivariate scatterplots, biplots provide an overall planar view of the multivariate relationships of parameters (Filzmoser, Hron, & Reimann, 2012).

3.1.2.2 Discriminant Analysis (DA)

Although PCA is able to reduce data dimensionality and complexity, and PCA provides parameters of great variability and similarities in waters in a study area, it lacks statistical means of associating observed source variation (pollution) to particular processes or activities (land use) in the sub-watersheds. Discriminant analysis (DA), on the other hand, is commonly used in pattern recognition and interpretation (Gonçalves, Esteves da Silva, & Alpendurada, 2006; Shrestha, et al., 2008). The analytical approach classifies cases into categorical-dependent values, where prior knowledge of membership of objects to a particular group is essential (Shrestha et al., 2008). Multiple quantitative attributes (in this study, water quality parameters) are used to discriminate between two or more occurring groups, providing a statistical classification of samples. In our study, DA was used to classify samples (sites) into 5 classes representing the main land-use groups in the study area. DA was carried out using SPSS, by defining water quality parameters as independent variables, and the land use types were considered dependent variables. Parameters common to a land use type are grouped together and considered pollutants and processes of interest borne by that group (Tong & Chen, 2002). DA also provides a classification accuracy assessment matrix, where 100% accuracy indicates a perfect discrimination of sites based on water quality characteristics.

3.2 Results

3.2.1 Field data description

Figure 3-2 to Figure 3-4 shows variation of the physical-chemical water quality parameters i.e. phosphate, nitrate, potassium, zinc, copper, cadmium, iron, dissolved oxygen, pH, salinity, EC, TDS and water temperature (C^o). Results in Figure 3-2 show a positive direct relationship between the concentrations of EC, TDS and salinity; such that high (low) traces of total dissolved solids (TDS) was accompanied by high (low) electro-conductivity (EC) and salinity. The pattern is repeated for all stations except at Site 3 (Figure 3-2).

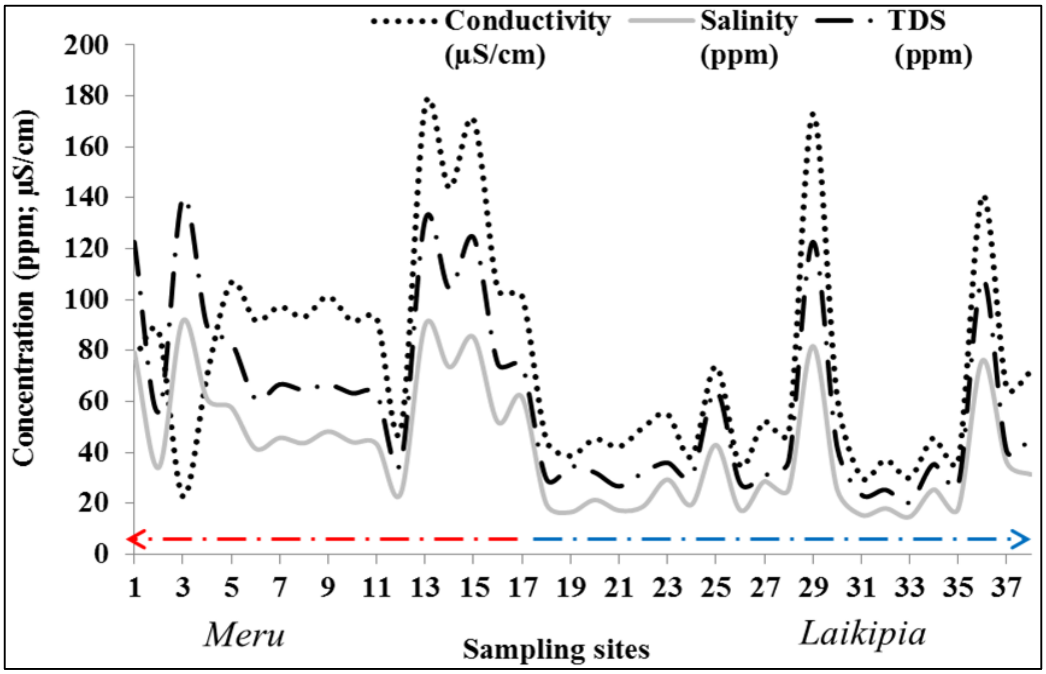

Figure 3-2: Scatterplot showing the spatial variation of electro-conductivity (EC, in µS/cm), salinity and total dissolved substances (TDS) concentration (ppm) across the sites in Meru (red line) and Laikipia (blue line).

The concentration of the three elements is extraordinarily high at Sites 13, 14, 15, 29 and 36 compared to other sites. Site 14 and site 15 are located on Gakuri and Gatauga Rivers, both are tributaries to Gitauga River where site 13 was located. The area surrounding these sites showed ongoing intensive SSHORT farming and very little stream bank cover. Likewise, sites 36 and 29 are located on the same river (Gakeu), with site 29 at the downstream of a large scale horticulture farm. These results (Figure 3-2) identify sites with extremely high electro-conductivity (EC), total dissolved solids (TDS) and salinity.

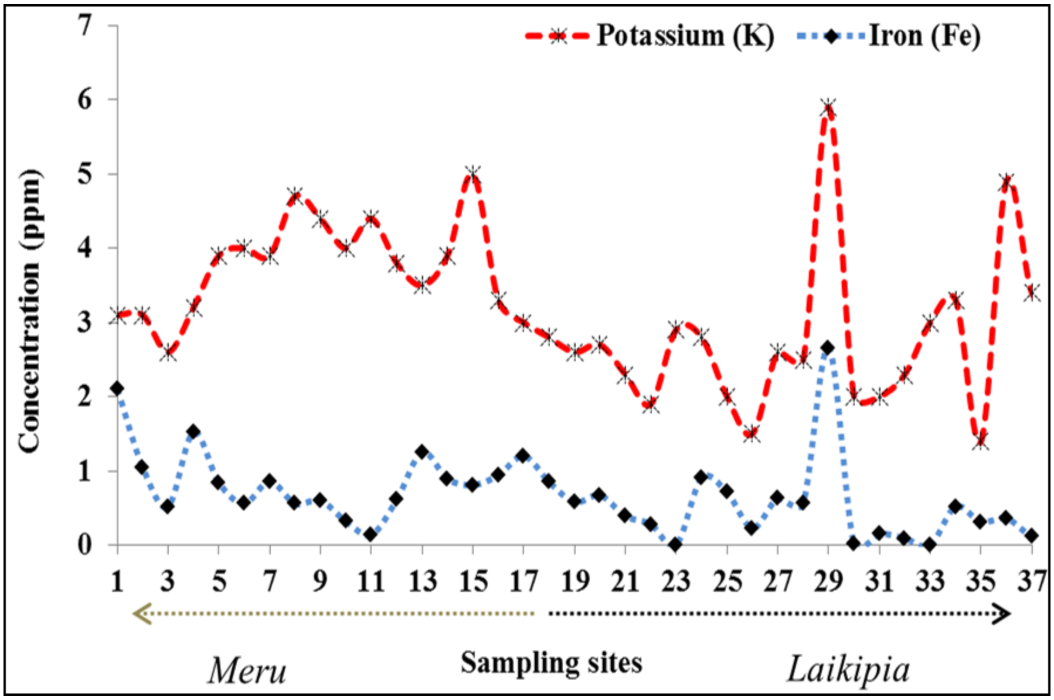

Figure 3-3: Spatial variation of potassium (ppm) and iron (ppm) across all 38 sampling sites in Meru (brown dotted line) and Laikipia (black dotted line).

In Figure 3-3, variability of both potassium and iron is greatest in Laikipia sub-watersheds than in Meru. Results show that while concentrations of potassium and iron in Laikipia sites are in synchrony such that iron increases as potassium increases. Their relationship in Meru sites is opposite (when potassium is high, iron is low and vice versa). Potassium concentration ranged from 1.4 - 5.9 ppm, with a mean of 3.2 ppm. The majority of sites had high potassium concentration (> 3 ppm), which spikes at site 29 and site 36 (both on Gakeu stream). It is interesting to note that sites with potassium peaks in Laikipia coincide with sites identified with high EC, TDS and salinity, suggesting common land use processes and source of pollution. Iron concentration ranged from 0.01

- 2.66 ppm, with a mean concentration of 0.65 ppm. Site 29 had highest iron concentration (2.66 ppm).

We also generated radar charts that describe the other measured elements of water quality. Radar charts primarily display multivariate observations with an arbitrary number of variables (Chambers, et al., 1983). Each individual ray on the chart represents the maximum magnitude of the variable. In our study, two radar charts (Figure 3-4A-B) were drawn in Excel®. The charts provided a meaningful way of examining the relative values of the individual data points at each site, thereby assisting to locate similar or dissimilar sites.

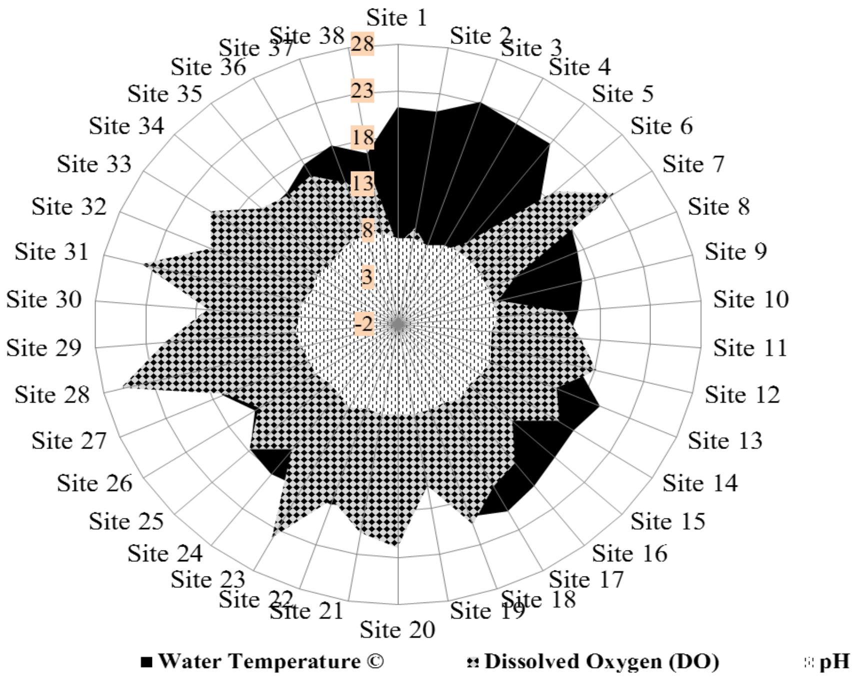

Figure 3- 4A: Radar plot of water pH, water temperature (C^{o}) and dissolved oxygen (DO), with water temperature and dissolved oxygen varying inversely.

In Figure 3- 4A, sites with high water temperature had corresponding low dissolved oxygen as shown on the chart. Samples taken in surface waters in Meru central showed higher water temperatures compared to Laikipia region, except 2 sites (24, 37). The pH across the sites was fairly smooth, with little variability, ranging ranged between 6.9 - 8.18, and with a standard deviation of 0.27.

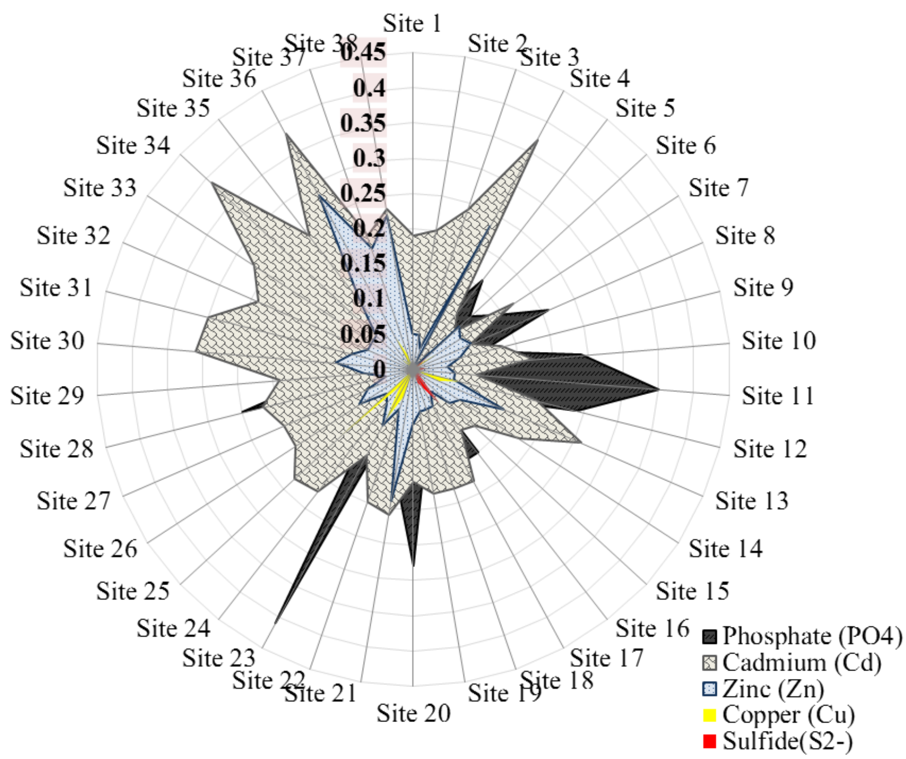

Figure 3- 4B: Radar plot showing concentration (ppm) of phosphate (PO_4), cadmium (Cd), zinc (Zn), copper (Cu), and sulphide (S^{2-}), as measured in water samples.

In Figure 3-4B, cadmium, phosphate, and zinc traces were prevalent across the sites, over copper and sulphide. 17 sites (44.7 %) had copper traces ranging between 0.01 - 0.22 ppm. 10 of these sites were found in Laikipia. 1**7** sites (44.7%) had traces of sulphide, ranging from 0.01 - 0.06 ppm. Sulphide was also found in Meru (10 sites out of 17 sites) and was highest at Mariara Rv. (below bridge), Njoe and Kithinu Rivers.

Phosphate was present in all samples except sites 27 and 30, ranging from 0.01- 0.61ppm. Notable high phosphate concentrations were found at sites 4, 8, 10, 11, 12, 20 and 23 (high spike 0.61 ppm). Surprisingly, all sites (100%) were found to contain traces of cadmium with concentrations ranging from 0.08 - 0.39 ppm. 5 sites, 30, 31, 34, 36, and 4, had cadmium levels > 0.3 ppm, and 20 sites (52%) with levels > 0.2 ppm. The majority of sites with cadmium also showed traces of zinc.

Zinc was present at all sites except site 5, ranging from 0.03 - 0.28 ppm. High zinc concentration was observed at sites 36, 4, 38, 21, 37 and 35 with values exceeding 0.18 ppm. Sites 37 and 38 were located on Sirimon River, immediate to Timau town centre, and heavy large-scale horticulture farming. Sites 21, 35 were near car wash and car repair stations in midwaters of Nanyuki River in Nanyuki town, while site 4 (on Thingithu River) was located at downstream of quarry activity in Meru.

Nitrate (not included in the plot due to scale variation) was found in 14 sites, and ranged between 0.04 -8 ppm. 11 out of 14 of these sites were in streams in Meru.

3.2.2 PCA results of water quality data from rivers sampled in Laikipia and Meru

3.2.2.1 Principal Components (PCs)

The field raw data consisting of all measured 14 variables and for all 38 sites were log transformed to make sure the data follow an approximate normal distribution (Kasangaki, Chapman, & Balirwa, 2008) prior to principal component analysis (PCA). The resulting single matrix consisted of 14 parameter measurements of concentrations (ppm; EC (μS/cm) and pH, water temperature (C^0). The Bartlett's sphericity adequacy test was performed to test data suitability for PCA. We obtained a significant ($p < 0.001$) score of 0.69, which was within the recommended range for PCA. A robust PCA was done in SPSS using varimax rotation. The PCA produced four rotated principal components (PCs) that accounted for 70% variance in water quality samples (Table 3- 2).

From the table, the PC1 had strong positive relations with EC, salinity, TDS, and potassium. The variables showing high scores for PC1 (i.e. > 0.8) were mainly in sampling points in Meru (Figure 3-2 and Figure 3-3).

PC2 has high positive loading with nitrate and water temperature, but negative loading with dissolved oxygen (DO).

Table 3-2. Results of PCA for all 38 sites located on main rivers in Meru and Laikipia regions. Loadings with absolute values < 0.4 were omitted (Hair et al., 1998; Mishra et al., 2002). PC denotes rotated principal components. EC is electrical conductivity; DO is dissolved oxygen; water Temp. is water temperature in C^o.

Variables	**PC1**	**PC2**	**PC3**	**PC4**	**% Explained Variance**
EC	0.89				32.34
Salinity	0.88				17.01
TDS	0.87				11.53
Potassium(K)	0.84				8.68
Sulfide (S^{2-})	-0.52	0.47	0.42		6.32
Cadmium (Cd)	-0.44			-0.43	6.22
Iron (Fe)	0.44				4.91
DO		-0.78			3.59
Nitrate (NO_3^-)		0.75			3.37
Water temp. (C^o)	0.50	0.73			2.75
Zinc (Zn)			0.77		1.56
pH		-0.42	0.60		0.96
Phosphate (PO_4^{3-})			0.58		0.67
Copper (Cu)				-0.81	0.09
Eigen value	**4.53**	**2.38**	**1.61**	**1.22**	
Explained variance	**0.30**	**0.18**	**0.12**	**0.10**	

The negative relationship between water temperature and DO is a natural occurrence due to decreasing oxygen solubility with increasing water temperature and vice versa.

Zinc and water pH had high loadings to PC3, while phosphate and sulfide showed moderate loadings.

Copper had a strong negative loading to PC4, while cadmium showed a moderate negative loading. Both loadings are heavy metal traces of environmental concern.

3.2.2.2 PCA biplots – loadings and scores

The biplots provide a standard tool for investigating and presenting the multivariate data structure, based on the overall correlation matrix (Reimann et al., 2008).

Since water quality data is expressed in part per million (ppm), or milligram/litre (mg/l), it is considered compositional data of multivariate observations (Filzmoser et al., 2012). Such data can be displayed in biplots (Gabriel, 1971) which provide a meaningful way of visualizing the relative information on single compositional parts as well as existing multivariate relationships of parameters (Filzmoser et al., 2010; Otero et al., 2005).

The PC scores and loading biplots (Figure 3-5A to Figure 3-5C), show distinctive groups of rays that spread from the origin to different direction, suggesting existing variation in parameters, and their magnitude in the systems.

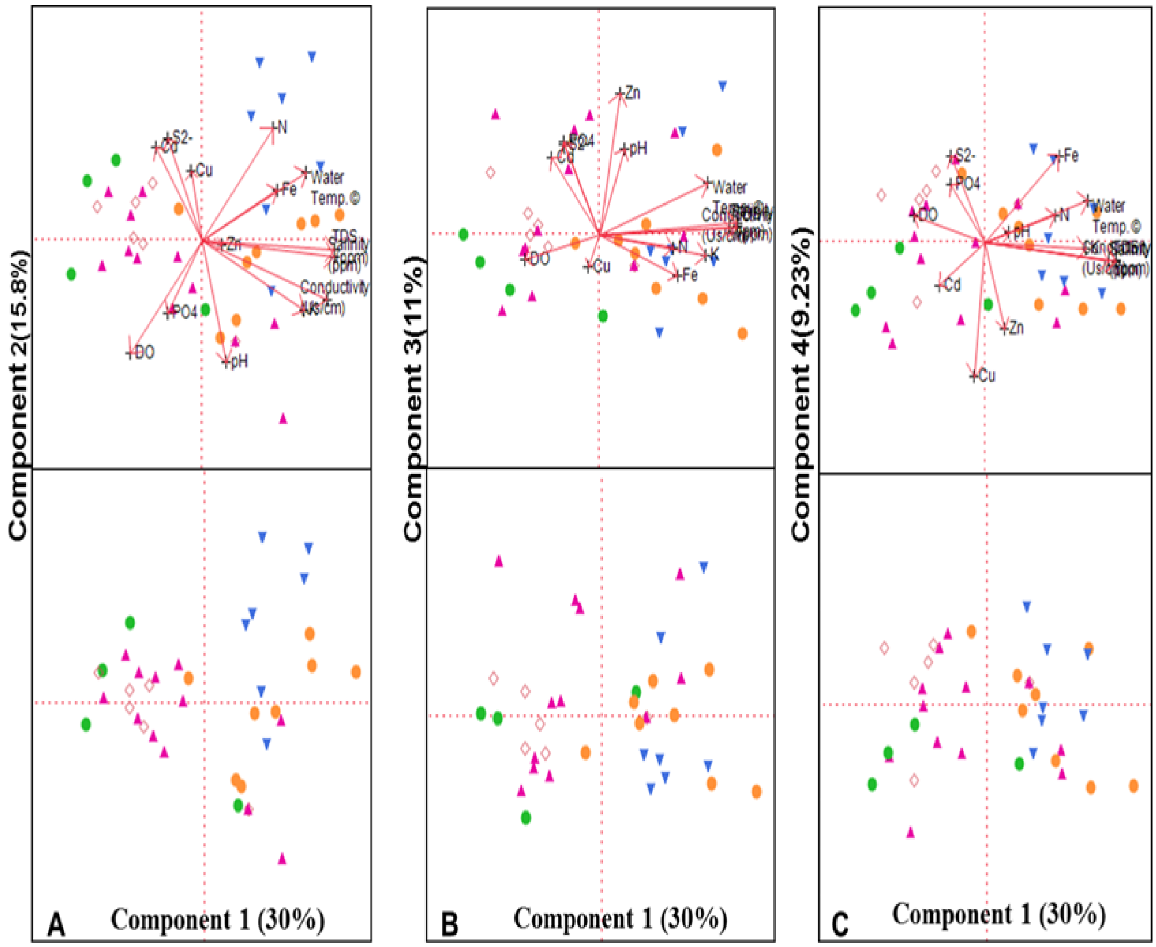

Figure 3-5: Biplots displaying PC loadings and scores. The highly correlating parameters form a small angle between the rays and longer rays show great variance and direction by the specific parameter loading. A) PC1 and PC2 explain highest variability, B) PC1 with PC3 and C) PC1 with PC4.

The rays in upper row biplots (Figure 3-5A-C) represented each of the parameters considered in the PCA. The symbols represent sites, which are color coded to represent the 5 land use types.

The rays on the left quadrants identify dominant parameters in this order: dissolved oxygen (DO) < cadmium (Cd) < sulphide (S^{2-}) < phosphate (PO_4) < copper (Cu); where sulphide and DO show longer rays indicative of high variability in the system. Rays on the right quadrants strongly defined nitrate, water temperature, salinity, conductivity, potassium, TDS, iron, pH and zinc.

3.2.3 Results of Discriminant Analysis (DA)

The main aim of DA was to categorize measured surface water quality parameters into land use types, thereby highlight potential pollutant source-processes. The DA yielded four discriminant functions separating the parameters into five land-use groups. A summary table of discriminant function analysis (DFAs) statistics is given in Table 3-3A for all four functions, including the Wilk's lambda ($p < 0.05$) test that determines the discriminating capability of the land-use groups.

The larger the eigenvalue, the more variance shared by the linear combination of variables. The eigenvalues are sorted in descending order of importance, with Functions 1 and 2 explaining great variation in land use type and related water quality characteristic. Discriminant function 1 significantly accounted for 80.36% of the variability in water quality, while function 2, 3 and 4 accounted for 14.59%, 3.61% and 1.45% of the variability respectively.

The Functions at group centroids showed a clear separation of the land-use categories as indicated by the large differences of their group means (Table 3-3B).

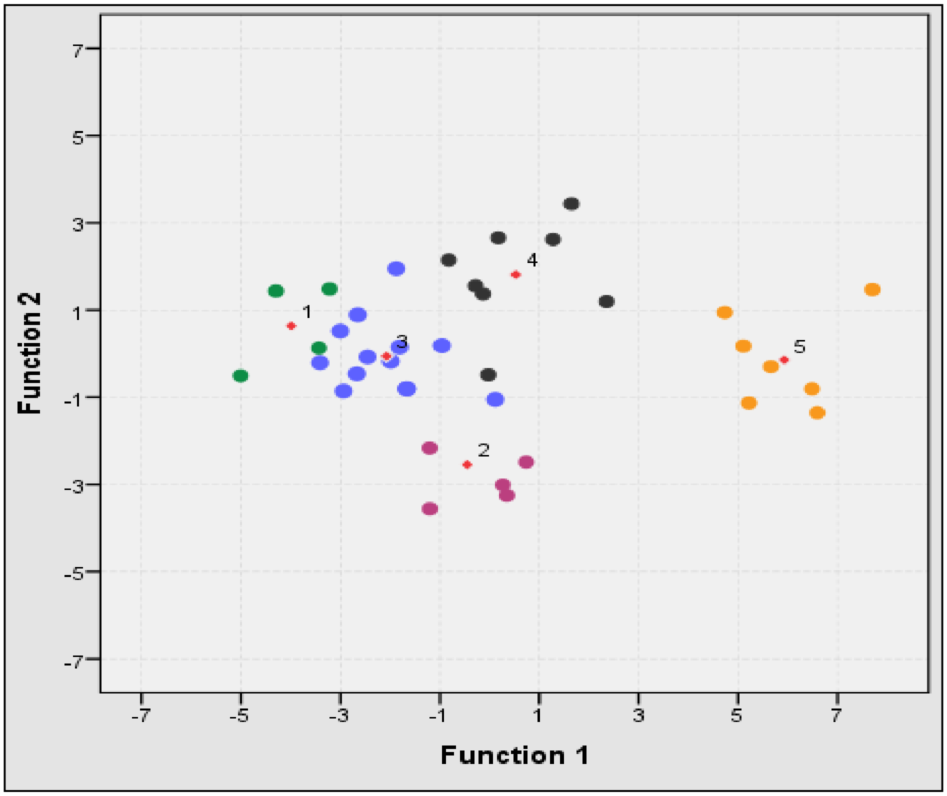

Figure 3-6: Canonical discriminant functions plot showing different color-coded land-use types. Groups 1-5 represent; =Forest; =Urban; =LSHORT; =SSHORT, and =Mixed agriculture land uses respectively.

Table 3-3. A) Summary of Discriminant Function Analysis Results

	Function 1	Function 2	Function 3	Function 4
Eigen value	11.18	2.03	0.50	0.20
% variance	80.36	14.59	3.61	1.45
Canonenical correlation % of variance	0.96	0.82	0.58	0.41
Wilks' Lambda	0.02	0.18	0.55	0.83

Table 3-3. B) Functions at group centroids

Land-use groups	Function			
	1	2	3	4
Forest	-3.99	0.64	-1.70	0.04
Urban	-0.45	-2.55	0.04	-0.53
LSHORT	-2.08	-0.06	0.49	0.40
SSHORT	0.52	1.81	0.34	-0.53
MAG	5.93	-0.14	-0.37	0.29

Table 3-3. C) Classification results and predicted group membership

		Forest	Urban	LSHORT	SSHORT	MAG	Total
Count	Forest	4	0	0	0	0	4
	Urban	0	5	1	0	0	6
	LSHORT	1	1	11	0	0	13
	SSHORT	0	1	0	7	0	8
	MAG	0	0	0	0	7	7
%	Forest	**100.0**	0.0	0.0	0.0	0.0	100.0
	Urban	0.0	**83.3**	16.7	0.0	0.0	100.0
	LSHORT	7.7	7.7	**84.6**	0.0	0.0	100.0
	SSHORT	0.0	12.5	0.0	**87.5**	0.0	100.0
	MAG	0.0	0.0	0.0	0.0	**100.0**	100.0

[a.] 89.5% of original grouped cases correctly classified.

The classification matrix resulted in 89.5% correct assignment of water quality parameters into corresponding land-use categories (Table 3-3). The values in the diagonal of the table show the correct classification of observations into groups. Forest and mixed agriculture (MAG) land-use groups achieved 100% correct assignations. Small scale intensive horticulture (SSHORT), large scale intensive horticulture (LSHORT) and urban land-uses received 87.5%, 84.6% and 83.3% correct assignations respectively. Some LSHORT sites were misclassified into Forest (7.7%), and as urban uses (7.7%), while SSHORT (12.5%) were misclassified as urban.

3.3 Discussion

3.3.1 Occurrence and variability of common elements in surface water

An initial exploratory evaluation of the raw surface water quality data was important in the present study in an effort to understand the prevailing water quality and source processes.

3.3.1.1 Electro-conductivity (EC), total dissolved solids (TDS), and Salinity

Our data suggest that electro-conductivity (EC), total dissolved solids (TDS), and salinity are highly correlated water quality indicators, central to stream health. These indicators commonly identify processes related to human disturbances such as farming, erosion and movement of suspended materials and contaminants into rivers (Kasangaki et al., 2008). In our analysis, the changes in EC, TDS and salinity (Figure 3-2) to high spikes at sites 13, 14, 15, 29, 36 correspond to zones of increased pollutant discharge into river system from adjoining land activities. At Site 13 and 14, snowpeas farming by SSHORT intensive farmers was observed, often occurring on stream edges. Farming practices along river banks reduces riparian vegetation buffers, providing an easy pathway of eroding materials into surface waters, affecting water quality. Similar conclusions were drawn by (Kasangaki et al., 2008), where poor water quality and loss of riparian canopy were negatively correlated to high concentration of EC, TDS, and salinity. Sites 36 and 29 are located upstream and downstream of large-scale horticulture farms. The ongoing large-scale greenhouse and open field horticulture activities likely contributed to observed spikes and variability in element concentration. The sudden decline in EC at site 3 was related to high deposition of fine clay material from upland erosion processes intensified by anthropogenic disturbance. Such disturbance has implications on the stream bank stability, as it limits stream functionality in sieving/preventing debris entry into the surface waters. Addition of oxygen depleting organic debris, nutrients and pesticides, trigger significant negative impacts on aquatic ecosystems. This suggests need for follow up monitoring, and a management strategy to control runoff and soil erosion by adding cover on riparian zones.

3.3.1.2 Potassium and Iron

Natural potassium concentration in rivers range ~ 2 - 3 ppm, resulting from weathering of minerals such as feldspars. Higher concentrations of potassium in our study show stronger links to anthropogenic sources than natural processes. While potassium concentration presents a smoother curve among sites in Meru, its behavior in Laikipia (sites 18-38) varied greatly, producing a rugged curve (Figure 3-3). This behavior highlights specific areas where use of potassium in surrounding landscape was high, causing spikes in concentration relative to the waters in the same region. The heterogeneous spatial pattern distribution of large-scale greenhouse farming (Justus & Yu, 2014) in the sub-watershed may explain the varied potassium peaks in Laikipia where such farming is common. The less noisy potassium concentrations across sites in Meru indicate consistency applications by small scale intensive horticulture (SSHORT) and mixed subsistence agriculture (MAG). Both types of farming are wide spread in Meru. The available land parcels are small yet can be turned into productive units under intensive SSHORT, while other farmers maintain tracks of tea farms.

Our results (Figure 3-3) also suggest the concentration of soluble iron is mainly a function of geological processes. As a matter of fact, kaolinite clays and montmorillonites clays are found in Meru and Laikipia respectively. These two clays behave differently in water (Palomino & Santamarina, 2005). Kaolinite clays could limit solubility of iron, resulting to low measured levels. On the other hand, montmorillonites clay could enhance solubility of iron.

3.3.1.3 Water Temperature, Dissolved Oxygen (DO), and pH

The prevailing temperature differences between the northeast slope (Meru), and the west slope of Mt. Kenya (Laikipia) contributed to the observed variation in water temperature, and consequently the measured DO in the samples. The warmer climatic temperature in Meru, directly influenced the water temperature, causing low DO, while in Laikipia, the prevailing cooler temperatures enhanced DO (Figure 3-4A). Stability of DO in river ecosystems is crucial for survival of aquatic plants and organisms. Moreover, high temperature and TDS in surface waters, lower oxygen solubility. They also concurrently facilitate river eutrophication particularly in presence of nitrates (Razmkhah, 2010). In our study, therefore, the co-occurrence of nitrate (Figure 3-5 to Figure 3-5C), warm waters, and very low DO present a critical resource management scenario that may accelerate water quality degradation. The use of manure and sludge by SSHORT and MAG farmers as substitutes for synthetic fertilizer is associated high nitrate concentration in surface water (Nyakeya, 2009).

3.3.2 Discussion of results from Principal Component Analysis (PCA)

3.3.2.1 Principal Components (PCs)

Up to ~70% variability in surface water quality in the study area was explained by four PCs (PC1, PC2, PC3 and PC4) (Table 3-2). The PCs were largely interpreted as processes related to increased commercial horticulture farming and effluent release to surface waters, encroaching farming onto forest lands, vegetation cover reduction, bank instability and erosion, mismanagement of waste streams from coffee factories, mechanical villages and urban waste. Geological weathering of underlying bedrock material was also identified as an important process affecting waters in both regions, and contributed to low iron concentration in Meru water. This interpretation was partially based upon field observation during sampling and site descriptions.

On a scale of 0 to 1, each of the 14 variables (termed as loadings after PCA) scored differently, contributing to the strength of extracted principal components (PC1 - PC4). A score close to +1 or -1 by a particular loading indicate a strong influence on the specific PC.

PC1 had strong scores from EC, TDS, salinity and potassium loadings. These processes were mainly associated with increased runoff from on-going SSHORT and MAG uses. The observed peaks in concentration, spatially corresponded to areas with intensive commercial horticulture, signaling effluents released into rivers from adjoining landscapes, and hence identifying critical pollution zones.

PC2 had strong positive loading (> 0.73) for nitrate and water temperature, and a negative loading for dissolved oxygen (DO). The high nitrate loading was linked to the soaring use of animal manure by both MAG and SSHORT farmers, unlike LSHORT where use of manure is not feasible. The high negative loading for DO shown by the long rays predominantly in left quadrants (Figure 3-5), was associated with cooler head waters exiting the forests. The mid and lower reaches of the rivers were warmer, presenting important implications for the survival of aquatic ecosystems. Limited stream bank vegetation cover, erosion, cultivation in on river banks, and cattle use of the waters are primary factors that significantly degrades the mid zones and lower waters. Steps towards minimizing such activities can be pursued in an effort to minimize effluent movement.

PC3 had strong to moderate scores from zinc, phosphate, and sulfide loading (Table 3-2). The strong zinc loading on PC3 can be allied to processes such as application of phosphate based fertilizers and agrochemicals, urban effluents from surrounding town center, car wash and repair station on the mid-waters of Nanyuki River in Nanyuki town (sites 21, 35), and quarrying activities. Our biplot loadings (rays) for phosphate and sulphide dominate the left quadrant (Figure 3-5 A to Figure 3-5C), where the primary land uses are LSHORT and forest. The presence of phosphate across sites indicates its augmented use in the region, with notable spikes in concentration (site 23) (Figure 3-4B), at sites neighboring on-going LSHORT farming, and sites adjoining tea farming zones (sites 10, 11 and 12 on the head waters in Meru). Interestingly, sulphide had a moderate loading on the PC1, PC2, and PC3, identifying common processes that generate waste effluents into streams. Such processes include industrial waste generated by coffee and tea processing factories in Meru; municipal effluents from residential areas of Nanyuki, and Likii. Common use of pit latrines and poor sanitation systems was also a plausible cause explaining observed sulfide traces.

PC4 had a negative moderate loading for cadmium and a high negative loading for copper (Table 3-2). Both elements are related to phosphate fertilizers, and identify anthropogenic sources of heavy metals and metalloids in surface waters in the region.

While our study presents a onetime sampling event, the obtained information is critical to set discussions on appropriate steps towards managing water resources in the sub-watersheds. Further investigation to examine seasonal variations and flux of parameters into water systems, and integrity of aquatic organisms may provide more insights into surface systems behavior.

3.3.3 Contributions of different land-uses on stream water quality as revealed by DA

The strength of DA in our study was in its ability to provide a statistical categorization of land use types as sources of pollution. Based on our analysis, the group centroids (Table 3-3B; Figure 3-6) provided a better predictive power to the discriminant function 1, as seen by the large differences between land use types. Up to 89.5% correct separation of land-use types was attained as shown by the classification matrix. The discriminant results (Table 3-3C) strongly illustrate the distinct variability in water quality as driven by land use. Similar conclusions were drawn by (Kanga, 2010) who argue that significant differences in land-use contributed to buildup of *Escherichia coli* and *Enterococci* bacteria, and heavy metals in stream waters.

3.3.3.1 Forest use and Mixed Agriculture (MAG) land use

DA results show that the forest and MAG land use types obtained 100% accuracy in classified water samples. This was supported by a large difference in the forest and MAG group mean (- 3.99 and 5.93 respectively, Table 3-3B) as shown by function 1. The complete separability of these two land use types by function 1 is an indication of the underlying variability in surface water quality.

Forest: The headwaters existing forest use had low temperatures, and high DO, which was not unusual. From our findings, the traces of pollutants in waters exiting forest land cover are mainly due to encroaching farming activities and clearing of trees and shrubs on slopes of Mt. Kenya (Figure 3-1).

Mixed agriculture (MAG): MAG was a significant source of nitrate, water temperature and iron (Figure 3-5). Soaring fertilizer prices in Kenya prompt subsistence farmers to seek affordable alternatives to crop nutrition (Kipkoech et al., 2010). Application of animal based manure is a common practice among MAG farmers, despite its association to stream water degradation.

Primarily, warmer waters in the MAG land use were attributed to naturally occurring warmer agro-ecological climate. Nonetheless, observed farming along river banks, reduced shade could also exacerbate stream temperatures. Traces of iron (Figure 3-5) found in samples in MAG were interpreted as resulting from geological weathering of underlying bedrock. The observed high zinc at one site in Meru (site 4 on Thingithu River) was a result of upstream quarry activity.

3.3.3.2 Large scale horticulture (LSHORT) land use

The LSHORT group mean was - 2.06, and with 84.6% classification accuracy (Table 3-3B-C). A complete separability was not achieved, because 2 sites were misclassified, one site as belonging to forest, and the other to urban uses, due to unclear boundaries between land uses. Besides, large-scale farms are rapidly encroaching on forest edges where access to water, by directly tapping the head waters provides a constant supply of irrigation water. Growth of settlements adjacent to LSHORT farming areas has created urban residential areas, which provide a plausible cause of the misclassification. Linking the DA finding to our earlier analysis, we find dominance of phosphorus, cadmium, copper, and sulphide in samples from the left quadrants (Figure 3-5A to Figure 3-5C) with LSHORT land use, and therefore recognize these elements as important primary pollutants related to LSHORT. This is an important finding because clustering of commercial companies in the region is ongoing, and poses long term impacts on stream ecosystems and their health.

Phosphorus promotes bud formation, and flowering. It is rigorously used by LSHORT as fertilizer formulations to promote crop development and increase yield. Soluble liquid fertilizers are applied on the plants foliage or through pressurized drip lines, placed near plant roots to enhance uptake. Both methods of applications (foliage and soil) are common in horticulture, and of concern due to nutrient leaching and runoff arising during excessive rainfall or frequent irrigation (Silberbush & Lieth, 2004). This provides a realistic explanation to observed traces of phosphorous. Besides, occurrence of cadmium and copper traces in soils under horticulture land-use is highlighted in several literatures (Better Farming; Gaw et al., 2006). Application of copper based herbicides and fungicides in intensive horticulture is also common place (Atkinson, 1956; Gaw et al., 2006). This corroborates our finding, of copper traces in water samples in LSHORT land use. Horticultural effluents are a global concern, necessitating standards of compliance to regulate the greenhouse horticulture industry. For example, Sweden prohibits greenhouse wastewater disposal into drains, watercourses, or groundwater (Alsanius, 2011), and in Netherlands, effort is underway toward zero nutrient emissions by the year 2027. Under the current situation, we suggest the use of constructed wetlands to collect and treat horticultural wastewaters, as a sustainable approach to manage the greenhouse wastewaters. Such wetlands are efficient and relatively inexpensive to construct and operate (Grasselly, 2005) when land is not limiting.

3.3.3.3 Small-scale intensive horticulture (SSHORT)

The DA results show a high accuracy of classification for SSHORT (84.6% in Table 3-3C). However, total separability was not achieved due to unclear land use boundaries, where one site was categorized into urban land use. Our findings identify potassium, EC, TDS and salinity as common indicators of surface waters in SSHORT land use. The domineering use of potassium by SSHORT farmers contributes to the observed less variability in potassium concentration across sites in Meru (Figure 3-3). Although weathering of rocks and minerals, and the type of parent rock may dictate the level of potassium in water system, our results (Figure 3-3) exceed the natural range of potassium in rivers (2 - 3 ppm). It is plausible that increased SSHORT play a key role in driving the observed values.

Moreover, intensive farming along river banks reduces the natural riparian buffer, creating an easy movement of eroded materials into surface waters. Such anthropogenic disturbances introduce suspended materials into river system, thereby augmenting the amount of dissolved materials, EC and salinity of surface waters within SSHORT land use.

3.3.3.4 Urban use

The urban land-use was highly separable with 83.3% classification accuracy (Table 3-3C), identifying patterns in water quality, associated with urban use. The DA finding support our earlier highlight identifying sulphide as a major trace element linked several processes among them urban waste water effluents. Urban residential areas and suburban settlements have increased in Laikipia, following the rise of commercial horticulture (Liniger, 2005; Ulrich, 2014). The sudden sprawl has a toll on water quality due to mismanagement of diverse waste streams loaded with pollutants that are swept into surface waters. The anaerobic decomposition of sulphur-containing organic matter, sewage, algae, industrial wastes from petroleum plants, paper mills, and heavy water plants are recognized as main anthropogenic sources of sulphide in the environment. Zinc traces in water samples were also likely due to waste dumped from mechanical automobile villages, car wash and repair stations in surrounding urban centers.

3.4 Conclusion

The study findings in this chapter resonated with an increasing body of literature highlighting the negative implications of intensive horticultural production on aquatic ecosystems. Pollutants from the farms are transported in runoff or through leaching into surface streams and contribute to declining water quality that can limit stream integrity and usefulness. Sub-watersheds experiencing increased commercial horticulture may be more vulnerable to rapid surface water deterioration. The multivariate statistical methods i.e. PCA and DA that were utilized to evaluate the field data enhanced our current understanding of the impacts of increasing horticulture on surface waters in central Kenya. PCA identified four important principle components that explained 70% of the total variance of 14 parameters examined in the study. Even though PCA provided proposition of existing variability in water quality in the study area, it alone was inadequate in providing a statistical approach of determining responsible source-processes. Discriminant analysis was effective in separating the heterogeneous samples into five land-use groups with high classification accuracy. Based on discriminant function 1, forest use and MAG land-use were perfectly separable, while a few mis-classifications occurred for LSHORT (2), SSHORT (1), and urban (1) land-use. This was mainly due to indistinguishable land-use boundaries.

Our results show that total dissolved solids, electro-conductivity and salinity were common in the waters, but increased in concentration at locations with intensive SSHORT and LSHORT horticulture farming. Traces of cadmium, phosphates and zinc were prevalent in study area, and highly driven by applications of phosphate based fertilizers. However, the applications among LLHORT seem intense or frequent prompting the spikes in concentration at sites proximate to such farming. Nitrate was prevalent in SSHORT and MAG, and linked to the use of farmyard manure. From our results, the relationship between surface water quality and land-uses in the sub-watersheds indicates that proliferating commercial horticulture and related activities e.g., rapid population pressure in a watershed, sprawl of urban areas, and encroachment into forests, has growing effect towards increasing nutrients loads and other pollutants of environmental concern to surface water.

We recognize that stream waters vary seasonally and diurnally and that several sampling events may provide more representative conditions of the water and land activity. Or else, biological assessment of the abundance and diversity of benthic macro-organisms study component may have been included to obtain a more accurate picture. The study recognizes that a laboratory of the examination of the water samples may have provided a validation to the on field kit results. However, due to a financial strain, time and geographical location of the study region (international laws and regulations and sample movement), one-time assessment of the physico–chemical characteristics of the rivers was done.

None the less, the results reveal interesting patterns that are very significant in watershed management. In a region where no previous works have examined the rivers considered in the study, and in relation to land use processes, our study provides baseline reference data for future investigations and follow up.

Identifying types and sources of pollutants, and how they impact the surface water systems, will help generate discussions on best management approaches towards sustainable horticulture farming in the region. Currently, the role of stakeholder participation in watershed management in Kenya need to be strengthened, such that the communities sharing of same natural resource base have an equal voice towards figuring what is best for all of them. This effort has been initiated in Laikipia. An integrated water-quality management and land-use planning in sub-watersheds experiencing rapid conversion of cover to intensive farming practices can help reduce stream degradation. This can also help reduce pollution of waters, while promoting biological integrity of aquatic ecosystems, and protection of human health protection. Further follow up investigations are necessary, that examine the biological integrity of the river systems, which can provide a longer term indication of the surface water quality status.

In the next chapter, 25 years of long term remote sensing data from the Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index from are utilized in evaluating the vegetation health of sub-watersheds to allow identification of pockets of vegetation decline, a plausible sign of environmental stress. Vegetation plays important role towards overall health of ecosystems including: water systems (quantity, quality, water temperature, buffer systems to eroded material, and aquatic diversity), hydrologic cycle, and sequestration of atmospheric carbon dioxide.

3.5 References

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CHAPTER 4

Vegetation response to intensive commercial horticulture and environmental changes within watersheds in Central highlands, Kenya, using AVHRR NDVI data

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Abstract

Climate conditions for world horticultural regions are projected to change, making horticulture farming extremely difficult and costly to the environment. In chapter 2 of this dissertation, we show that the spatial distribution of greenhouse commercial is highly skewed within sub-watersheds, which may impede sustainable natural resource utilization and management. Further, in chapter 3, we highlight sites with impaired surface water quality in streams draining regions of intensive farming. From both chapters, it is conceivable that sub-watersheds with increased farming may be more vulnerable to changes in climate. Even so, a broader research that examines the rapidly changing agro-ecosystems is essential to be able to develop viable management strategies. Vegetation health is examined in this chapter, as integral research component that can provide useful information towards understanding the linkage between vegetation responses and the varying disturbances in sub watersheds. This chapter sought to understand the scope of impact on vegetation by evaluating: i) inter-annual variability in averaged Normalized Difference Vegetation Index (NDVI), ii) trends in average annual NDVI before and after 1990 -the presumed onset of rapid horticulture and iii) relationship between the average annual NDVI and large-scale commercial farms, population density, and mean annual rainfall in sub-watersheds. Overall, results showed considerable variations in vegetation condition due largely to mixed factors including intensive farming, drought, and rainfall variation. Statistical analysis showed significant differences in slopes before-1990 and after-1990 ($p < 0.05$; $p < 0.1$ respectively). Negative (decline) trends were common after-1990, linked to increased commercial horticulture and related anthropogenic disturbances on land cover.

Keywords: Vegetation, NDVI, intensive horticulture, population density, trend

4. Introduction

The worldwide growing demand for food, water, fiber, and biofuels has fueled a need for increased agriculture production, improved food security and overall socio-economic development in many sub-Saharan countries (Sayer & Cassman, 2013; Turner II, Lambin, & Reenberg, 2007). Extensive schools of literature identify agricultural expansion and intensification as possible ways to meet the increased food demand, enhancing food security and economic development (Dile et al., 2013; Tilman et al., 2011). Several sub-Saharan economies have successfully engaged in high value intensive horticulture farming to meet a growing international demand for fresh produce, often achieving improved per capita growth in agricultural sectors. These include Zambia, Kenya, Ethiopia, and South Africa. As appealing as it sounds, there are also disadvantages to these approaches primarily because agriculture has major global environmental impacts including contribution to green gas emissions, increased land clearing, and habitat fragmentation that continue to threaten biodiversity (Dirzo & Raven, 2003; Kiteme & Wiesmann, 2008; Owiti & Oswe, 2007; Tilman et al., 2011; Ulrich et al., 2012). Moreover, climate conditions for world horticultural regions are projected to change, making such farming challenging and costly to the environment (Webb, Darbyshire, & Goodwin, 2014).

Kenya is the third largest flower exporter in the world, next to Netherlands, Colombia (Rikken, 2011). Numerous large-scale commercial horticulture farms are found clustered in particular sub-watersheds, where capital resources of production and favorable topo-edaphic factors are available (Aeschbacher, Liniger, & Weingartner, 2005; Justus & Yu, 2014; Ngigi, 2002; Owiti & Oswe, 2007). The horticulture sector has been successful in generating jobs and improving per capita incomes. However, research on the long-term impacts of the intensive production activities on watershed resources and contribution to resource degradation is limited.

Quantitative studies illustrate that the environmental impacts of meeting the increasing demand for agricultural commodities will be determined by how the global agriculture expands (Sayer et al., 2013). Continued trends of intensification in richer nations and expansion (through land clearing) in developing nations may have reversed effects on the effort to reduce the global greenhouse emissions (Tilman et al., 2011).

At the regional and local scales, the importance of sustainable management of watersheds resources emerges as a critical issue due to projected impacts of climate variability. Watersheds perform important ecosystem functions that benefit multiple flora and fauna. Consequently, their ability to cope with increasing global and local environmental changes, and still be able to sustainably support intensive agricultural activities is a matter of concern. The heterogeneous spread of agriculture due to population pressure positions some watersheds at higher risks towards more rapid degradation than others, limiting their effective function and ability to provide environmental services. The role of humans in propagating environmental degradation particularly in the Sub-Saharan region has been a subject of discussion for decades. In the early 1970s, MacLeod (1974) and Eckholm (1975) hypothesized that increased atmospheric dust over the region, resulted from over-cultivation, overgrazing and burning of rangelands reduced local rainfall and encouraged shift in climate. The discussion now focuses more on land degradation, driven by increased soil erosion from mismanaged agricultural practices, and population pressure on productive agriculture zones. Other studies view the decline in vegetation in the region as a drought induced phenomenon (Nicholson, Davenport, & Malo, 1990; Olsson, Eklundh, & Ardö, 2005) where the role of human is negligible if any. In both cases, removal of dense forests has more pronounced effects on local climate than removing sparse vegetation, more so because dense forests have a lower albedo, higher canopy cover, leaf area index and higher maximum transpiration than many grassland/savanna mosaic ecosystems (Bonan, 2002).

Remote sensing approaches are common to monitor terrestrial vegetation condition and its responses to the climate through time. Advances in remote sensing (dating back to the early 1970s) have enabled synoptic monitoring of vegetation dynamics at global, regional and fine local scales. The sun’s electromagnetic energy arriving on plant surface is absorbed/transmitted or reflected. Plants utilize the energy from the visible bands in photosynthesis; however, radiation emanating from the near infrared band is mainly reflected by the internal cell arrangement of the leaves. Using remote sensing techniques focusing on these two types of energy have provided a breakthrough in terrestrial research on vegetation dynamics and health including drought, stress indication, carbon output, climate modeling, and disease response (Pettorelli et al., 2005).

Attempts to assess land degradation patterns in sub-Saharan Africa using remote sensing data provide important insight towards understanding the scope of the problem. Regional and local scale studies on vegetation condition can highlight the capability of watersheds to provide ecosystem goods and services, e.g. food, timber, clean water, wildlife habitats. Such studies also facilitate identification of hotspots vulnerable to environmental degradation, climate change, and inherent food insecurity. This is essential to effective watershed resource management. To date, vegetation indices such as Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI) and Soil Adjusted Vegetation Index (SAVI) have been developed to aid determination of vegetation phenological activity. NDVI is one of the most extensively used indices, and highly correlates with such parameters as green leaf biomass, vegetation greenness (Myneni et al., 1997), the density of chlorophyll contained in plants (Sellers, 1985) and leaf area index (LAI), all are parameters that gauge vegetation activity and health (Wang et al., 2010). NDVI is presented as the ratio of the difference between near-infrared reflectance and red visible reflectance to their sum. Continuous NDVI data is available for an extended period for the study area (Mishra & Chaudhuri, 2015; Pettorelli et al., 2011), hence NDVI is chosen as our primary index for vegetation healthfulness and environmental condition. Other index data may not be available for the same period due to unavailability of specific wavelength bands in older instruments (for example, the AVHRR sensor lacks the blue band). A few challenges and limitations of the NDVI, are noted:, e.g. in presence of scattered vegetation canopy, great amount of background spectral response can be picked by the radiometers, leading to spurious ratio; also, the index is highly affected by aerosols and particulate matter in the atmosphere, requiring rigorous data cleaning before use; other authors have pointed instances of NDVI saturating way before maximum leaf or plant biomass is obtained, providing nonlinear relationship (Hobbs, 1997; Thenkabail, Smith, & De Pauw, 2000). However, these challenges remain relatively negligible in the study, compared to the versatility of the index (Santin-Janin et al., 2009).

Wessels et al. (2007) investigated potential of distinguishing human-induced land degradation from the effects of rainfall variability in a case study in South Africa using AVHRR NDVI and modeled net primary productivity data in 1985-2003. Their findings indicate that both positive and negative NDVI trends may result from natural ecological processes, such as the carry-over effects of rainfall in previous years, and therefore accurate determination of likely causes of negative trends need to be determined by local investigations.

In Kenya, (Waswa et al., 2012) used Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index (MODIS/NDVI) 500m product together with climate data for the period from 2000–2009. From their results, degrading areas span across different agro-ecological zones suggesting existence of diverse regional drivers of degradation. Previously, Bai and Dent (2006) had shown that a combination of NDVI derived biomass indicators and rain use efficiency trends provided more robust indicators of degradation processes highlighting hot spots locations. In both examples, the authors emphasize that even though the assessments provide visual extents of environmental degradation, NDVI does not identify the actual causes of degradation, necessitating field observations to ascertain causes of observed trends.

This study evaluates the long-term vegetation dynamics to determine vegetation responses to local environmental changes, focusing on agriculturally productive sub-watershed geographical units' in central highlands of Kenya in which intensive horticulture production originates. This is necessary to evaluate the impacts of increased horticulture and population buildup on watershed vegetation condition, and towards sustainable watershed resource management. In particular, we evaluate; i) between-year NDVI variability trends for select 33 sub-watershed over 25 years; ii) between sub-watershed variability, analyzing before 1990s (1982-1989) and after 1990s (1990-2006) NDVI trends to detect changes in slope (negative or positive) and significance in observed trend line coefficients (before and after) to understand how vegetation communities are responding to increasing intensive farming and changing environmental landscape; and iii) determine the relationship between average annual NDVI and large-scale commercial farms, population density, and the mean annual rainfall for respective sub watersheds. 1990 is used as the base year when major shifts to intensive farming and diversification from traditional cash crop farming occurred. Negative NDVI trends are recognized as indicators of declining plant vegetation condition (Yapp et al. 2010).

Following this introduction section, we will discuss the study area and methodology in detail. Results from data analysis will be presented in the third section. The fourth section presents a discussion of these results, and we conclude with a summary and proposals for future research.

4.1 Data and methods

4.1.1 Study area- 33 sub-watersheds in central highlands with ongoing commercial horticulture

Our analyses were conducted at two nested geographical scales: the larger central highlands region, primarily focusing on ongoing large-scale greenhouse commercial horticulture farms established in chapter two of this work. 33 sub-watersheds were selected, 23 of which had active commercial horticulture from 2000-2006, and 10 adjoining sub-watersheds. 10 adjoining sub-watershed were included in the assumption that even though they had no greenhouses, they bordered hotspot production areas providing settlement, towns, and other necessities for the commuting working groups and therefore may have undergone significant environmental changes as the ones with greenhouses within.

As described in chapter 2, the study area exhibits high variability in annual rainfall, which constrains the types of vegetation. There are 5 primary catchments in the study area, i.e. Lake Victoria (1); Rift valley and inland lakes (2); Athi River and coast (3); Tana River (4) and Ewaso Ng’iro (5) Figure 4-1.

The climate patterns are highly driven by the Inter-Tropical Convergence Zone (ITCZ), effects of El Niño Southern Oscillation (ENSO) and sea surface temperature (Funk et al., 2003; Myneni, Los, & Tucker, 1996; Shisanya, Recha, & Anyamba, 2011). The sub-watershed data layer, population statistics and rainfall data used in this chapter, were the same as highlighted and described in chapter 2.

4.1.2 Satellite data

Long-term time series data are essential in detection of vegetation trends (Beck et al., 2011). We used the biweekly maximum value composited Global Inventory Modeling and Mapping Studies (GIMMS) NDVI data with an 8-km spatial resolution from 1982 to 2006 (Tucker et al., 2005) and was recently extended to 2010. The NDVI is unit-less, with values ranging from –1 to +1. Earlier versions of the NDVI dataset have been widely used in detecting vegetation growth change (Ciais et al., 2005; McDowell et al., 2008; Samanta et al., 2010).

Healthy green vegetation generally has the highest positive values while surfaces without vegetation, such as bare soil, water, snow, ice or clouds typically have low NDVI values near zero or somewhat negative. The long-term standardized data are derived from NOAA AVHRR imagery using the NOAA satellite series 7, 9, 11, 12, and 16. This version of the GIMMS NDVI dataset is corrected through a series of processing steps to alleviate known limitations of the AVHRR measurements induced by inter-sensor calibration differences, orbital drift, cloud cover, solar zenith and viewing angles differences, volcanic eruptions, and other atmospheric contaminations (Slayback et al., 2003).

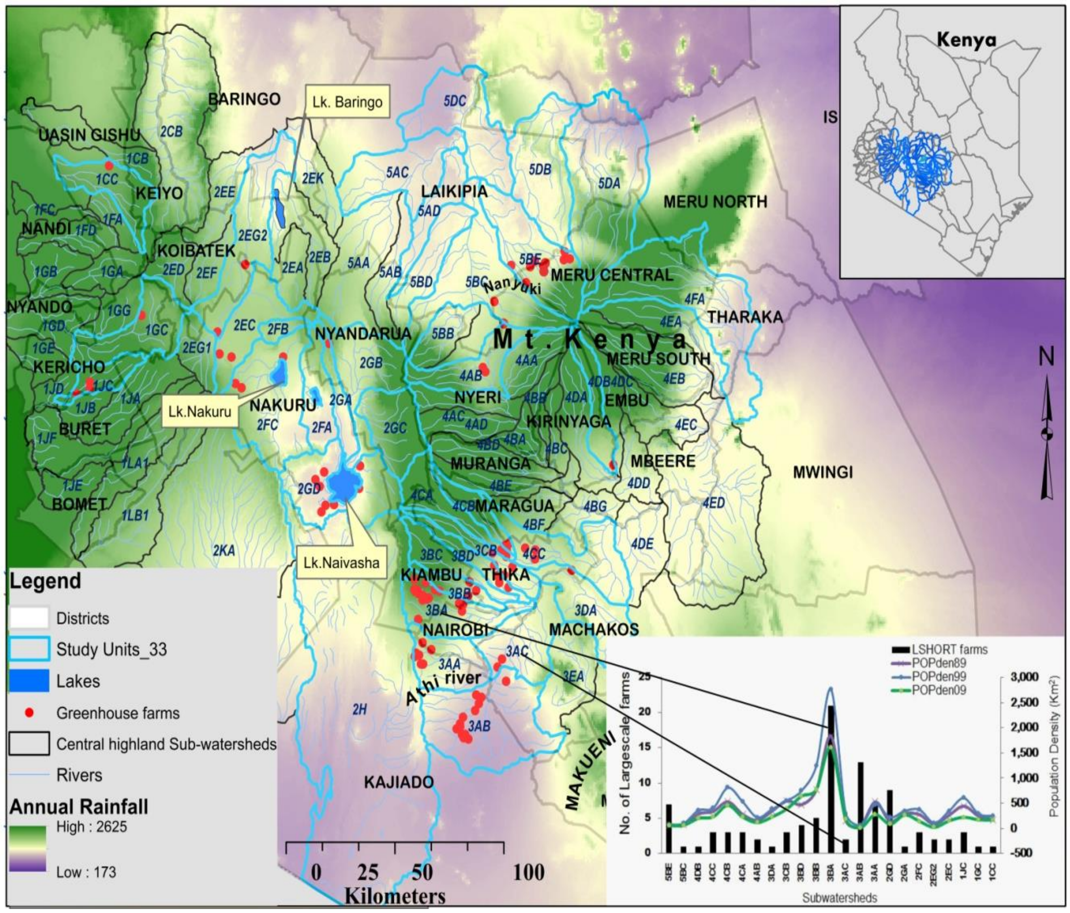


Figure 4-1: Map of the study area in central highlands of Kenya. Sub-watersheds are overlaid with the mean annual mean rainfall (mm/year). Inset (lower right) show the population density trends in selected sub-watershed for 1989, 1999 and 2009 census alongside the number of large-scale horticulture greenhouses - shown as red dots on the map.

Beck et al. (2011) show that the GIMMS data is the most accurate AVHRR-NDVI dataset for assessing vegetation variability and trends. The excellent spatial coverage and relatively long-term observations by this NDVI dataset enable reasonably reliable trend analyses.

4.1.3 Data preparation and analysis

A total of 33 sub-watersheds with known large-scale commercial greenhouses (23) (chapter 2) and the adjoining neighbors (10) in central highlands were considered in the current study. This was necessary to be able to determine relationship between intensive commercial farming (number of farms), increased human activities (population growth) in sub-watersheds, with vegetation index (NDVI). Since the maximum value composite (MVC) NDVI (a maximum daily NDVI value during the 15-day period) minimizes atmospheric contamination and cloud effects, we used the larger 15-day MVC NDVI for a month to produce monthly NDVI datasets. To reduce the impact of bare and sparsely vegetated pixels on the NDVI trend, all pixels in sub-watershed were used in zonal statistics (in ArcGIS®) to derive a single maximum NDVI for the first 15 days of the entire sub basin. The average inter-annual NDVI for years between 1982 and 2006 were derived for all sub watersheds mapped with greenhouses between 2000-2006 (Justus & Yu, 2014). This was necessary to be able to relate it with the number of commercial greenhouse farms in the sub-watersheds.

To assess the before and after 1990 variability in vegetation condition, the data was separated to two time periods; a) before-1990 (years 1982-1989), and 2) after-1990 (years 1990-2006). Time in years was used as an independent variable, and the average annual NDVI as a dependent variable with the intention to quantify NDVI trends using linear regression. The slopes and explained R^2 (coefficient of determination) were noted for the individual sub-watersheds in both time periods and the significance of the differences in slope of the average annual NDVI trends between the time periods tested.

To determine relationship of intensive farming and vegetation condition in sub-watersheds, we fit a linear regression model on the large scale farms data in sub-watershed against averaged NDVI (2000-2006), with the time period coinciding with the base year used in mapping commercial greenhouses.

4.2 Results

4.2.1 Inter-annual NDVI trends and variation across sub-watersheds

Our observations of inter-annual (year to year) variations in averaged NDVI across the sub-watersheds are grouped into five categories as shown in Figure 4-2A to Figure 4-2E (1s, 2s, 3s, 4s, 5s), representing the five main watersheds in Kenya. This was done to achieve meaningful interpretation and comparison of results. Generally, the findings show a reasonable range of NDVI values (0.24 – 0.7) for the type of ecosystems and vegetation characteristics in the study region, indicating ability of GIMMS data to map phenological activities as widely acknowledged. High NDVI values are interpreted to range between 0.6 - 0.9, and correspond to dense vegetation such as that found in temperate and tropical forests or crops at their peak growth stage. Moderate values between 0.2 - 0.5 represent sparse vegetation such as shrubs, grasslands or senescing crops, while low values of 0.1 and less correspond to bare rocks, sands or fallow areas. Vegetation response to key droughts of 1984 and 2000 was observed across the study area, and was characterized by very low integrated mean NDVI peaks indicating far reaching effects of the droughts.

From Figure 4-2A, the range of integrated mean NDVI for the 5s was between 0.35-0.46, indicating moderate vegetation condition and high variability between years. Comparing NDVI values between sub-watersheds in 5s (left panel), we find that 5BC (with values close to 0.46), was on the higher edge, while 5DC had low values close to 0.32. All the other sub-watersheds in the group had values in between. Geographically, this group of sub-watersheds are located to the east of the central highlands i.e. Laikipia-Nanyuki, Timau (see study area map-Figure 4-1), where vegetation is primarily of savanna grasslands interspaced with low shrubs.

In Figure 4-2B the range of integrated mean NDVI for the 4s was between 0.38 - 0.55, and with less variability compared to 5s (Figure 4-2A). We also observed a delayed vegetation response to the 2000 drought, reflected in 2001 unlike the other groups (5s, 3s, 2s), where sharp low NDVI peaks occur in 2000. Within this group (4s- left panel), sub-watershed 4CA had moderately higher NDVI values often above 0.5; while 4CC had low values often below 0.45. As shown in Figure 4-1, these sub-watersheds (4s) are partly covered by Mt. Kenya towards Meru central, Nyeri and Embu.

In the 3s (Figure 4-2C), the range of integrated mean NDVI was 0.34-0.45, and highly variable between years unlike the other two groups (5s and 4s). The higher NDVI values in 3s were shared interchangeably by 3BD and 3CB (0.48 and 0.56 respectively), and therefore, no dominance of a specific sub-watershed among these group. The integrated mean NDVI plot (Figure 4-2C) illustrate declining trend of NDVI values across sub-watersheds, especially after 1995. Geographically, these sub-watersheds are located in Athi River catchment, which typically has vast grassland ecosystems, but has lately experienced increased urban sprawl (harbors the city of Nairobi and its suburbs) and expanding intensive horticulture farming.

In the 2s (Figure 4-2D), the range of integrated mean annual NDVI was between 0.4 - 0.5. Moderately high NDVI values (often above 0.55) occurred in 2GC, while 2H had characteristically low all time values (slightly above 0.32). It is important to note that sub-watersheds in this group are within Lake Naivasha basin and border Aberdare ranges. This watershed has undergone extensive commercial horticulture and increased land conversion to urban uses and small-scale irrigated horticulture in recent years.

In the 1s (Figure 4-2E), the integrated mean NDVI was generally high, ranging between 0.63 - 0.65, and with very low variability between years. There was little visible effect of 1984 and 2000 droughts on vegetation compared to other groups. The sub-watersheds in this group are found in the Kakamega tropical forest and the high elevation areas of Kericho, where commercial horticulture has yet to exploit.

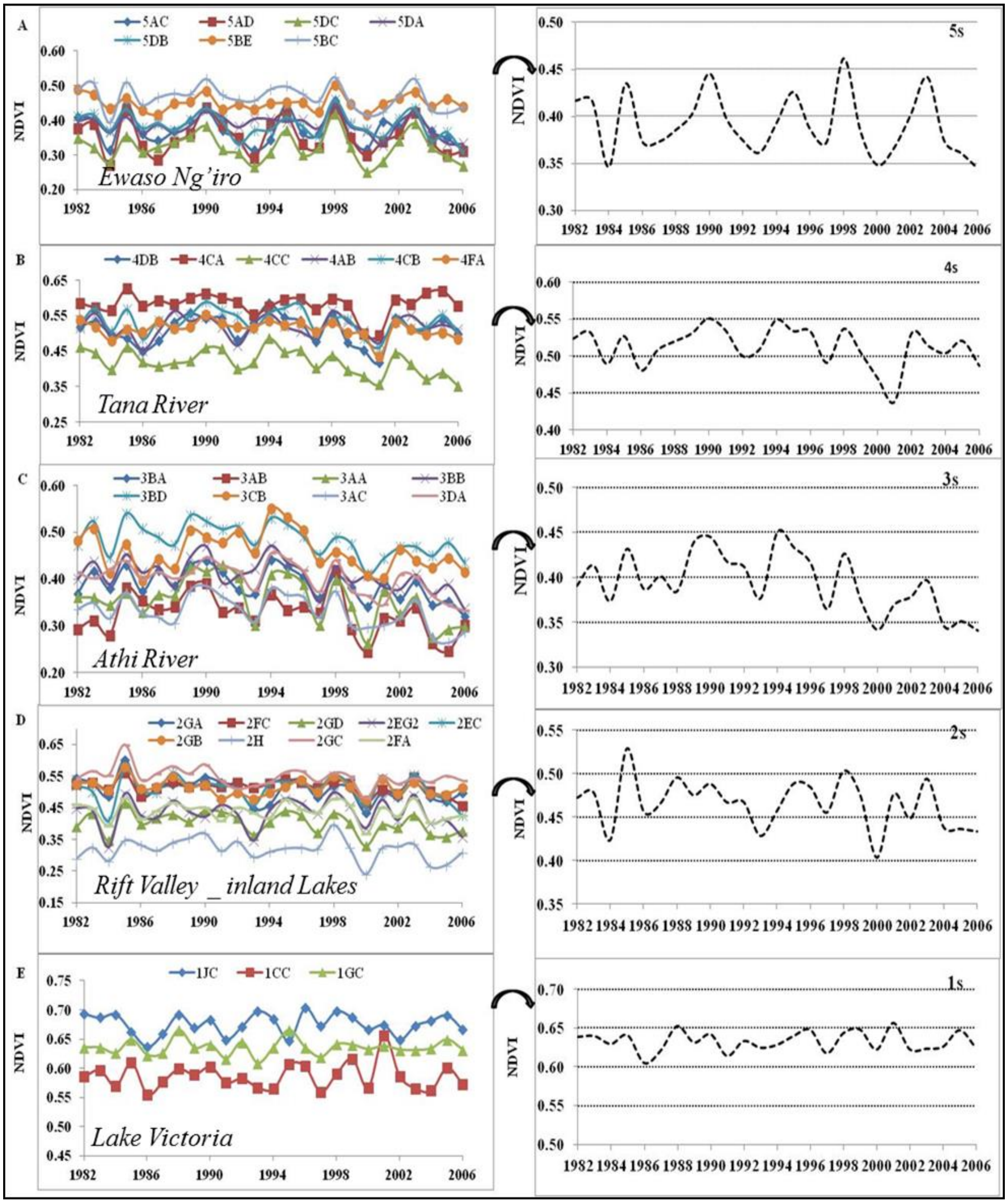


Figure 4-2A-E: Spatial variation in inter-annual average NDVI within sub-watersheds (A-E left panel) and the integrated mean annual NDVI (A-E right panel top to bottom) between 1982 and 2006. Sub-watersheds are categorized into five groups (5s, 4s, 3s, 2s, and 1s), representing the 5 main watersheds in Kenya.

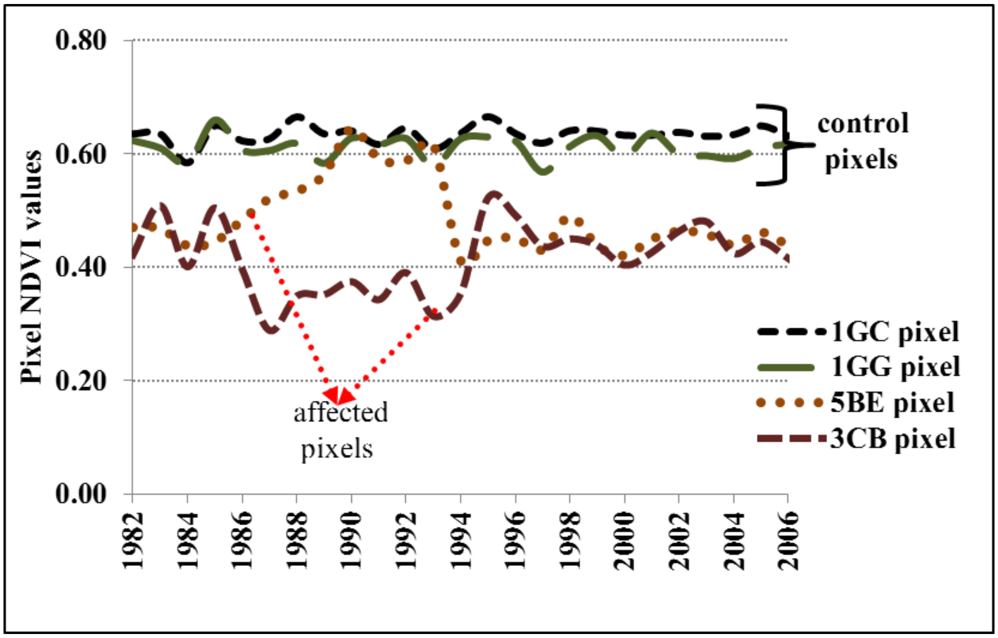


Figure 4-3: Affected and non-affected (control) pixels.

4.2.2 Shifts in the NDVI trends (slope) and strength (before and after 1990s)

We report results of observed spatial variability in average annual NDVI trends before and after 1990s in the selected sub-watersheds. The trend plots (Figure 4-2A-E) illustrate time (in years) as an independent variable, and the average annual NDVI as a dependent variable. In Figure 4-4A-B, the slopes of least squares regression lines (sign) before and after 1990 show that before 1990s, slightly more than half of the sub-watersheds (51%) had significant ($p<0.05$) positive trends (as indicated by the positive slope), while 42% had negative trends. Notable sub-watersheds with strong positive trends before-1990s are 3AB (50%), 2H (46%), 3AA (26%), 3BA (15%), while strong negative trends in the same period were observed in 4CC (27%), 5AD (12%), 5BE (32% Laikipia), and 5DA (17%).

Interestingly, after-1990, almost all sub-watersheds had reversed from positive significant trends ($p < 0.05$) to negative marginally significant trends ($p< 0.1$) (Figure 4-

4A). This provides explanation to the observed variation in r sq. values (Figure 4-4B). Strong decline in NDVI (high r sq. value) occurred in sub-watersheds within Athi river catchment i.e. Kiambu, Nairobi, Athi River town area (3s) in Figure 4-3A, and also within the Ewaso Nyiro basin catchment (5s) i.e. Nanyuki, Timau, Laikipia.

Results also show that after-1990s, some previously strong negative trends attained reduced slope (less steep) with lower coefficient of determination (r. sq.) indicating improving/recovering vegetation condition or perhaps increased greeness resulting from irrigated croplands. For example, sub-watershed 5BE showed improvement from 32% to almost stable 0%, 5AD from 12% to 6 %, 5DB (from 13% to 8%).

In additions, there was a continued decline in some sub-watersheds in both time periods (Figure 4-4B), as shown by the increasing r. square percentage values. Some examples are, 4CC (27% to 46%), 4CB (1% to 30%), 4FA(0% to 34%), 5DA (17% to 37 % double rate), 2GD(4% to 28%) and 2FC(3 % to 28%) see Figure 4-4B (red dotted lines). For subwatershed that showed complete reversal of trend from positive to negative trends, perhaps expansion of farming/disturbances into new lands, and/or conversion of marginal lands and forested areas into other land-uses may explain the observed reversed trends.

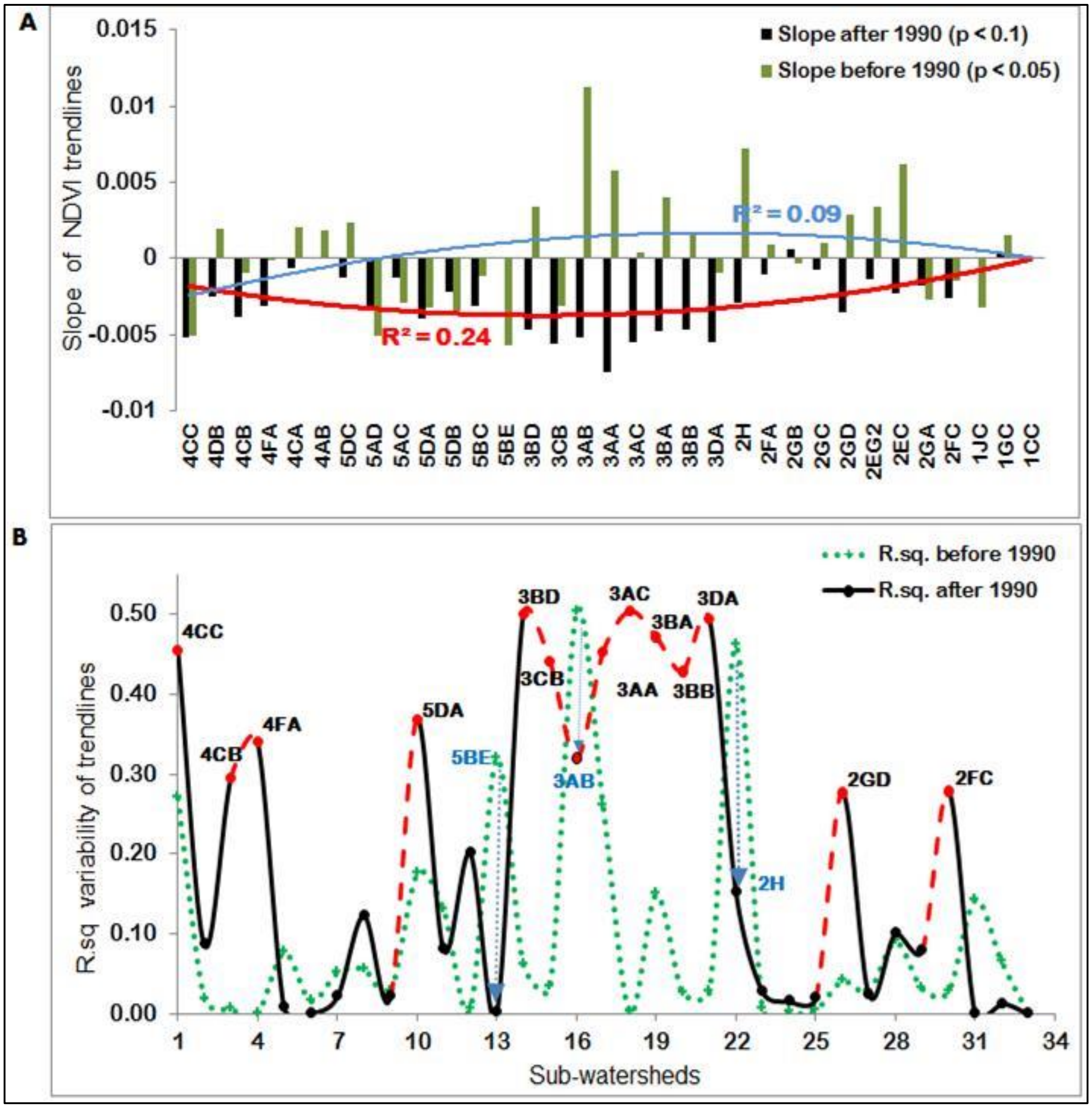


Figure 4-4: (**A)** Changes in slope of regression lines (-/+ sign) and (**B)** coefficient of determination (r square) of averaged annual NDVI for sub-watersheds. Green bars indicating trends between 1982-1989, and black bars representing trends between 1990-2006. Only selected r square values are labelled.

4.2.3 Relationship between intensive horticulture, NDVI, rainfall and population density in sub-watersheds

The relationship between number of large-scale commercial horticulture greenhouses per sub-watershed with the averaged annual NDVI (2000-2006)(Fig 4-5A) reveal a linear negative relationship (r.sq.= 0.28; p< 0.01) Table 4-1. Results indicate that as the number of farms increases per sub-watersheds (along the X axis), the average annual NDVI declined sharply up to about 0.31. High clustering of farms was observed at NDVI values between 0.. - 0.5 (Figure 4-5A). Such low values are indicative moderate to low vegetation covers, mainly grassland patches. However, for 3AC (Figure 4-5B-C), despite having a few greenhouses, there was a decline in NDVI. This is perhaps linked to the sprawl of cities and land use changes within Machakos County.

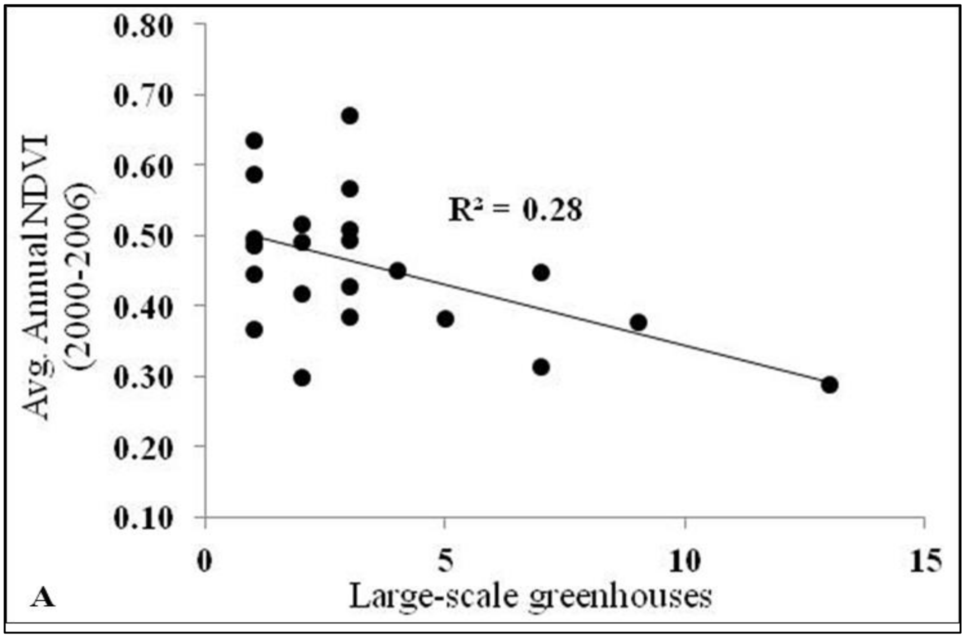
Table 4-1. Relationship between number of large scale farms per sub-watersheds with avg. NDVI 2000-2006.

Multiple R	**R. Sq.**	**Adj. R Sq.**	**Std. Error**	**No. of Sub-watersheds**
0.53	0.28	0.24	0.09	21

ANOVA	***Df***	***SS***	***MS***	***F***	***Sign. F***	***Coefficients***	**Std. Error**	***t. Stat.***	***P-value***
Regression	1	0.06	0.06	7.35	0.01	0.519	0.03	17	0
Residual	19	0.16	0.01			-0.018	0.007	-3	0.014
Total	20								

In Figure 4-5B, the general mean annual rainfall pattern closely follow patterns of average interannual NDVI. This was not unusal since vegetation condition predominantly varies along a precipitation gradient. High rainfall promote plant biomass and increased total productivity, reflected as high vegetation index values towards western zones of the highlands in Kakamega and Kericho and also around Mt. Kenya (4s). Occurrence of fewer farms in Kericho (western Kenya) and presence of a tropical forest in Kakamega likely facilitated the observed high annual average NDVI seen in sub-watersheds with 1's.

In Figure 4-5C. interestingly, but not unexpected, we found increase in population density somewhat corresponded to the intensity of farming (number of farms per sub-watershed). However, 5BE, 3AB, 3BA and 2GD (Figure 4-5C) have extremely high number of large scale commercail farms compared to the other sub watersheds. We consider these subwatershed outliers of importance, corresponding to known hot spots of commercial horticulure (Nanyuki-Laikipia district, Athi River area and Lake Naivasha region respectively). Population density is recognized as an important significant variable in commercial horticulture owing to high labor demand in production processes (Justus & Yu, 2014). Conspicuous high peak in population density (~2800 per Km^2) was observed in 3BA, Nairobi and Kiambu region. Nairobi is the capital city, whose population has skyrocketed because of rural urban migration in search of employment. As a result, farming occurs in the outskirts of the city.



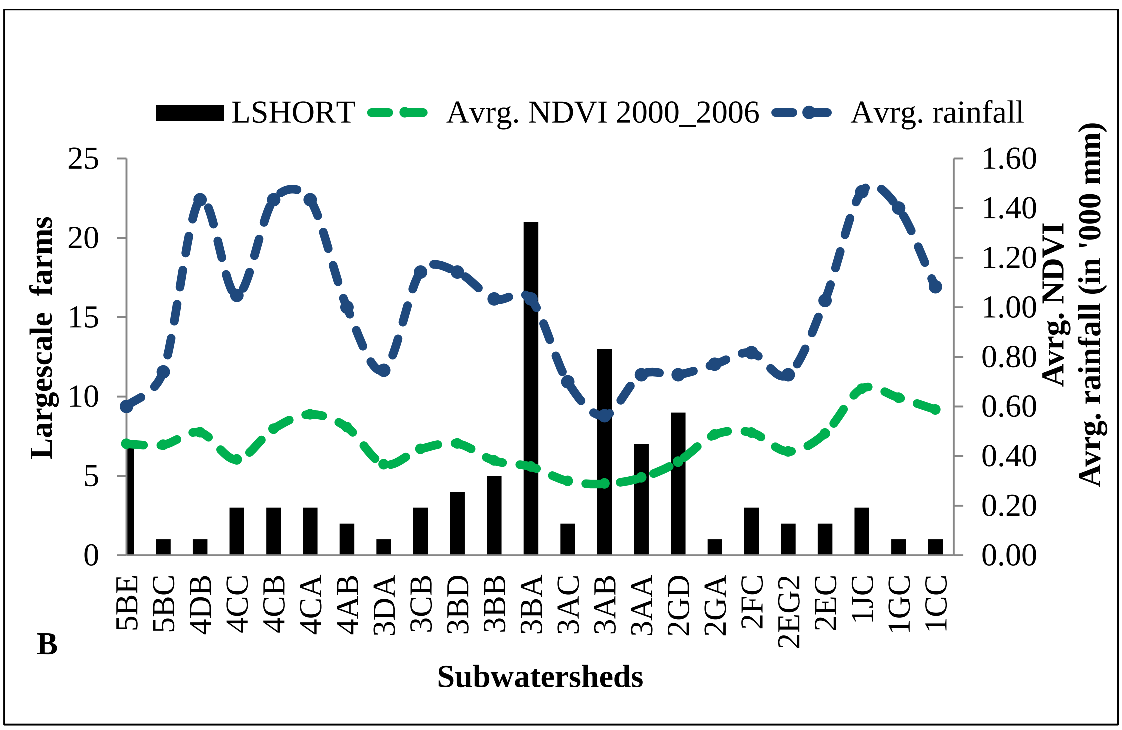


Figure 4-5A-B: Relationship of intensive farming, averaged NDVI, and average rainfall (A) Averaged inter-annual NDVI (2000-2006) for sub-watershed; (B) Number of large-scale commercial greenhouse farms per sub-watershed, general mean annual rainfall and NDVI.

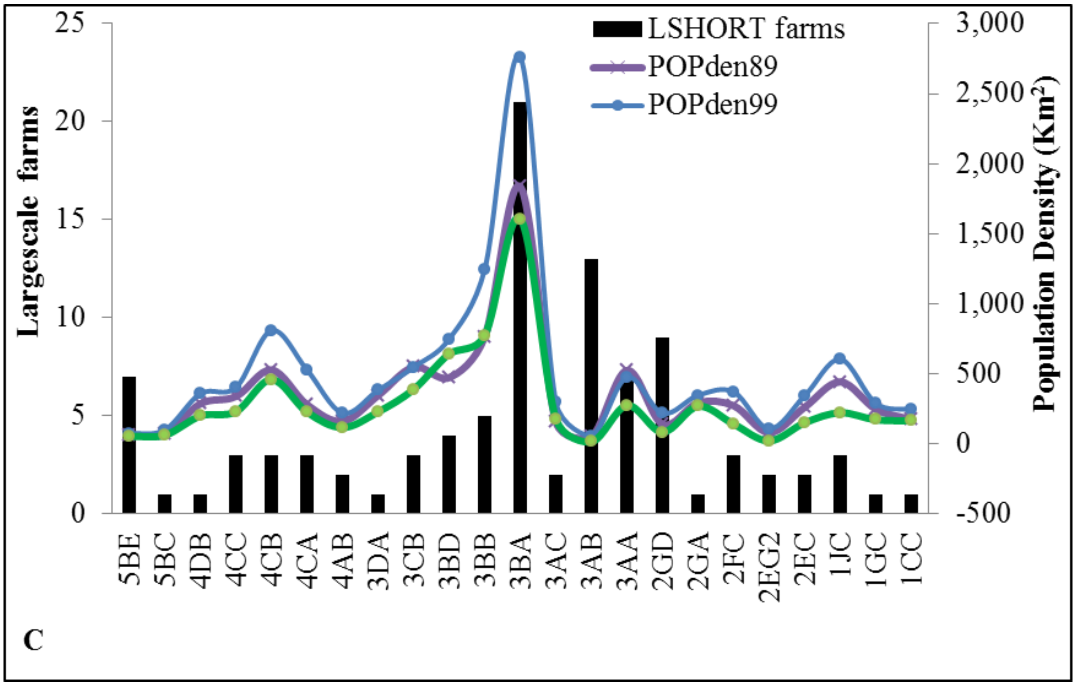


Figure 4-5C: Number of farms and population density in the sub-watersheds.

4.3 Discussion

4.3.1 Inter-annual variability in NDVI within the sub-watersheds

From the results (Figure 4-2A-E), some important observations on changes in vegetation characteristics over the study period emerge. Overall, the observed spatial temporal inter-annual variations in NDVI in sub-watersheds are interpreted as results from mixed factors including drought, variation in rainfall, and the level of human activities over time. First, the effect of 1984 and 2000 droughts on vegetation occurred across the majority of the sub-watersheds, whereas the response to human related disturbances is teased out in specific sub-watersheds, particularly in 3s (Athi River catchment) where there is notable decline in NDVI (Figure 4-2C). Drought, defined as an extended period of deficient rainfall relative to the average for a region, affects various physiological processes of plants, mostly due to high heat and lack of enough moisture to support vegetation. Studies also show that droughts can increase the plants' attractiveness and susceptibility to phytophagous insects (Mattson & Haack, 1987) leading to a decline in vegetation health and vigor. The increase in the 1985 integrated average NDVI (Figure 4-2A-D) across the sub-watersheds was facilitated by increased rainfall that followed the 1984 drought (Nicholson et al., 1990), which is regarded as the worst drought in the twentieth century in the Horn of Africa (Steve, 2000). Our results show notable decline in NDVI in response to 1984 event, but followed by high values in 1985. Nicholson *et al.*, (1990) indicated that rainfall was below normal (less than 200 mm) in 1984 for most of North and eastern part of Kenya, but it increased to above 500 mm nationwide in 1985. This provides plausible explanation for the observed fluctuation in integrated mean annual NDVI between 1984 and 1985.

Second, the response to drought was not spatially instantaneous. Some sub-watersheds show a delayed response (see 4s in Figure 4- 2B), attributed to differences in vegetation cover/types and canopy density and the influence on local climates. For example, in 4s (Figure 4- 2B), which are partly within Mt Kenya forest and Aberdare ranges, the 1984 drought presented a relatively low NDVI peak compared to the other sub-watersheds, while the effect of the 2000 drought (low NDVI peak) is delayed to 2001. In addition, among the 1s (Figure 4- 2E), presence of extensive canopy by the Kakamega forest influence NDVI values to exhibit very low year to year variations, making it difficult to differentiate the responses to drought events from the normal yearly phenological cycles. Thick canopy cover and cooler forest atmosphere help reduce evaporation, which enables longer period of moisture retention that promotes vegetation growth (Makarieva et al., 2014). Studies show that NDVI is strongly related to total primary production over the growing season (Fung et al., 1987) and therefore, the presence of continuous cover can promote somewhat stable vegetation conditions with less temporal variations.

Third, we also observed that over the years, and across most of the groups (Figure 4-2A-E), sub-watersheds with dominant (lagging) high (low) edged NDVI values remained stable over the entire study period. However, in groups where vegetation conditions varied due to factors other than natural occurrences (drought, rainfall etc), for instance disturbances relating to human use of land, then NDVI patterns varied such that no specific sub-watershed dominated or lagged in NDVI over time. For example in 3s (Figure 4-2C), where interactions of different factors are presumed to be at play, there was no particular sub-watershed that remained with high (or low) in NDVI for the entire period but fluctuated, indicating a breadth of disturbances across such sub-watersheds.

Following this observation, we can argue that the observed variability could be a result of either affected or non-affected regions. We followed this hint by designing a simple sub-objective investigation to observe type of variations in NDVI for selected pixels in different environments of the study areas that represented a) highly disturbed, b) moderate disturbance and c) no known disturbances (forest). The selected pixels in different landscapes were followed through the 25 years, and results are shown in Figure 4-3.

4.3.2 Is it a question of control versus Affected?

The control pixels (1GC and 1GG) indicated relatively high mean annual NDVI patterns and with low inter-annual variability. Conversely, like discussed above it was difficult to tell whether the slight low NDVI in 1984 was an effect of drought or just normal year to year variation. Interestingly, the affected pixels in 5BE and 3CB illustrate highly variable inter-annual NDVI trends, more so between 1986 and 1994, after which the pixel values stabilize. In 5BE pixel, the NDVI value increased tremendously from 1986 because of high rainfall (Nicholson et al., 1990) and likely less disturbances, up until 1994 when the trend reversed, resulting in low NDVI, which suggests decline in vegetation condition. We attribute the observed decline of NDVI in 5BE to increasing human disturbances and lack of rainfall, which affected vegetation growth over Laikipia. In recent years, declining rainfall and increasing drought frequency in the region was reported (Pricope et al., 2013; Shisanya et al., 2011). Further, what we observe in the pixel 3CB is interesting. Unlike 5BE where there was continued increase in NDVI before decline, in 3BE, the NDVI value declined rapidly between 1986 and 1994, before attaining a stable pattern similar to 5BE pixel after 1995. This observation was likely caused by the extensive land use and cover conversion from its natural state to farming and residential uses, which now becomes the common types of land use in the sub-watershed. The trend has since settled, likely because all-season intensive farming has since picked up, providing a continuous “greenness” emanating from crop land.

4.3.3 Spatial variability and shifts in the NDVI trends (slope) and strength -before and after 1990s

The start of 1990s to mid-1990s is recognized by various literatures as the period when proliferation of intensive horticulture took root (Jaffee, 1995; Minot & Ngigi, 2004). The remarkable change from positive to negative slopes, and with strong coefficients of determination (Figure 4-4A and B) in numerous sub-watersheds after-1990 indicate pronounced decline in vegetation condition in central highland of Kenya. Conversely the severity of decline is spatially non-uniform across sub-watershed, providing hints that processes contributing to observed vegetation patterns may be analogous within those sub-watersheds. The period before-1990s had more positive trends in average NDVI (Figure 4-4A 51.5%) compared to the period after-1990s (6%). The trends were statically significant or marginally significant ($p < 0.05$ and $p < 0.1$ respectively), an indication of changes in vegetation dynamics in sub-watersheds between the time periods.

4.3.3.1 Before 1990

Intensive horticulture farming was not a common practice in early 1980s, and therefore the observed variability and decline in vegetation condition before 1990s as seen in 5BE, 5AD, 5DB,5AC, 5BC, 4CC (Figure 4-2A-B) can be explained by factors such as drought and variability in rainfall that occurred prior to our estimated time of entry of intensive farming. Decreasing precipitation has direct effects on vegetation productivity (Pricope et al., 2013). Broad literature indicates connection between vegetation greenness (NDVI) and rainfall patterns in East Africa that is coupled to ocean-atmosphere phenomena of El Ni˜no, Southern Oscillation (ENSO) and the Indian Ocean Dipole (Jessicca et al., 2013; Williams et al., 2008). ENSO causes atypical rainfall patterns that lead to higher than normal photosynthetic activity (Anyamba, Tucker, & Eastman, 2001) and often followed by drought conditions over the region. The 1984 and 2000 droughts are recognized as events linked to ENSO (Anyamba et al., 2001; Huho & Mugalavai, 2010; Shisanya, 1990).

There are concerns that decades of drought (fueled by frequent low precipitation) may permanently alter landscapes, allowing encroachment of dominant ephemeral grasslands species that are able to cope with irregular moisture conditions (Nicholson et al., 1990). This is important because even though grasslands have lower NDVI (0.3 - 0.4) compared to forested areas (> 0.65), they have high biodiversity, and support a wide range of livestock, wildlife and human communities (Scholes & Walker, 2004).

From our findings, the observed severe decline in average annual NDVI in particular regions characterized by savanna vegetation makes the above hypothesis a probable process that explains the low NDVI prior to the rapid environmental changes and shifts to intensive horticulture. In addition, following the prolonged 1984 drought, national agencies started drawing attention towards developmental programs to alleviate hunger and rural poverty among marginalized communities due to its linkage to malnutrition. They began encouraging irrigated agriculture to enhance food productivity and security, but poor farming practices including clearing of vegetation for cultivation, presented challenges such as increased soil erosion, which could further reduce vegetation cover. In fact towards the late 1980s, dry areas where shifting cultivation and bush fallow systems had been widely practiced started experiencing the land rush (Weekly Review 1991a,c; Galaty, 2013) rapidly filling the dry fallow lands and grazing lands with crop fields and farming communities. Although it was necessary to increase farming so as to support growing communities and improve food security (Kasperson, Kasperson, & Turner II, 1993), the farming practices in this period took inadequate consideration of conserving the environment resources.

4.3.3.2 After 1990

Results reveal important observations during this period, which help interpret patterns of variations in NDVI, and therefore vegetation dynamics in the study area. First of all, a wide range of literature recognize the years after 1990 as the era of intensive export horticulture in Kenya (Jaffee, 1995, 2003; Minot & Ngigi, 2004). Socio-economic factors such as failing cash crops prices (coffee, tea, tobacco), trade agreements that supported production and export of duty free commodities and international demand of fresh produce are reasons behind the rapid rise of horticulture post the 1990s (Dolan, Humphrey, & Pascal, 1999). These initiated a rush for cultivation space, leading to expansive clearing of land cover, and land fragmentation to small parcels for more intense farming particularly in the central highlnads where climate condtion is favorable. These changes are largely reflected in our results as spatially localized pockets of declines in average NDVI in particular subwatersheds e.g. 3s (Athi River basin Figure 4-4 A-B), 5s (Ewaso Nyiro basin) and 2s (Rift Valley and in land lakes). These areas are commercial horticulture hot spots, such as areas around lake Naivasha (2GD), Laikipia (5BE) and expanding urban towns, and have adverse effects on vegetation.

For subwatershed that showed complete reversal from positive to negative trends, expansion and conversion of marginal lands and forested areas into other land–uses may be the reason. Such trends are common today, with studies shwoing that more intensive forms of land use even in Asia and elsewhere (Rasul, Thapa, & Zoebisch, 2004) are replacing traditional farming approaches. Pricope et al. (2013) indicate that population growth and land tenure policy prompted changes on land ownership in Central Rift valley. Moreover, government policies that encouraged cultivation of high potential areas in the arid and semi-arid rangelands of Kenya (Campbell, 1981; Oba & Lusigi, 1987) perhaps indirectly promoted decline in vegetation condition at more rapid rates in specific sub-watersheds than others. For instance in Laikipia (5BE) the migration of cultivators into the formally livestock and wildlife ranches deprived pastoral communities in the region of access to their usual dry season retreats, increasing land use-land cover (LULC) transformation and increase its vulnerability to extreme weather. The number of large scale intensive horticulture farmers in Laikipia increased, with reported heightened cases of water and land resource conflicts within and between local communities (Aeschbacher et al., 2005; Kiteme & Wiesmann, 2008). Other reports relate increased farming to failure of urban and civil governments to provide job opportunities at pace with growing demand. This prompted many menfolk to return home to farm creating a new cycle of agricultural intensification and experimentation in many communities since the beginning of the 1990s (Tiffen & Mortimore, 1992). These socio-economic factors/processes alter land cover dramatically, contributing to rapid decline in vegetation conditions and therefore shifts in NDVI trends over years.

The 2000 drought (Fratkin, 2001; Shisanya et al., 2011) had far reaching effect on vegetation, prompting record low NDVI indicating decline in vegetation status across the sub-watersheds. Approximately 30 % of Kenya was affected by this drought resulting to severe land degradation (UNEP, 2002), accelerated soil degradation and reduced per capita food production (GoK., 2002). This drought and recent other droughts in the region have forced pastoral communities to shift from purely livestock keeping to adopting farming as an alternative, leading to more rampant land demarcation and privatilzation of formerly communal lands. We believe that these environmental land use and land cover changes to more intensive and expansive farming impacted vegetation condition in the region leading to the observed increased negative trends post 1990s.

Our results indicated strong decline in NDVI (high r sq. value) in sub-watersheds within Athi River catchment, i.e., Kiambu, Nairobi, Athi River town area (3s) in Figure 4-3A, and also within the Ewaso Nyiro basin catchment (5s), i.e. Nanyuki, Timau, Laikipia. Both of these regions are of arid to semi arid climates, covered by vast grasslands type of ecosystems with mosaics of woody vegetation and shrubs. Studies show that large variations in vegetation composition and growth occur in arid and semiarid areas (ASALs) where rainfall is sporadic and the response of vegetation to such rainfall is rapid (Griffin & Friedal, 1985). To detect occurring variations, analysis of long term data trends is important in revealing pockets of land degradation especially at local scales. Herrmann, Anyamba, and Tucker (2005) indicate that while short term impacts on vegetation such as pest and disease outbreak can cause rainfall-independent annual deviations in NDVI, the long-term trends are more likely to be induced by human factors such as changes in land use, exploitation of natural resource base and agricultural production strategies. These discussions support our study findings and hypothesis that after the 1990s, rampant growth of commercial horticulture alongside population density increase in agriculturally productive sub-watershed contributed to the observed decline in vegetation condition in those pockets.

Even so, the extent to which increased commercial horticulture and related anthropogenic disturbances on vegetation are to blame is tricky. Occurrence of severe droughts and decline in rainfall in the region impacted NDVI values in both time periods, and so played a role in the observed shifts.

However, localized (specific) strong decline noted in for instance 3AB, 3AA, 2H, 2GD, 5BE, 5DA, 4FA and 5AD (Figure 4-4A and B) agree with reports of increased horticulture farming, population pressure, and threats to biodiversity (through destruction of local species habitats) and growth of settlement within these sub-watersheds. Clearing of forests to create agricultural land and burning of charcoal are factors that contribute to severe forms of environmental degradation (Vargas et al., 2009).

4.3.4 Relationship between intensive horticulture, NDVI, rainfall and population density

The study region is characterized by high spatial and temporal variability in precipitation which directly affect vegetation productivity (Oba & Lusigi, 1987) and water resources. The observed decline in the average annual NDVI correlates with increasing number of intensive large scale horticulture (LSHORT) farms (Figure 4-5B) and expansion (Justus & Yu, 2014), which raises important concerns regarding impacts of such farming on the environment.

The presence of greenhouse explained about 28% of observed variation in average annual NDVI (2000-2006). Most greenhouses are constructed of plastic covers to shield crops from weather conditions, pest invasion and disease spread. However, the plastic cover is highly reflective unlike vegetation cover/canopy, and the resulting NDVI values of pixels covered by greenhouses is relatively low, and therefore, as the number of greenhouses and presumably area under plastic covers (and other farm infrastructures) in particular sub-watershed increases, there is a decline in observed average annual NDVI trends. This may seem obvious for interpretation, but when we vision the area under plastic cover as occupied by plants which grow and develop normally and if exposed, then the observed NDVI values may perhaps be higher, prompting a direct relationship. Methods that can detect the response produced by the plastic could be used to discriminate on crops under plastic greenhouse (Montesinos & Fernández, 2012), and therefore reduce inherent ambiguity. Nonetheless, from another perspective, an increase in number of farms in sub-watersheds can be associated with increased disturbances on land cover, which could translate to lower NDVI values. The transformation of land resource for different purposes can impact the amount and frequency of rainfall, creating unstable and fragile ecosystem. This limits not only horticulture and subsistence farming but also habitability of watersheds, and the level of forage productivity to support other ecological systems (Scholes & Archer, 1997).

Clustering of greenhouse farms was prevalent in low to average rainfall areas, and with very low NDVI (often below 0.35, see Figure 4-5A). Generally areas of low NDVI correspond to rainfall below 500mm (Nicholson et al., 1990) primarily representing grasslands interspaced with woody vegetation in marginal (less productive) lands. As rainfall increases, so does the averaged NDVI (Figure 4-5B). It appears that intensifying farming pushes towards highly unstable ecosystems (low NDVI and low rainfall regions); further destabilize sustainability in regions primarily dependent on precipitation for maintenance of the mosaicked grass-shrub species and wildlife. With increasing pressure, sustainable resource utilization and management within such unstable watersheds presents an increasing challenge (Tamásy, 2013).

For example, the expanding farms require massive water for irrigation, which in turn exerts pressure on regional hydrologic systems due to increased water demand and extraction. Water responds rapidly to changes within landscapes such as land-use change and reductions in forest cover (Pielke et al., 2007).

The development of farming systems towards intensification is interrelated to population density and market access (Diao et al., 2014). Increased population in agro-pastoral regions results in intensification or expansion of agriculture activities, high livestock stocking and increased wood extraction (Vargas et al., 2009). Consequently, this leads to resource over utilization and unchecked forest clearing, which can increase vulnerability of sub-watersheds to more rapid environmental degradation (Pricope et al., 2013), and failure to provide necessary ecosystem services. In their study, Pricope *et al.* (2013) note that between 1990 and 2010, the mean population density increased in some target areas in central Kenya, which was accompanied by significant reduction in NDVI, suggesting link between population density and vegetation degradation in the hotspots. It turns out that these hot spot areas detected in their study overlap areas with increased horticulture and population explosion in our study, supporting our findings.

Watershed management in areas at crux of intensive horticultural production and population increase is complex but is an urgent, necessary step to strengthening local economies and ensure food security and long term sustainability. There are arguments that intensification of agriculture in a deforested, degraded area could well restore partial tree cover through on-farm and boundary planting of trees. While this can possibly substitute for forest products (such as fodder and wood fuel), the replacement of water-storage and distribution functions of the forest would require elaborate physical structures and management systems (Kasperson et al., 1993; Tiffen & Mortimore, 1992). Therefore, it is essential to evaluate vegetation condition in order to identify pockets of vegetation decline particularly in marginalized and over populated sub-watersheds. Land degradation encompasses the physical degradation of the resource base for national production, including the life-support and livelihood needs of the rural poor. Promoting land-use intensification as a solution to poverty alleviation versus land degradation has thus been a paradox of modern day in many sub-Saharan nations.

In our study, we closely examine this paradox of the quest of horticulture sector to exploit available natural resource base predominantly in central highland (with production factors) to meet international markets demand for fresh commodities. How these efforts proceed in view of the prevailing droughts and climate variability which exacerbates the core issues surrounding economic developments and food security efforts in the country will be interesting. From our point of view, increased commercial horticulture farming creates employment that also leads to a surge in population density in specific areas of farm clusters. Horticulture sub-sector has by far risen as the second foreign currency earner in Kenya, and a source of employment for thousands of people. While this is positive socio-economic development, the impact on environmental resources is attenuated due to over utilization and mismanagement, contributing to land degradation. As we show in our analysis, the negative correlation between farms and vegetation condition highly suggest underlying negative impacts of increased production activities in the studied sub-watersheds.

4.4 Conclusion

This research explored vegetation condition in sub-watersheds experiencing increased and expanding intensive horticulture farming activities alongside increased population density in central highland of Kenya. We demonstrate the ability to combine various data sources to identify at risk sub-watersheds populations which is crucial when gauging impacts of climate variability, design of mitigation and adaptation procedures.

The study used long-term NOAA GIMMS NDVI data (1982-2006- 24 years) to assess trends and slope in average NDVI before and after 1990, presumed periods of start of horticulture. We also used data on large scale commercial greenhouse farms and census population statistics for the selected sub-watersheds in determining likely relationship between farming and vegetation index. Growth of the horticulture sector in Kenya was rapid in the last two decades, creating spatially heterogeneous clusters of large-scaled commercial enterprises more so in select agriculturally productive locations that provided favorable capital production factors.

We identify spatial pockets with low average annual NDVI, which coincide with intensity of farming (number of farms per sub-watershed) and population density for the majority of the study area. A notable decline (negative slope) in vegetation condition is observed primarily after-1990 suggesting a link to ongoing intensive horticulture farming. Some adjoining neighbor areas where no farming is mapped but had low NDVI may specify regions where other human disturbances such as establishment of settlement, land clearing to residential housing for working population has influenced land cover as shown in the investigation of affected versus unaffected pixels.

Drought and moisture variability may have played a role toward the observed decline in vegetation status in 1984 and 2000. However, we think that the continued decline in vegetation is more likely linked to increasing anthropogenic disturbances within the sub-watershed.

Overlap of decline in vegetation index, low to moderate rainfall, and population density with intensive horticultural farming raises concerns of current global discourse to reduce agricultural impacts on environments, enhance food security and community health through sustainable agriculture. The presumed post-1990s increase in intensive and expanding horticulture and human activities may have conceivably accerelated the environmental degradation process in some regions which had low average NDVI (e.g. 5DA, 4CC, 4CB, and 5BC), even before our estimated time period. Such overlap locations represent hotspots highly vulnerable to environmental degradation, rapid climate change, and inherent food insecurity, which require immediate intervention mechanisms. Our future work intends to explore the impact of increased horticulture production and related human activities in the region by quantifying land use and land cover transformation and rates of change.

4.5 References

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CHAPTER 5

Land use and Land cover (LULC) transformation in semi-arid to arid sub-watersheds of Laikipia and Athi River basin as influenced by expanding intensive large-scale horticulture, and revealed by Landsat data

Abstract

Agriculturally productive watersheds in Kenya are experiencing important land transformations with consequences on environmental resources. Our analysis in chapter four identified spatial pockets of vegetation decline across the study area. While this is crucial information in delineating impacted regions, it is important to understanding type of occurring changes, spatial patterns and the rate of change. The study focused in Athi River and Laikipia regions which have intensified commercial horticulture, yet marginalized semi-arid to arid environments. The study quantified land use and land cover changes (area and rate) between 1984 and 2009/2010, identifying areas of change. Landsat (5 TM, MSS and 7 +ETM) multi-temporal data were used in classification and change detection analysis. From the results, both regions experienced intense land transformation at varying magnitudes during the 25 years period. Woody grasslands covered vast areas. In Laikipia, the percentage annual rate of land change to settlements/urban use was highest (20.2%). There was a decline in barren area, forest and wooded grasslands (–1.4 %, -0.7% and -0.3% respectively). In Athi River region, the percentage annual rate of changes was in the order of agriculture, water, settlement, bare soils, woody grasslands (37.7%, 17.2%, 8.4%, 3.9, 2.9% respectively) while dark bare soils, and forest cover declined (-3.4% and -3.3% respectively). Observed LULC transformations were largely attributed to socio-economic drivers including increased human migration into agriculturally productive sub-watersheds fueling growth of settlement, increased irrigation farming and therefore increased area under water, and growth of cities and industrial areas.

Keywords: Land transformation, deforestation, horticulture, population

5. Introduction

Land use and land cover (LULC) transformation is an important research item due to the increasing impacts on ecosystems and link to global, regional and local climate change and variability (Bajocco, De Angelis, & Salvati, 2012; Liu et al., 2014; Mahmood et al., 2006; Turner II et al., 2007; West et al., 2010). The common drivers of LULC include agricultural encroachment, deforestation, road construction, dams and irrigation, wetland modification, mining, expansion of urban environments (Liu et al., 2014), and coastal zone degradation (Patz, 2008). At the watershed scale, land cover changes pose risks of water pollution due to loss of vegetative cover, which acts as a barrier to the movement of materials into water systems, reducing runoff (Notter et al., 2007; Schneider & Gil Pontius Jr, 2001). This significantly increases possible impacts on terrestrial and aquatic systems, and social-economics of communities (Adger, Arnell, & Tompkins, 2005). In addition, deforestation, which is the removal, cutting or clearing of forest cover for reasons such as logging, crop land expansion, settlement *etc,* disrupts hydrological patterns and material output (sediments loads) from watersheds to rivers, affecting the metabolism and productivity of important ecosystems like estuaries (Hopkinson, 1995).

The proliferation of intensive commercial horticulture in Kenya in the recent past has influenced LULC changes (Becht, Odada, & Higgins, 2005; Francis, 2014), particularly in central districts that are agriculturally productive. The uneven clustering of large scale farms, over-extraction of surface water for irrigation, clearing of marginal lands and continuous tilling to increase all year production of fresh produce are some activities impacting the use and management of environmental resources (Aeschbacher et al., 2005; Owiti & Oswe, 2007). The horticulture sector is labor intensive, attracting population into sub-watersheds, causing an increase in population density and growth of unplanned settlement (Muriuki et al., 2011).

Unrestrained growth in limited spaces of sub-watersheds exerts pressure on environmental resources, enhances degradation and competition between and within species (Barrow, 2006), which augment watersheds vulnerability to climate change effects. Regions with high clusters of horticulture production include Naivasha, Thika, Kiambu, Limuru and Laikipia (Justus & Yu, 2014). In Laikipia, the annual population growth is 5% to 6% (Kiteme & Gikonyo, 2002), and recognized as an exogenous factors influencing land use allocation (Stéphenne & Lambin, 2001). Population increase exceeding the carrying capacity of a region it is destructive, often causing an over burden on other species within those areas which can result to reduced biodiversity (Oehl et al., 2003). Studies show that population and human settlement have a strong negative correlation with net primary productivity (NPP), with trends of NPP shown to decrease as settlement, or population increases (Haberl, 2007; Dengsheng Lu et al., 2010). Recent regional observation (Pricope et al., 2013) show that areas experiencing reduced main-growing season precipitation in East Africa coincidentally experienced increasing population pressures, and vegetation browning. However, the drying precipitation patterns only partially explained the observed vegetation browning trends, an indication that other factors such as population increase and land-use changes could be responsible for the decline in vegetation condition.

The drivers of land transformation are complex, and region dependent, requiring area based studies to investigate amount and rate of changes (Kasperson, Kasperson, & Turner, 1996). Attempts to understand LULC changes in Kenya provide mixed conclusions on nature, extent and impacts on ecosystems. Baldyga *et al*., (2008), show that the Mau forest underwent major changes after 1995, due to deforestation. Vast forest cover was converted to mixed small-scale agriculture and managed pastures resulting to spatially variable landscapes theorized to have significant impacts on ecological and hydrologic systems in the area.

In Laikipia district, which encompass sub-watersheds in the Upper Ewaso Nyiro basin (Mutiga et al., 2010), rapid changes in both land ownership and land use is linked to population growth (Mungai et al., 2004) as a result of augmented regional intensive horticulture. Work by Kithiia (2012a), examined effects of changing trends in land use on soil erosion and sediment transport within Athi River basin, and results indicated that intensive agriculture, industrial activity and population pressure influenced surface water quality in the basin, requiring remedial actions and better resource management.

These findings are important in understanding the impacts of increasing LULC changes on natural resources in the region. However, the dynamics of land use conversions and rate of change between uses, which provide more specific indication of for example the sources and potential pathways of pollutant/sediment transport within watersheds, remain unquantified. Areal numbers provide magnitude of change, providing information necessary in designing management strategies to ease pressure. It is an issue of urgency for environmental resource managers and policy makers, requiring an integrated approach to understand diverse issues driving LULC changes in natural landscape in order to design practical and applicable mitigation strategies.

Currently, the research to monitor, quantify and understand environmental consequences of changes in earth systems (Giri, Zhu, & Reed, 2005; Yang et al., 2013) at different scales and time period has widely utilized remote sensing data. Infact, there is increased interest in making scientific progress through integration of remote sensing information and socio economic data (Liverman et al.,1998). Unlike field based data collection approaches, remote sensed data provide faster and consistent means of studying land surface changes over time, and without accessibility hindrances (Jensen, 2005; Lu et al., 2004). This enables robust, efficient and cost-effective method to map land cover, biomass distribution globally and locally (Maingi & Marsh, 2001). Currently, there are numerous remote satellite sensors in operation; MODIS (Salomonson et al., 1989); MISR (Diner et al., 1989), Landsat missions (NASA); (SPOT, IKONOS), which differ in spatial, radiometric and spectral resolutions for data capture.

LULC change detection investigations, commonly utilize freely available Landsat data. It provides a long history and higher frequency of archives, and continuous data that enable comprehensive examinations and mapping of LULC (Abd El-Kawy et al., 2011; Wulder et al., 2008). Such investigations are gaining interest in developing sub-Saharan nations due to increased anthropogenic perturbations on terrestrial cover, and likely feedbacks to climate variability. Kashaigili and Majaliwa (2010), used Landsat TM and ETM+ images to map LULC changes in the Malagarasi river catchment in Tanzania. Their findings show significant land transformations linked to increased settlements and cultivation, at least by 1.05% annually in a period of 18 years. Bakr, Weindorf, Bahnassy *et al.*, (2010), used multi-temporal remotely-sensed data to monitor land cover changes in a newly reclaimed area of Egypt noting that it provides an effective and precise estimation of human impact on the environment. In central Kenya, Imbernon (1999) used remote-sensing data from 1958, 1985 and 1995 to study land-use changes in the upper Embu area and found a minor loss of tree cover, but a high loss of bush land. Recently, Kirui *et al.* (2013) used Landsat data to map mangrove forest cover along the Kenyan coastline. They reported that within the 25 year of study (1985-2010), the rate of mangrove loss was 18% (0.7% per year), and varied both spatially and temporally due to legislative inadequacies and differences in habitat alteration patterns. From this literature, it is undeniable that vast areas of natural cover have been transformed and the processes of transformations are continuous, posing varied consequences to the environment.

This research investigates the dynamics of land use and land cover transformations in two case study regions with characteristically increased intensive commercial horticulture and human pressure, on arid to semi-arid type of climate thus increased susceptibility to environmental degradation. The specific objectives were to develop maps of LULC change between 1984 and 2009/2010, to determine quantity of cover/use change, the annual rate of change, and the trends of population density in sub watersheds within the study zones. Data on acreage of land conversion over years and maps of change shed light into dimensions and probable drivers of change, providing a base for future studies. The study contributes information critical to designing improved watershed management plans and policies on resource allocation.

The succeeding sections of the study include; a detailed materials and methods section which present a short description of the study regions, the available satellite data, and its processing; a section highlighting the results and discussions and finally a conclusion of the study and suggestions for improvement.

5.1 Materials and methods

5.1.1 Study areas

5.1.1.1 Laikipia study area

The Laikipia study region comprised of a subset of 5 sub-watersheds, covering 6188 sq. km within the semi-arid to arid land of Ewaso Nyiro catchment (Figure 5-1A). It mainly falls on the eastern escarpment of the Rift Valley, primarily occupied by extensive ranches, mixed small scale agriculture, vast savanna grasslands and woodland, forest cover surrounding Mt. Kenya, and large scale farms at the foot zone of Mount Kenya (Figure 5-1A).

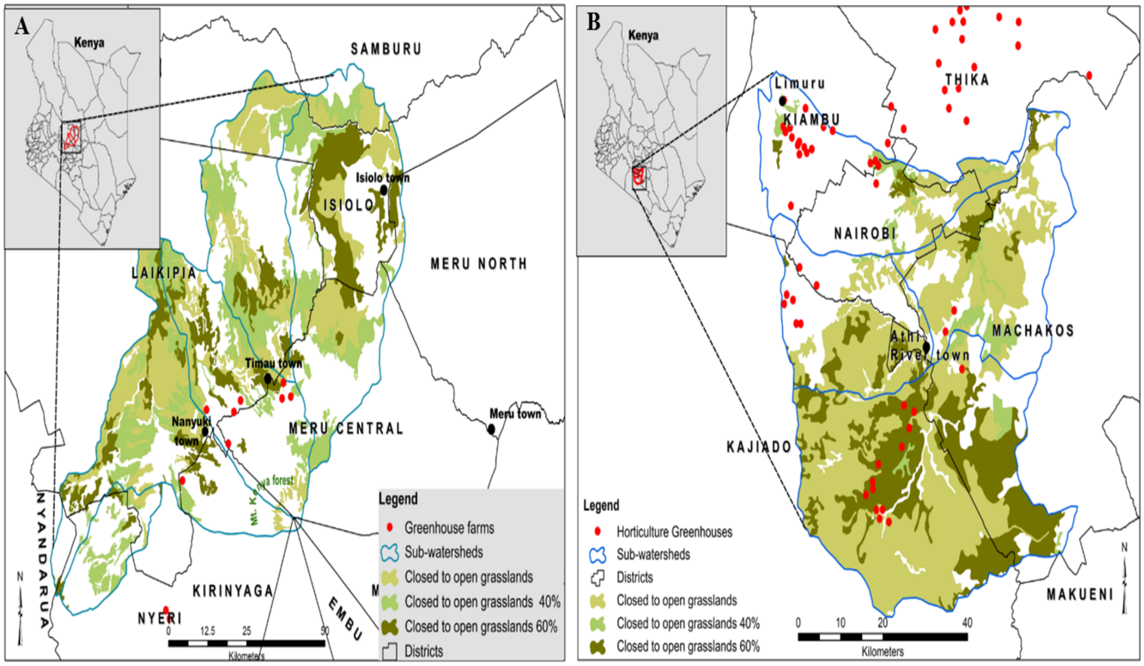

Figure 5-1A-B: Study area (A) Laikipia (B) Athi River area encompassing 5 sub-watersheds with increased large-scale greenhouse horticulture. Both regions have vast grasslands compared to other cover types.

The 5 sub-watersheds had clusters of large-scale greenhouses for commercial horticulture (Justus & Yu, 2014). Settlements and urbanizing town centers are common with remainder of land area occupied by wildlife habitat, forest reserves and conservation parcels. The rainfall is generally bimodal with an average annual rainfall of about 700 mm/year (Gichuki et al., 1998; Thomas & Liniger, 1994).

The long rains occur from March through June, and short rains occur from October through December (Berger, 1989; Notter, 2003). Between the two seasons, dry conditions persist influencing the type of vegetation cover to that of savanna ecosystems. Besides, the presence of Mt. Kenya at high elevation, form a highland-lowland system that prompts a striking climatic and ecological gradient, from humid moorlands and forests on the mountain slopes to arid Acacia bushland in the lowland, with a diverse pattern of land uses (Decurtins, 1992; Mutiga et al., 2010).

Most part of Laikipia is on the leeward slopes of Mt. Kenya, which makes the area exhibit arid and semi-arid climatic characteristics. Soils are primarily deep vertisols (verto-luvic Phaozem) of dark gray clays, that are imperfectly to moderately drained, and developed from volcanic activity of Mt. Kenya (Liniger et al., 1998). These soils support little rain-fed agriculture, and limited land use due to their high erodibility (Weismann, 1998). The Ewaso Nyiro River is a main source of water towards the drier outer areas of the study zone, while Mt Kenya forms a water source for several rivers that support farming at the mountain foot zones.

5.1.1.2 Athi River region

This study region was a subset of 4 sub-watersheds covering 4199.2 sq. km within the greater Athi River catchment (Figure 5-1B). Like Laikipia, shrubs and woody grasslands cover a vast area in this study region towards the southern arid and semi-arid zones of Kajiado district, where only 8% of the district land has potential to support rain-fed agriculture. The soils are predominantly deep black Vertisols that support and maintain the rangelands and pastoralist activity. The upper catchment is shared by Nairobi County (at the core), and Kiambu county towards the northwest (Figure 5-1B). In Kiambu, towns like Limuru and its surrounds are dominated by intensive agriculture that supports approximately 70% of the population (MoPND, 1994).

The rapid expansion of Nairobi city and its environs has huge expense on the natural landscape. Large tracks of forest land, mixed rangelands and bush lands (UNEP, 2008) have been converted to urban dwellings, roads and city infrastructure, causing receding forest cover. The demand for food by the proliferating population led to major changes in land use and cover patterns in the outskirts of the city, converting to agricultural more intensive commercial large scale horticulture in the marginalized areas of the Athi River basin (MDC, 1993; Tibaijuka, 2007). The mean annual rainfall vary between 300-800 mm, and occur in two main seasons; October to December months (short rains) and March to May (long rains). This kind of annual rainfall is inadequate for rain-fed agriculture. The vegetation is predominantly open grasslands of *Themeda* and *Chloris* types, that are distributed along a altitudinal gradient, with *Themeda* species occurring at 1100-200 m, and *Chloris* occurring at 450-1200 m (Rattray, 1960). There are few types of woodland and bushland composed of *Acacia-Commiphora* and semi-deciduous *Combretum, Acacia,* and *Premna* species that occur on hill slopes in wetter areas (de Leeuw, Peacock, & Cisse, 1986). Forest cover is minimal to the south, and where present, it is confined in isolated patches on hill tops and along the flat low lying phonolithic lavas ranges similar to those found in the Laikipia plateau. The primary sources of water to the Athi River basin are mainly Ondiri springs, Tigoni falls, Kikuyu escarpments, Kabete and Karura forests (de Leeuw, Grandin, & Bekure, 1991). The mix of land use types coupled by arid to semi-arid climatic conditions in the basin make it vulnerable to land and environmental degradation besides the high rates of soil erosion and bare barren surfaces (Tiffen & Mortimore, 1992).

Both Laikipia and Athi River basin study areas share almost similar climatic characteristics (aridity, low rainfall, vegetation gradients, rapid population expansion into marginal lands), which make them vulnerable to climate changes and declining land productivity and therefore a unique case study.

5.2 Methods

The study integrates both remote sensing and geographic information systems (GIS) techniques to investigate land use and land cover (LULC) dynamics in two study areas delineated as regions with increasing large scale intensive commercial horticulture production and rapid population growth. The study incorporates demographic information i.e. population density of the sub-watersheds derived from census data and graphed to visualize trend in population, a prominent key driver of LULC changes.

5.2.1 Remote sensed data, processing and change detection

5.2.1.1 Image selection and acquisition

Landsat-5 Multispectral Scanner (MSS) and Thematic Mapper (TM) and Landsat-7 Enhanced Thematic Mapper (+ETM) images were obtained for the years 1984, 2009/ 2010 (Table 5-1), a period of 25/26 years which provide ample time to monitor LULC change. An effort was made to acquire cloud free image scenes. It is easier to note phenology differences in vegetation during dry seasons than in wet vegetative seasons, however, in this study, not all cloud-free scene acquisition dates coincided with dry seasons. The conditions in 1984 in both study zones were mainly dry.

5.2.1.2 Image pre-processing

The images were already geo-referenced to rectify for alignment, and co-registered to the Universal Transverse Mercator (UTM) projection system (zone: 37N, datum:WGS-84) avoiding the need for geo-rectification which would have employed ground control points (GCPs), paying attention to acquire the least root mean square error (RMSE) in pixels. The image layers were imported and layer stacked to form multispectral images. These steps were carried out in ERDAS Imagine 2014.

5.2.1.3. Atmospheric correction of scenes

Remotely sensed satellite data is affected by artifacts such as haze resulting from water vapor and aerosol particles present in the atmosphere which influence the sensor signal. For land cover change detection using multi date satellite derived images, proper atmospheric correction is necessary because differences in the atmosphere for the two dates can present false indication of change or mask areas of real change (Richter, 1996; Townshend, 1994). Works exploring the impacts of atmospheric correction on image classification are evaluated (Kaufman, 1994). Hazy conditions on scenes at the top of Mt. Kenya (5,199 masl) in Laikipia and a prevailing rugged terrain that introduce varying illumination e.g. sunny, shady hills - conditions that modify the actual spectral behavior of earth surfaces as seen by the sensor necessitated atmospheric correction of the scenes to reduce significant errors in image classification. Besides, the use of multi-temporal images requires atmospheric correction of scenes before classification processes. The study utilized ATCOR terrain and flat modules which eliminate haze, atmospheric and solar illumination effects. This was used alongside a Shuttle Radar Topographic Mission (SRTM) 90 meter digital elevation model (DEM) to generate correction files for ATCOR. These files account for slope, aspect, shadowing, that is presented by the somewhat hilly topography.

Table 5-1. Remotely sensed data used in the analysis of land use/cover change. TM = thematic mapper sensor; +ETM = enhanced thematic mapper plus sensor.

Year	Satellite _Sensor (Image)	Path/Row	Acquisition date (m/d/yr)	Spatial Resolution (m)	Sun Azimuth	Sun Elevation	Season
1984	Landsat5 MSS	P168/60	4/21/1984	60	69.63054	53.46713	Dry
1984	Landsat5 TM	P168/61	8/27/1984	30	71.22358	53.1759	Dry
2009	Landsat7 +ETM	P168/60	1/12/2009	30	127.0982	52.38331	Dry
2010	Landsat 7 +ETM	P168/61	12/17/2010	30	131.2164	55.23683	Rain

5.2.1.4. Image Classification

A supervised land cover classification system was used to classify the images into 7 main land cover/land use categories of: water (WAT), forest (FOR), agricultural land (AGR), woodland and grasslands (WG), settlement/urban (SET), dark bare soils (DAR), bright bare soils (BAR) (Table 5-2). Two classes of burnt scar (BSCAR), and cloud and cloud shadows (CL) were added in some scenes to enhance accuracy. Supervised classification method allows the user to define areas of interest (AOIs) that identify and recognize features on the image. A collection of AOIs form a signature file that is used in classifying entire image. This is in contrary to unsupervised classification where computer algorithm generates the classification. The maximum likelihood decision rule, commonly used in supervised classification was used as a parametric rule (Richards & Jia, 2005). For each of the defined class categories, signature training sets of pixels that best represented the cover were selected (not less than 15 sets per class). The training sets develop unique spectral signatures that are associated with each class, hence ability to categorize an entire image accordingly. The results of this step were evaluated using histograms, band by band scatter plots and a separability analysis (in ArcGIS) to estimate the expected error, covariance between bands in the classification for various feature combinations (Landgrebe, 2003). High covariance between bands is an indication of poor separability between cover categories, and therefore a need to refine class signatures to attain less covariance (ArcGIS resources). Signature collection was repeated where the results were not satisfactory.

5.2.1.5 Generation of Google Earth reference points

Reference points for the two study regions were generated aligned to the extent of the study area shapefile. A total of 300 points were generated for Laikipia and 125 points for Athi River study area. The points were converted to kml files, for overlay on Google Earth imagery. This was necessary to assess accuracy of classification results and modification of land cover categories. Historical Google Earth imagery (dating to January, 1976) was used as reference/validation (Zhao et al., 2014) for the 1984 cover categories, while recent Google Earth imagery (2010) were was used to verify classification results for 2009 and 2010.

5.2.1.6 Accuracy Assessment

Accuracy assessment analysis was carried out to validate precision of classification. Frequency tabulations of classification results alongside referenced ground cover classes from Google Earth were developed.

These were converted to pivot tables from where error/confusion matrixes detailing the overall accuracy, user's accuracy and producer accuracy were calculated. The error matrix provides the users' accuracy and producer's accuracy (Campbell, 2002) for the cover classes based on referenced points and classified output. The user's accuracy present the number of correctly identified pixels in one class divided by the total number of sets recognized in that class.

Table 5-2. Land cover classification scheme used for the study.

	Generalized land cover classes	**Description**
1.	Buildup lands (settlements/urban)	All residential, commercial and industrial area, transportation infrastructure, settlements (may include greenhouse plastic covers)
2.	Water	Permanent open water, lakes, reservoirs, streams, dams, bays and estuaries.
3.	Forest	Deciduous forest land, evergreen forest land, mixed forest land.
4.	Agriculture	Cultivated large-scale farms, fallow, cultivated crops such as wheat, maize, beans, vegetables *etc*.
5.	Woodlands and grasslands	Dwarf shrubs and shrub land, wooded wetlands, grasslands
6.	Bare bright soils	Very bright barren soils with barely any vegetation, rocky mountain
7.	Dark soils	Composed of rocky mountains areas with little to no cover, wet and dark swampy areas where the pixel signature appears mixed.
8.	Cloud and cloud shadow	Clouds and cloud shadows present in some images
9.	Burn scar	Burnt cover area in (Laikipia study area only)

The producer's accuracy is obtained by dividing the number of correct pixels in one class by the total number of pixels derived from reference data. The USGS proposes a minimum accuracy level of 85 percent for LULC mapping using Landsat data (Anderson, 1976). A Kappa coefficient commonly used to measure map and classification agreement (Hudson, 1987) was obtained. Bakr *et al.* (2010) indicate that the overall classification accuracy and Kappa statistics from the error matrix need to be close to 100% as much as possible.

5.2.1.7 Post processing of classification results

A degree of noise is often encountered in classification results due to isolated pixels or small regions of pixels in the image output. Post processing of the output raster reduces such noise, thereby improving the quality of classified output. Using ArcGIS tools, a majority filter (4*4) was applied which replaces cells in a raster based on the majority of their contiguous neighboring cells. Smoothing the class boundaries and clumping of the classified output was done. The final output was a land cover raster, which was converted to a polygon feature class from where the LULC area was calculated.

5.2.1.8 Change detection

Detecting the amount and location of LULC changes is important particularly when seeking to understand drivers of change and the interaction of processes (Congalton & Green, 2009; Mundia & Aniya, 2006; Yeh, Gar, & Xia, 1996). Indeed, different methods to detect changes in LULC from remote images are available (Jensen, 2005; Kashaigili & Majaliwa, 2010), and vary in complexity depending on the purpose of the studies. In this work two approaches, image differencing using the atmospherically corrected data and post classification comparison were employed.

The image differencing technique is straight forward, easy to interpret and robust. The first date image is subtracted from the second date image, pixel by pixel, however, the result, is an absolute difference value spread between 0-1, with the brightest tone representing highly changed pixels. This does not provide detailed change information.

For a reasonable interpretation of the image differencing result, the scaled (0-1) output image was classified into 3 categories of low change, moderate and highly changed regions. The output map was then used in conjunction with the supervised classification land cover maps to visualize areas of changes in pixel values and correspondence to the post classification.

Post classification comparison approach was used to assess changes between the multi-date multispectral images. It is a common approach in change detection studies (Coppin et al., 2004; Kashaigili & Majaliwa, 2010; Kiage et al., 2007), suitable in that it bypasses the challenges associated with the analysis of images acquired at different dates, by different sensors and at different times of the years (Yuan et al., 2005).
However, the optimal accuracy of resulting cover changes is highly dependent on individual classification which can be subject to errors (Zhang et al., 2002). Nevertheless, changes in cover classes are identified by comparing the multi date classified images, pixel by pixel using a change detection matrix. A change detection matrix table was

derived by examining coverage (in sq. km) of individual classes in 1984 and in 2009/2010.

5.2.1.9 Assessing rate of cover change

To assess dynamics of LULC changes in the study areas between 1984 and 2009/2010, for the different coverage classes the approach by Kashaigili and Majaliwa (2010) was applied. The percentage change in cover was obtained by subtracting the area in 1984 (1st date) from coverage area in 2009/2010 (2nd date). The annual rate of change was computed by dividing the change between 1st date and the second date by number of years between the dates i.e. 25 for Laikipia and 26 years for Athi River region. The percentage annual rate of change was derived by dividing the change between dates by the product of area of cover at 1st date multiplied by number of years, expressed as a percentage.

5.2.2.0 Population data and analysis

Population increase is associated with increased land use and cover conversion within watersheds (Lathrop & Haag, 2007). To evaluate the trend in population growth within the sub-watersheds comprising the study areas, the census data for 1989, 1999 and 2009 were utilized. The purpose of this step was to obtain an overall picture of trends in population growth, but whether these trends were a statistically significant driver of changes in the region is not tested. The census data follows administrative boundaries (i.e., districts and sub-locations), where the sub-locations are administrative units at a lower level than the districts and locations. The census population statistics in Kenya were obtained at this level, and aggregated to the district level. The 2009 census data obtained from Kenya National Bureau of Statistics (KNBS, 2009) were joined to the district layer and population numbers for each sub-watershed extracted using ArcGIS®, and the population density derived by dividing the total population per sub-watershed by area of the sub-watershed.

5.3 Results and discussion

5.3.1 Land cover maps (1984, 2009/2010)

The resulting maps indicate broad variations in LULC that occurred during the 25/26 years of study for Laikipia and Athi River. Figure 5-2A-C and Figure 5-3A-C show the land cover maps for 1984 and 2009/2010 for Laikipia and Athi River study regions.

5. 3.1.1 Classification accuracy Matrix

The overall accuracies of between the LULC maps were above 85%, and Kappa statistics were above 0.8 (Table 5-3) indicating a strong to moderate acceptable agreement between the classification map and the Google Earth reference information (Anderson, 1976). The producer accuracy for bright soils and dark soils were moderate, indicating misclassification most likely due to inability to distinguish bare and dark land which could be fallow agricultural lands or damp areas near wetlands etc.

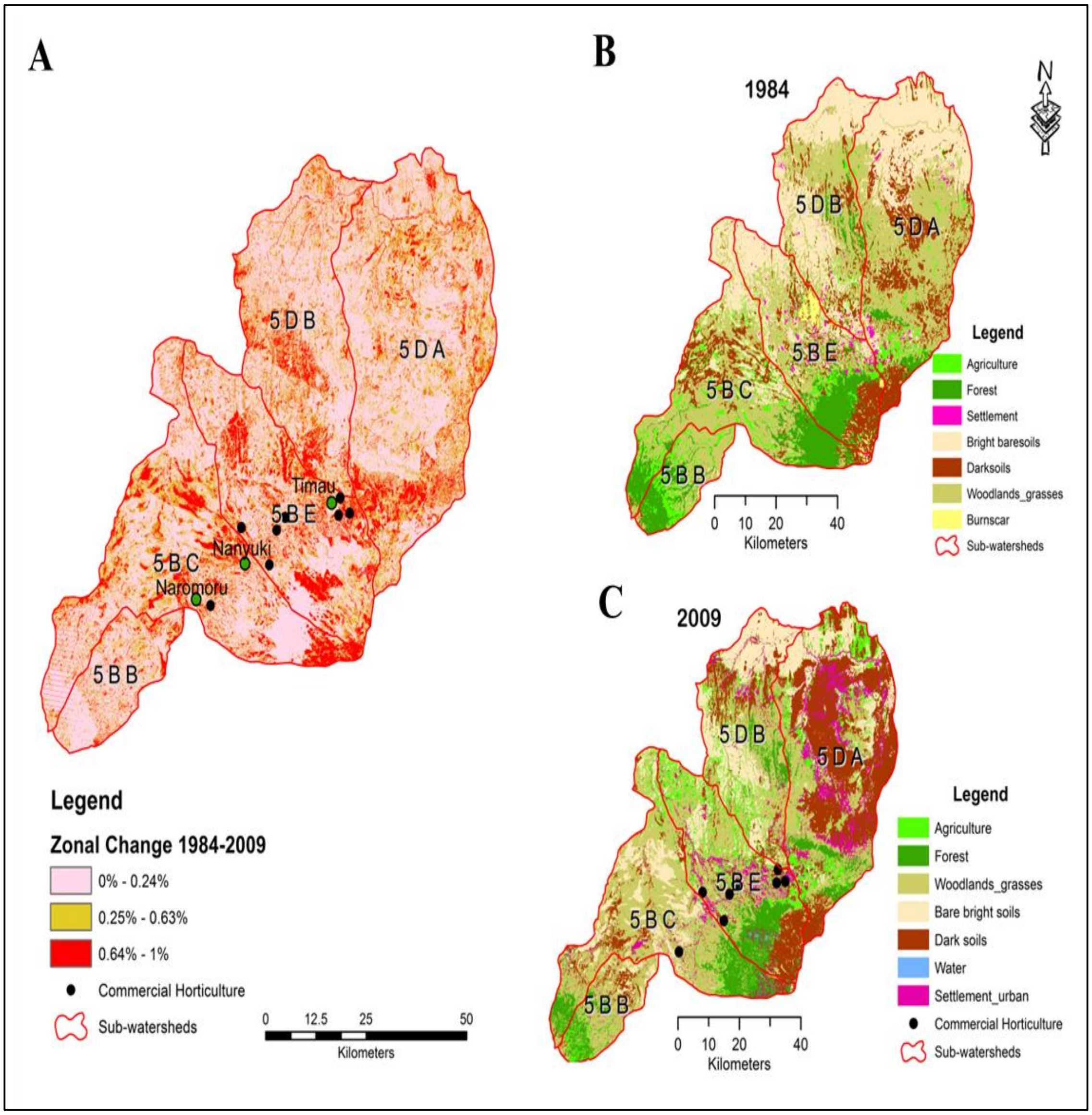

Figure 5-2A-C: Illustrates the land use and land cover types for Laikipia between 1984 and 2009. (A) Change detection results via image differencing, (B) LULC in 1984 (C) LULC in 2009.

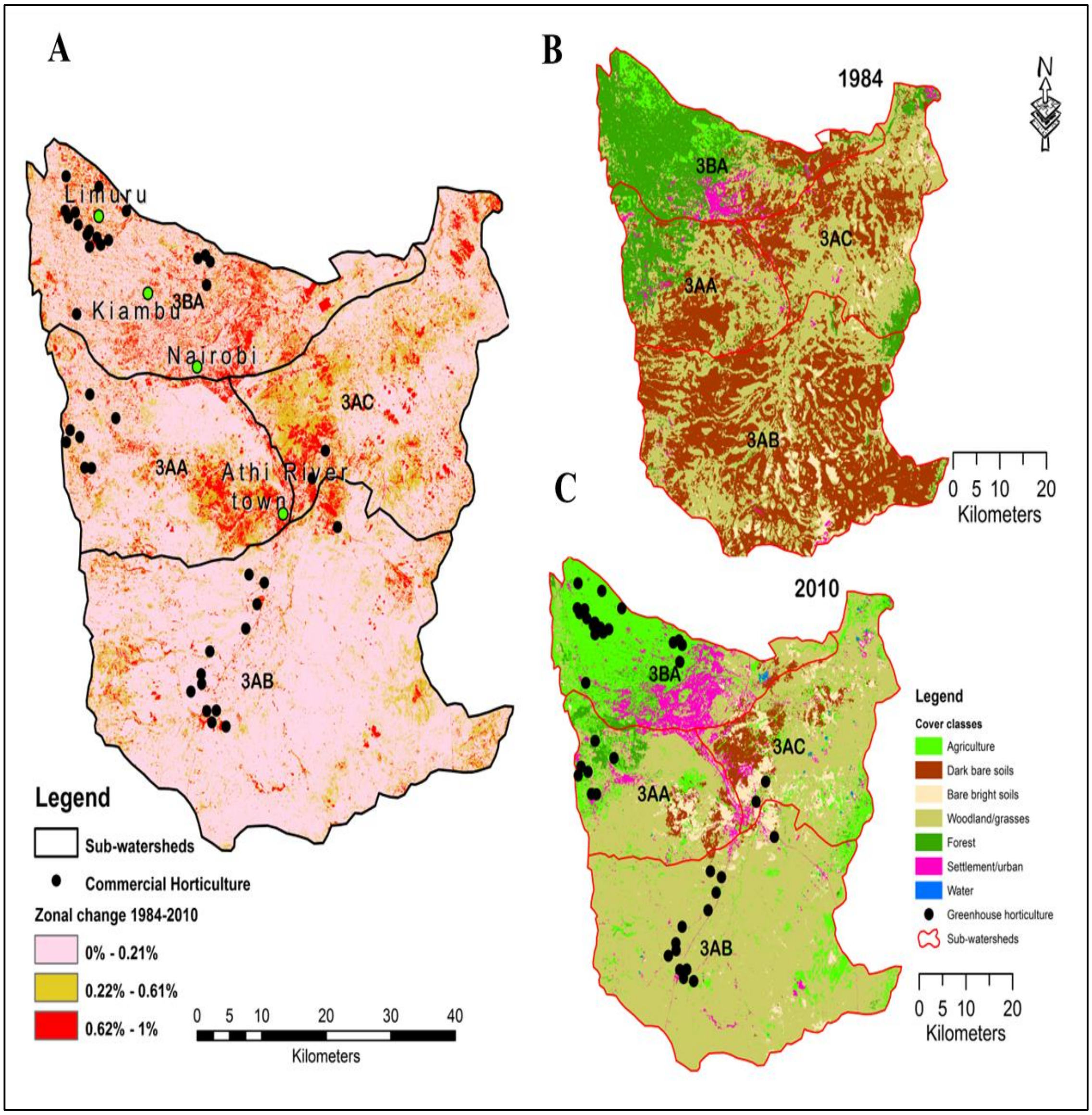

Figure 5-3A-C: Illustrates the land use and land cover types for Athi River region between 1984 and 2010. (A) Change detection results via image differencing, (B) LULC in 1984 (C) LULC in 2010.

Misclassification (Lu et al., 2003) of cover types while using MLC in remote sensing data is a common challenge often rectified by integration other geo-rectified data such as previous classified results, transportation networks, digital elevation models (Jensen, 1996, 2005) to correct the misclassifications.

Table 5-3. Shows percent corrects classifications and kappa statistics for all cover types for the dates (2010/2009 and 1984)(Manandhar et al., 2009).

	Athi River study area				**Laikipia study area**			
	2010		**1984**		**2009**		**1984**	
Classified land cover/use types	User accuracy	Producer accuracy	User accuracy	Producer accuracy	User accuracy	Producer accuracy	User accuracy	Producer accuracy
Agriculture	89.6	88.8	93.2	95.8	87.0	86.9	97.6	95.3
Dark soils	82	77.8	85.3	85.3	78.3	77.8	75.8	92.9
Bright soils	100	75.6	95.0	93.8	72.5	75.6	64.3	75.5
Woodlands/grasses	87.3	96.5	71.8	100.0	85.7	93.3	80.6	87.5
Forest	100	100.0	96.9	81.6	76.7	100.0	73.5	76.7
Settlement	85.7	92.3	81.0	100.0	85.7	75.0	87.5	100
Water	66.6	100.0	73.4	83.3	66.7	100.0	87.0	87
Google Earth reference points	*125*				*300*			
Overall classification accuracy((	OA= 88.6%		OA= 89%		OA= 80%; K=0.74		OA=85%	
Overall Kappa statistics (K)	K= 0.82		K= 0.82				K=0.78	

5.3.1.2 Changes in cover area in Laikipia region

In both time periods Laikipia study area (6852.5 sq. km) was predominantly covered by woody grassland (WG), bare bright soils (BAR), and dark barren soils (DAR), with proportions varying between 14.5% and 37.5% (Table 5-4) . Forest (FOR) cover, agriculture (AGR), and settlement/urban occupied lesser proportions of the total area cover (Table 5-4).

Table 5-4. Coverage (in sq. km) for each LULC category in 1984 and in 2009/2010, changed area and the percentage annual rate of change during the study period in Laikipia.

	2009		**1984**			**Annual rate of change (change in area/time)**	**% annual rate of change**
Cover class	**Cover area (sq. km)**	**% Cover area (sq. km)**	**Cover area (sq. km)**	**% Cover area (sq. km)**	**Change (sq. km)**		
AGR	659.1	9.6%	496.3	7.2%	162.8	6.5	1.3%
WG	2351.0	34.3%	2573.1	37.5%	-222.1	-8.9	-0.3%
BAR	1260.9	18.4%	1936.2	28.3%	-675.4	-27.0	-1.4%
DAR	1457.6	21.3%	994.2	14.5%	463.4	18.5	1.9%
FOR	574.9	8.4%	699.4	10.2%	-124.5	-5.0	-0.7%
SET	513.8	7.5%	85.1	1.2%	428.7	17.1	20.2%
BSCAR	0.0	0.0%	68.2	1.0%	-68.2	-2.7	-4.0%
WAT	2.5	0.0%	0.00	0.0%	2.5	0.0	0.0%
CLD	33.0	0.5%	0.0	0.0%	33.0	1.3	0.0%
Total area (sq. km)	6852.7	100.0%	6852.5	100.0%			

Note: AGR= agriculture; WG= woodland and grasslands; BAR = bare bright soils; FOR = forest; DAR= dark soils and wet areas; SET = settlement/urban; BSCAR= burn scar; WAT= water; CLD=cloud and cloud shadow.

Results show dynamic changes in cover proportions that occurred between 1984 and 2009. For example, area under agriculture (AGR) increased from 496.3 sq. km

(7.2%) to 659.1 sq. km (9.6%) at an annual rate of 6.5 sq. km/year. WG which occupied vast cover area in both time periods (i.e. 37.5% and 34.3% respectively) declined by -222.1 sq. km, indicating an annual loss of -8.9 sq. km/year. BAR had the highest decline in cover (-675.4 sq. km), losing about -27 sq. km of land area annually (-1.4%). DAR increased from 994.2 to 1457.6 sq. km (7%), which was attributed to fallow agricultural lands during the off season agriculture period in the region. Besides, frequent droughts and poor rainfall in region (Funk et al., 2003; Pricope et al., 2013) linked to changes in climate and affect terrestrial vegetation, reducing existing cover types to bare grounds, and therefore the observed increase in DAR.

The burn scar in 1984 imagery (68.2 sq. km) changed to other cover types by 2009 (Figure 5-2). Results also indicate a decline in forest cover (-124.5 sq. km) during the study period, at an annual rate of -5 sq. km. This change was relatively minimal considering changes in the other main cover types in the area. Mount Kenya forest is the primary forest in this study area, and strongly influence the micro climate of the region. It was declared a biodiversity hotspot following rapid deforestation in the early 1980s, which perhaps explain the observed minimal rate of cover decline. Even so, controlled farming occurs on the forest edges, with plots allocated to farmers who tend to tree nurseries under the afforestation program.

The area under water increased from merely 0.001 sq. km to 2.5 sq. km. This increase is attributed to increased water abstraction into ponds/dams for irrigation water. The rapid rise of commercial horticulture increase in the region (Justus & Yu, 2014;

Ulrich, 2014), prompted an increase in surface water abstractions points as reported in (Aeschbacher et al., 2005; Kiteme & Gikonyo, 2002).

Interesting, the area under settlement/urban use (Table5-4) increased intensely by 428.7 sq. km, at an annual rate of 17.1 sq. km (20.2%). This was by far the highest increase in cover/use area in the region for the last 25 years. However, this was not unexpected given the migration of rural populace in search for employment and land for development goals.

Considering the percentage annual rate of change for the different LULC categories, BAR, FOR and WG declined annually at –1.4 %, 0.7% and -0.3% respectively, while SET, DAR and AGR increased annually at 20.2%, 1.9%, and 1.3% respectively.

Change detection results via image differencing approach (Figure 5- 3A) indicated varied spatial changes in pixel values. The regions with a deep red color indicate areas where the change in pixel value varied between 0.64% and 100% (100 % being a total change in pixel value) between 1984 and 2009/2010. The values between 0.26% and 0.63% indicated areas of moderate change, while 0% to 0.25% represented regions where little to no change in pixel value occurred. High change was noticeable in sub- watersheds 5BE and 5BC, while the rest of highly changed area are along the border lines of the forest where wheat plantations extend into former forested area. Moreover, areas experiencing a decline in WG and the re-growth on the burn scar in 1984 classification image are shown as red or yellow color transitions where the change was not very high.

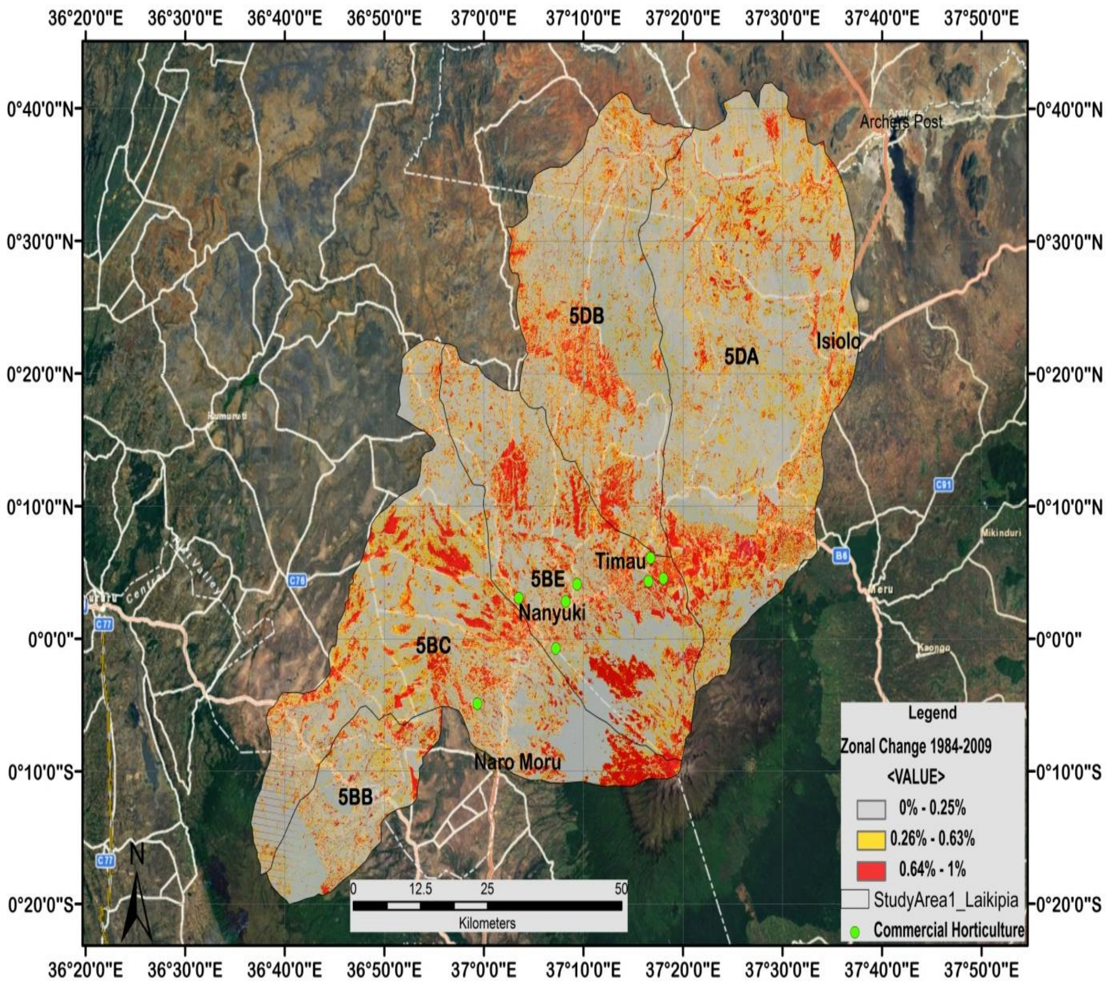

Figure 5-4: Change detection by image differencing output for Laikipia.

5. 3.1.3 Changes in cover area in Athi River region

In 1984, Athi River study region was primarily covered by woody grasslands (WG) and dark bare soils (DAR) occupying 1699.0 sq. km (40.5%) and 1538.2 sq. km (36.6%) respectively (Table 5-5). These proportions changed tremendously by 2010, where WG increased to 2611.6 sq. km (62.2%) and the DAR declined from 36.6% to 3.8%. The change in DAR cover (-1378.7 sq. km) indicated an annual percentage decline of -3.4% during the 26 year period. The area under agriculture (AGR) increased from just

1.8% to 18.9% (Table 5-5), at an annual rate of change of 27.7 sq. km. Based on the results, AGR had the highest percentage annual rate of .change (37.3%), followed by the area under water (17.2%). The increase in AGR area, concurrently to increase in area under water was most perhaps a result of increased dams and water storage ponds for irrigation agriculture, and open sewage reservoir near the city. Clusters of horticultural greenhouses are observed in the upper part of the study area towards Limuru in Kiambu district, and the lower southern parts (Figure 5-1B). The clusters were not present in 1984 image, but developed at later dates. Unlike rain-fed agriculture, intensive horticulture utilizes all-year round irrigation systems for crop production. Furthermore, the expansion of the Nairobi city and the sub-urban (UNEP, 2002) prompted need for food supplies prompting a rapid conversion of cover to agricultural land. In fact, the results show significant increase in settlement/urban use from 85.4 sq. km to 272.8 sq. km (8.4%). Dark bare soils (DAR) and forest cover (FOR) declined annually by 53 sq. km and 21.9 sq. km respectively.

Considering the two study area, the observed percentage annual rate of change between cover classes in Athi River were higher, and with a smaller total land area (4199.1 sq. km) compared to Laikipia which has a total land area of 6852.0 sq. km. The increase in LULC was in the order of AGR<WAT<SET<BAR<WG (37.7%, 17.2%, 8.4%, 3.9< and 2.9% respectively) while DAR<FOR declined at -3.4% and -3.3%.

Table 5-5. Land cover area, changed area and the rate of change over 26 years (1984-2010) in Athi river region.

Cover class	2010 Cover area (sq. km)	2010 % Cover area (sq. km)	1984 Cover area (sq. km)	1984 % Cover area (sq. km)	Change area (sq. km)	Annual rate of change (change /time)	% annual rate of change
AGRI	794.6	18.9%	74.2	1.8%	720.3	27.7	37.3%
SET	272.8	6.5%	85.4	2.0%	187.4	7.2	8.4%
BAR	256.1	6.1%	126.8	3.0%	129.3	5.0	3.9%
WG	2611.6	62.2%	1699.0	40.5%	912.5	35.1	2.1%
DAR	159.5	3.8%	1538.2	36.6%	-1378.7	-53.0	-3.4%
FOR	97.9	2.3%	668.4	15.9%	-570.5	-21.9	-3.3%
WAT	6.62	0.2%	1.21	0.03%	5.4	0.2	17.2%
CL	0.00	0.0%	5.83	0.1%	-5.8		
Total Area (sq. km)	4199.1	100.0%	4199.1	100.0%			

Note: AGR= agriculture; SET= settlement/urban; BAR= bare bright soils; WG= woodland/grasslands; DAR= dark soils and wet areas; FOR = forest; WAT= water; CL=cloud and cloud shadow.

The change detection results (Figure 5-4) illustrate major changes in pixel values (deep red color) around Athi river town and Nairobi city, patterns consistent with expansion of settlement/urban use in the classification result of 2010 (Figure 5-3). Besides increasing economic activity around the city, the reported spread of greenhouse horticulture in lower zones of the study area (Kithiia, 2012b) could partially explain the detected high to moderate changes in pixel values, implying changes in LULC. Most farm workers commute between Athi river town center and the farm locations, which explain the concentrated changes around the town. Moderate to high change in pixel values occurred around Limuru, Kiambu, as indicated by the yellow to red colorations, identifying wider regions of cover transformation likely result of urban sprawl and expanding cultivation.

5.3.2 Land covers transformation

5.3.2.1 Laikipia

The transition matrix (Table 5-6) highlights changes that occurred between LULC classes during the 25 years of study. The bold diagonal numbers indicate the cover area (sq. km) that remained unchanged between 1984 and 2009, while the other numbers show the area of specific LULC (sq. km) that changed to another class. The magnitude of change from one class to another varied between the two dates.

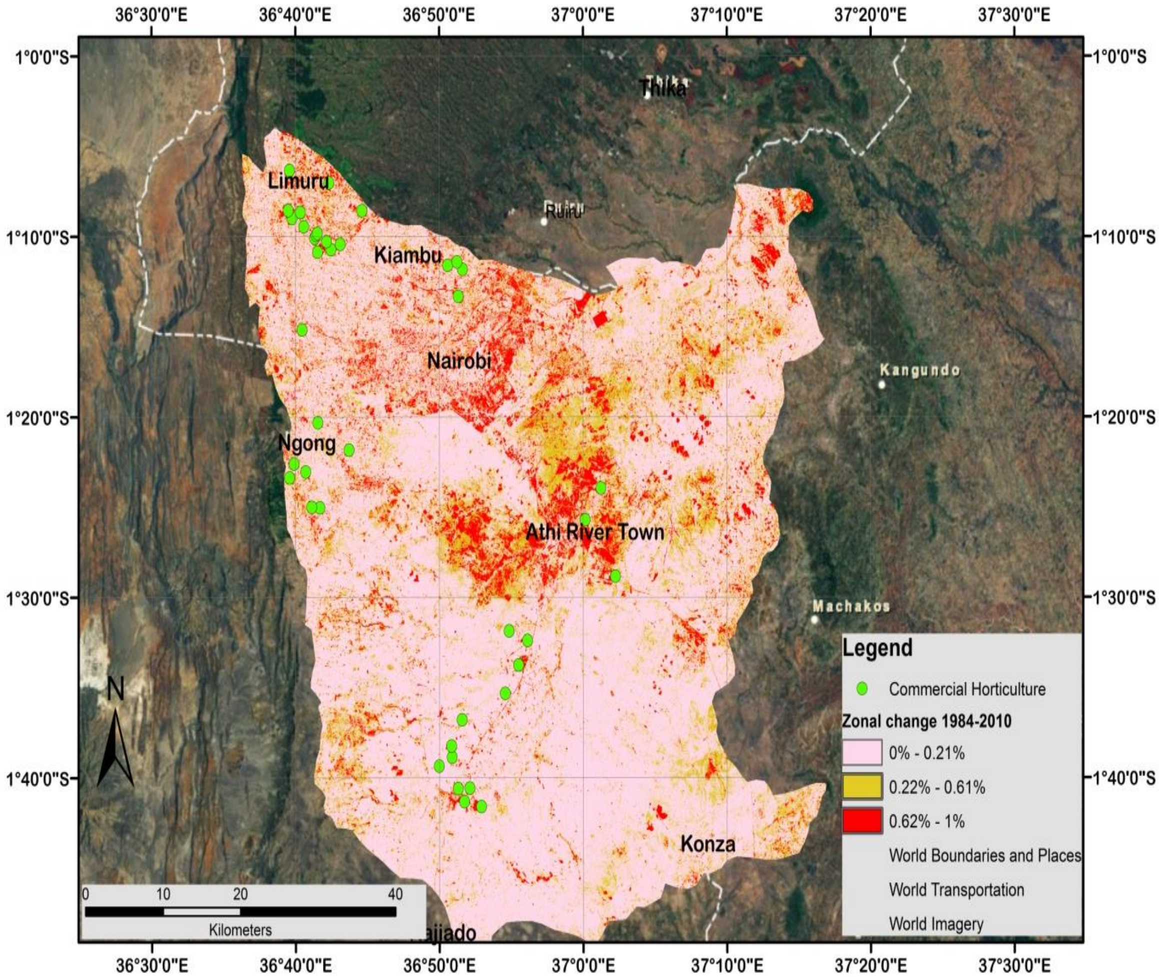

Figure 5-5: Change detection by image differencing output for Athi river region.

For example, along the row of woodland and grasslands (WG), 250.1 sq. km of WG cover were converted to AGR, 1270.2 sq. km remained unchanged, 284.9 sq. km was changed to BAR, 477.5 sq. km changed to DAR, 89.8 sq. km changed to FOR, 197.9 sq. km changed to SET, 0.1 sq. km changed to water and 2.6 sq. km was cloud cover and shadows.

The entire burn scar area (BSCAR 100%) transitioned to WG and DAR at 25.7 and 22.4 sq. km respectively, by 2009 (Table 5-6).This was a reasonable finding given the arid to semi-arid climate in the region, which mainly supports vast grasslands that characterize savanna ecosystems. Fire episodes are common in savannas, and essentially promote re-generation of new vegetation cover promoting life.

Large area under FOR remained unchanged (419.3 sq. km),(Table 5-6, and Table 5-7) which as explained earlier, is attributed to international recognition of the region as a rich harbor for threatened reservoirs of plant and animal life (UNEP, 2008) and therefore increased surveillance to monitor illegal deforestation and charcoal burning on the forest lines. Even so, some portions of forest cover changed to other LULC e.g. WG (185 sq. km), SET (30.9 sq. km) (Table 5-6).

A summary of cover classes that underwent change, or remained unchanged during the study period is shown in Table 5-7. Notice that the percentage unchanged represents the percentage area of the original area (1984s) which remained unchanged for the duration of study, while the percentage changed represent specific cover class area that changed to other classes. Agriculture cover changed to other forms by 94%, woodlands and grassland by 51%, bare soils bright soils by 58%. Interestingly, a small area remained under agriculture (31.1 sq. km) by 2009. This was unexpected given the increased large-scale greenhouse commercial horticulture in the region.

However, given that the greenhouses have plastic covers, the pixel signature was interpreted as settlement or urban, and not agriculture use.

Table 5-6. Change detection matrix for different LULC categories (in sq. km) between 1984 and 2009 for Laikipia.

Cover in 1984 (sq. km)	**Cover in 2009 (sq. km)**									
	AGR	**WG**	**BAR**	**DAR**	**FOR**	**SET**	**BSCAR**	**WAT**	**CL**	**Total**
AGR	**31.1**	238.3	87.9	44.2	32.3	61.2	0.0	0.1	1.1	496.19
WG	250.1	**1270.2**	284.9	477.8	89.8	197.6	0.0	0.1	2.6	2573.13
BAR	150.9	299.9	**816.9**	355.1	2.0	309.8	0.0	0.1	1.1	1935.82
DAR	52.9	317.8	40.1	**529.0**	28.5	20.6	0.0	0.1	5.3	994.25
FOR	16.4	185.0	1.2	23.3	**419.3**	30.9	0.0	2.2	21.1	699.40
SET	9.9	13.3	25.1	6.0	1.0	**29.0**	0.0	0.0	0.8	85.12
BSCAR	2.5	25.7	5.3	22.4	1.9	9.5	**0.0**	0.0	1.0	68.21
WAT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	0.0	0.01
CL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**	0.00
Total	513.7	2350.2	1261.4	1457.8	574.81	658.6	0.0	2. 54	32.8	6852.1

Note: AGR= agriculture; SET= settlement/urban; BSAR= burn scar; BAR= bare bright soils; WG= woodland/grasslands; DAR= dark soils and wet areas; FOR = forest; WAT= water; CL=cloud and cloud shadow. The diagonal bold numbers indicate cover areas that remained unchanged between 1984 and 2009.

Table 5-7. Observed percentage changes of respective cover classes in Laikipia between 1984 and 2009.

Cover class	**Unchanged**	**Changed**	**% Cover unchanged**	**% Cover changed**
Agriculture	31.1	465.1	6%	94%
Woodlands/grasslands	1270.2	1302.9	49%	51%
Bare bright soils	816.9	1118.9	42%	58%
Dark bare soils	529.0	465.3	53%	47%
Forest	419.3	280.1	60%	40%
Settlement/urban	29.0	56.2	34%	66%
Burn scar	0.0	68.2	0%	100%

Rain-fed agriculture is highly dependent on ample rainfall, and therefore rainfall fluctuations and unpredictability could limit agricultural yield and therefore a decline in agricultural area. This explanation suffices for the observed moderate percentage change in bare bright soils (58%) and woody grasslands (51%). Low or decline in vegetative cover exposes soils with varying degree of mixed backgrounds.

5.3.2.2 Athi River region

The transition matrix for Athi River is shown in Table 5-8. The bold numbers on the diagonal illustrate the cover area which remained unchanged between the two years, while the other numbers (sq. km) illustrate the changes to other cover/use classes. LULC change between classes was highly dynamic, with widespread cover conversion. For instance, along the row of WG 179.6 sq. km was changed to agriculture (AGRI), 112.6 sq. km to settlement/urban (SET), 187.6 sq. km to bare bright soils (BAR), 1157.4 sq. km remained unchanged, 50.6 sq. km to dark bare soils (DAR), 8.6 sq. km to forest (FOR), and 2.6 sq. km was covered by water (WAT).

Table 5-8. Change detection matrix for different LULC categories (in sq. km) between 1984 and 2010 for Athi River.

Cover in 1984 (sq. Km)	**Cover in 2010 (sq. km)**								
	AGRI	**SET**	**BAR**	**WG**	**DAR**	**FOR**	**WAT**	**CL**	**Total**
AGRI	**64.4**	3.3	0.1	2.8	0.0	3.5	0.0	0.0	74.2
SET	13.6	**42.6**	5.1	19.1	2.2	2.3	0.5	0.0	85.4
BAR	3.7	0.6	**15.7**	106.5	0.1	0.1	0.2	0.0	126.8
WG	179.6	112.6	187.6	**1157.4**	50.6	8.6	2.6	0.0	1699.0
DAR	102.3	60.6	42.1	1223.8	**104.8**	2.3	2.4	0.0	1538.2
FOR	429.9	52.3	4.8	99.3	0.3	**81.0**	0.7	0.0	668.4
WAT	0.6	0.2	0.0	0.1	0.0	0.1	**0.2**	0.0	1.2
CL	0.5	0.6	0.7	2.5	1.5	0.0	0.0	0.0	5.8
Total Area	794.6	272.8	256.1	2611.6	159.5	97.9	6.6	0.0	4199.1

Note: AGR= agriculture; SET= settlement/urban; BAR= bare bright soils; FOR = forest; CL= cloud-cloud shadow. The diagonal bold numbers indicate unchanged cover 1984 and 2010.

Table 5-9. Observed percentage changes of respective cover classes in Athi River between 1984 and 2010

Cover class	Unchanged	Changed	% Cover unchanged	% Cover changed
Agriculture	64.4	9.9	87%	13.3%
Settlement/urban	42.6	42.8	50%	50.1%
Bare bright soils	15.7	111.1	12%	87.6%
Woodlands/grasslands	1157.4	541.6	68%	31.9%
Dark bare soils	104.8	1433.4	7%	93.2%
Forest	81.0	587.4	12%	87.9%
Water	0.2	1.0	16%	83.9%

The results in Table 5-9 present a summary of changed and unchanged cover classes between 1984 and 2010 in the Athi River study area. The percentage cover unchanged illustrate the percentage of a certain cover class that remained unchanged, while percentage changed represent the percentage cover area that changed to other land cover/use between the study dates. The area originally under agriculture underwent the least change (13.3%), while 1433.4 sq. km (93.2%) of DAR cover changed to other LULC classes, primarily WG (1223.8 sq. km) as shown in Table 5-8. Increase in WG was perhaps due to a general increase in greenness as the scene was obtained during a rainy season prompting an over estimation of cover compared to the 1984 imagery. Never the less, the study area is dominated by grasslands and low shrub cover, a similar situation with Laikipia climate-vegetation regimes.

There were tremendous changes in forest cover (87.9%) with 587.4 sq. km converted to other uses (Table 5-9). From the LULC cover map (Figure 5- 3), the expansion of Nairobi city and growth of suburbs towns, industrial centers and mining companies on the periphery of the city enhanced LULC transformation. Reports indicate that towns of Athi River and Mlolongo town (in sub-watershed 3AB), have emerged as strong grounds for horticulture farming and industrial growth in recent years (UNEP, 2008), a finding corroborated by Justus and Yu (2014). Expansion of intensive horticulture into arid and semi-arid marginal areas has implications for rangelands managements and resource use.

5.3.3 Population density and LULC dynamics

This section examines the classification results in conjunction with population trends in the sub-watersheds (Figure 5-6A-B). In both study areas, 1999 had the highest number of people per sq. km in the sub-watersheds, but this declined in 2009. In fact, the decline was way below the 1989 trend for Laikipia sub-watersheds except 5BB (which neighbors very populous areas along foot zones of Aberdare ranges).

The rapid increase in population density in 1999 is attributed to influx of people into the regions following expansion of, and economic vibrancy brought about by the regional horticulture farming. This increase in population density of the sub-watersheds, plausibly explain the observed increase in area under settlement (20.2%) between 1984 and 2009 in Laikipia (Figure 5-6). This was exceptional in that all other annual percentage rates of cover change were within a range of 1% to 2%, except the burn scar that entirely transformed. Recent decline (2009 is the latest census in Kenya) in population density in both study area could imply movement of people to other areas. It is also possible that the 2008 post-election violence affected demographic structure in these regions, pushing "immigrants" out, as a result of ethnic-political issues/instigations. Reports indicate that the horticulture sub-sector suffered huge loss following the violence, due to poor employee turn outs at work places (Ksoll et al., 2009, 2010).

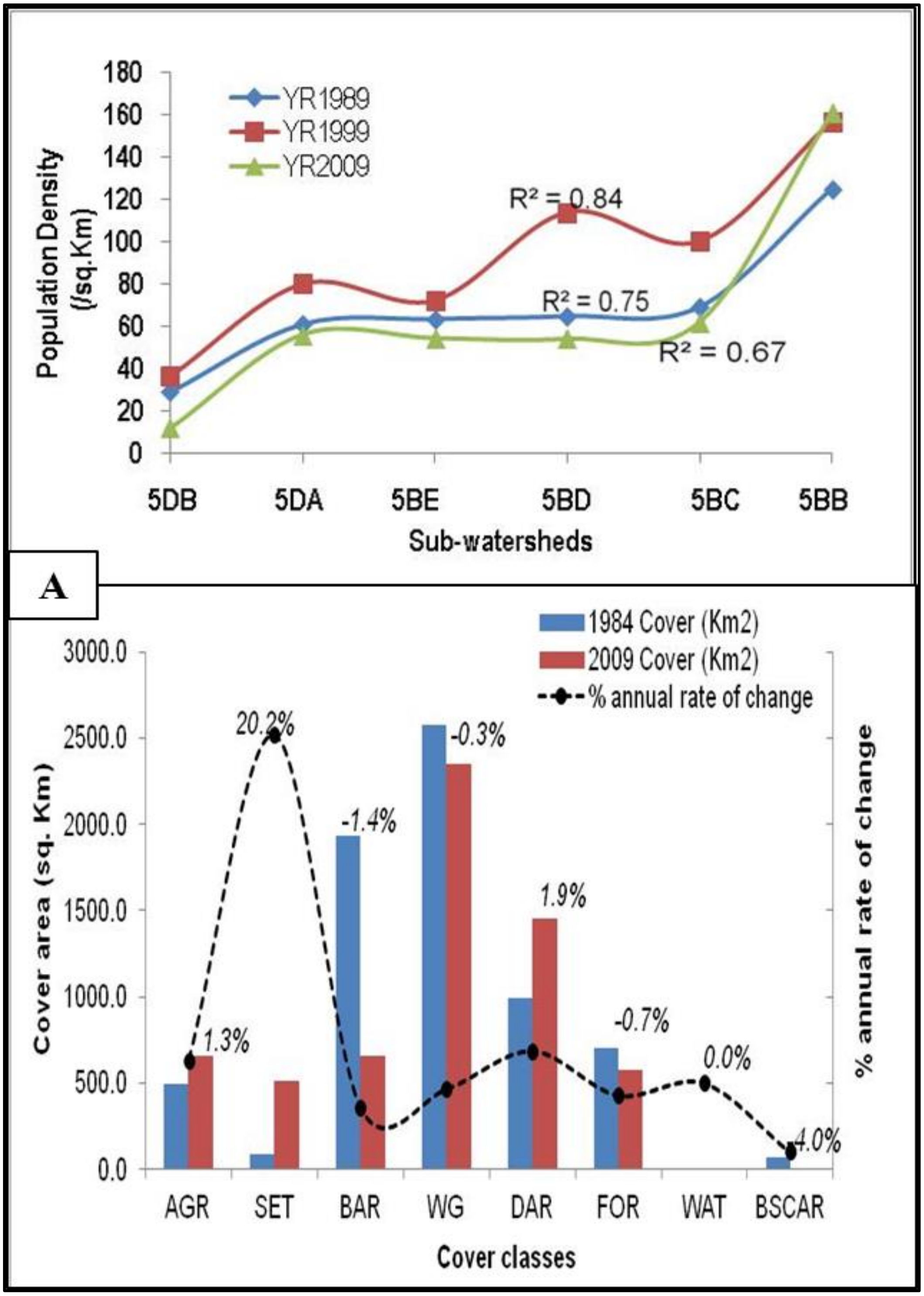

Figure 5-6A: A) Population trends (1989, 1999, and 2009) in the sub-watersheds and LULC dynamics in Laikipia study area

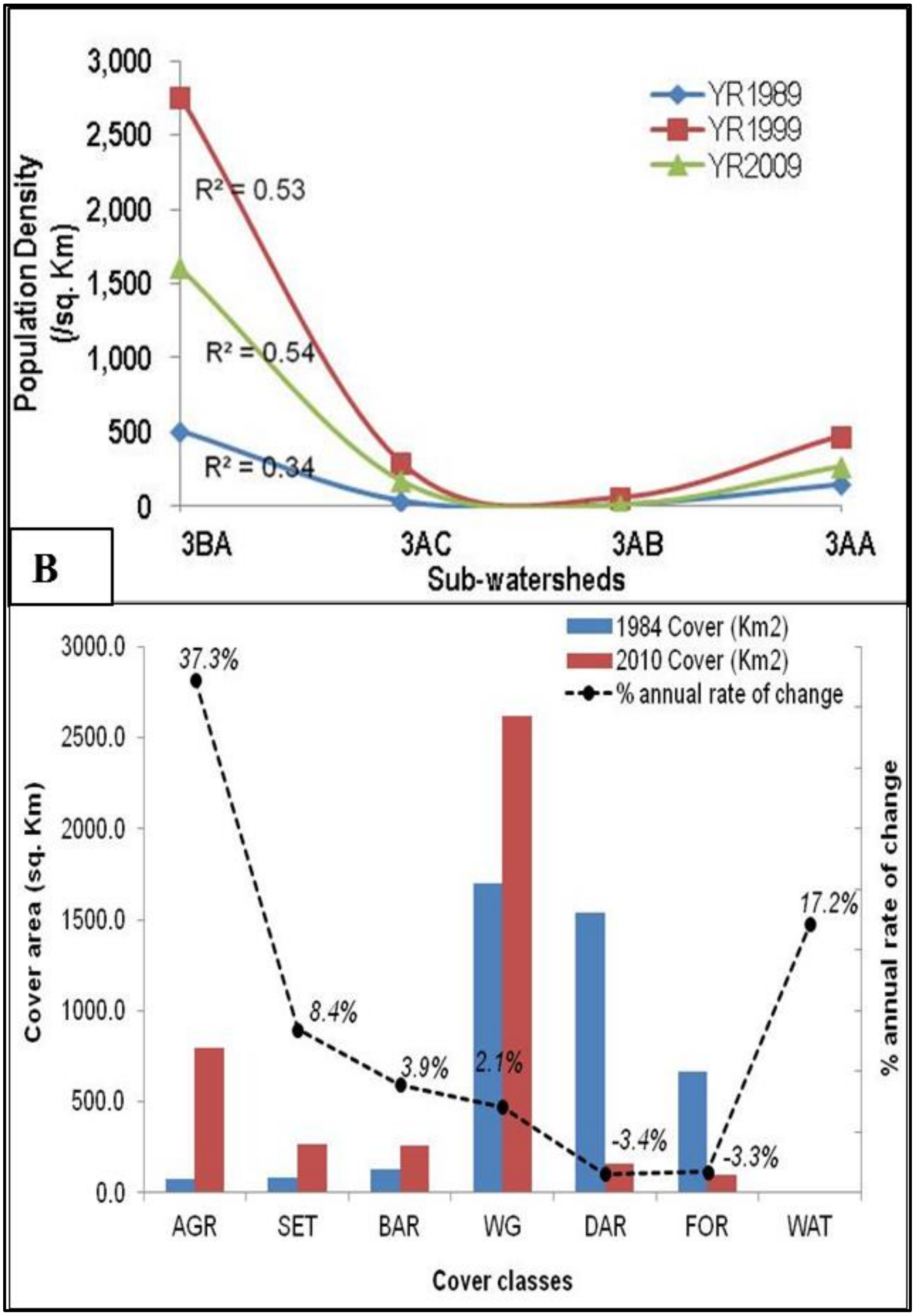

Figure 5-6B: B) Population trends (1989, 1999, and 2009) in the sub-watersheds and LULC dynamics in Athi River study area

In Figure 5-6B, sub-watershed 3BA (which is shared by Nairobi and Kiambu counties) has had high population density through time. The rapid urban growth of Nairobi city during the last three decades has played a big role in land transformation due to influx of migrating population in search of employment and economic gains. Following the implementation of the economic reforms and open-door policy after independence (1963), enormous population moved from rural to urban areas. The effect of increased population density (Figure 5-6B) for example in sub-watershed 3BA enhanced LULC transformation, associated with characteristic settlement problems and environmental degradation (Olima, 2001). Emerging sub-urban towns in the outer skirts of the city, also rapidly influence LULC transformation. For instance, Athi River town was largely an industrial and mining center, but has greatly transformed following influx of large-scale horticulture companies. Altogether, unlike Laikipia where settlement/urban use increased parallel to increase in population density (1989-1999), in Athi River, agriculture use had a remarkable annual increase (37.3%), followed by area under water (17.2%) and settlement/urban (8.4%).

Increased demand for agricultural food commodities by the expanding city population reasonably explains the observed spike in percentage annual increase in land under agriculture and water. Intensive small-holder farming and greenhouse horticulture farming are common in Limuru and other parts of Kiambu districts, forming a key source for agricultural produce. Good road networks within the cities, to the Jomo Kenyatta International Airport *etc.* provide means to deliver produce to target markets. These changes have affected other cover classes; FOR and DAR, which have declined at -3.3 and – 3.4% respectively.

5.3.4 Variations in detected changes and limitations

Classifying cover in the highly heterogeneous landscape of very bright to very dark surfaces, mosaics of low grass cover and interspaced with woody shrubs and agriculture presented an interesting situation. Using few LULC classes produced in accurate representation of cover types, however, this was overcome by increasing the number of cover classes and selecting separable signatures, providing more accurate land cover maps. These are important factors towards achieving satisfactory classification results.

Also, during classification some LULC categories were spectrally mixed making it difficult for complete separation following the supervised classification. For example, problems were encountered in classification of green landscapes within settlement/urban areas, with some pixels erroneously classified as agriculture use especially within Nairobi city, Athi River towns. The 2010 classification output for Athi River show a vast area under WG, which at first present the impression of over-estimation of the cover type. However, the date of imagery coincide with a rainy season, which may explain the overly WG cover. On contrary, Athi River basin has a high percent of grass cover mixed with low shrubs, typical of savanna lands (Kithiia & Ongwenyi, 1997). This can be confirmed from the grasslands data layer created by World Resource Institute (WRI) and used as overlay in Figure 5-1B. Water coverage in Laikipia in 1984 appears underestimated, mainly due to poor signatures. Surface waters had substantial cover along banks which introduced mixed pixels and therefore misclassification as green corridors of agriculture/woodlands along the waterways. To improve the final LULC results, an ArcGIS overlay was applied and each cover class visually examined to counter check accuracy of classification, thereby increasing accuracy and the quality of the LULC maps (Shalaby & Tateishi, 2007).

5.3.5 Implications

The proportion of agriculturally productive land in both study regions is small compared to the vast arid and semi-arid land (ASALs) primarily covered by grasslands ecosystem. Grasslands are rich in biodiversity and concurrently represent fragile environments that are extremely vulnerable to habitat destruction (Hogan, 2012; Shiyomi & Koizumi, 2001). The occurrence of grassland on easily farmed topography invite for monoculture production, livestock keeping *etc* that transforms the landscape. As such the rapid decline of grassland ecosystems due to human activities is linked to dramatic loss in biodiversity and decline of keystone species (Ceballos et al. 2010).

In the ASALs of sub-Saharan Africa, anthropogenic interference enhances effects of aridity and land degradation, causing high erosion rates and evapo-transpiration from bare land surfaces. This is a common problem that challenges resource management and conservation, and necessitate urgent tactics to improve the condition of grasslands (MEA, 2005).

In Kenya, conservation efforts to protect remaining patches of forests around the city of Nairobi for istance, Karura forest, Ngong forest, are manned through the ministry of Natural Environment Management Agency (NEMA). However, these efforts are often complexed by ineffective policies and corruption issues. Besides, positive growth of the horticulture sub-sector is an important economic engine to the country, through improved Gross Domestic Product (GDP), foreign income from fresh produce exports and job creation.

Even so, it is important to evaluate LULC impelled by expansion of the sub-Sector, and therefore seek sustainable approaches to achieve positive socio-economic growth while practicing stewardship of the natural environment and its resources. Egoh *et al.* (2011) show that focusing conservation on areas that are important for provision of various ecosystem services could benefit biodiversity and vice versa, and more so if similar management regimes are needed. High population density within the sub-watersheds creates competition for food and land, which implies that both agricultural systems, and the remaining natural landscapes, are vulnerable to continued degradation, increasing biodiversity loss (Tilman et al., 2001) and dysfunctional ecosystems (Hector & Bagchi, 2007).

The study results are helpful for policy makers to better understand and address the complex relationships between LULC, population growth, urbanization, and environment. Considering the findings, important policy suggestions may include intensifying the regulation and administration of urban land, balancing cultivated land

and forestry, and encouraging the development and utilization of unused land if environmental impact assessments permit. Comparable suggestions have been proposed for rapidly growing urban areas (Yang et al., 2012). Other studies (Ikiel et al., 2013) propose encouraging the use of unexploited land by local government to reduce environmental damage and relieve pressure on the land demand for urban use.

5.4 Conclusion

An investigation was carried out to determine the dynamics of LULC changes in sub watersheds within Laikipia and Athi regions, regions experiencing an increased growth of intensive commercial horticulture, and population growth. The study integrated various approaches to understand occurring LULC changes and likely environmental effects. The specific objectives were; to develop maps of LULC, quantify the dynamics and rate of LULC change and an evaluation of population trends in the sub-watersheds. Remote satellite data obtained from Landsat-5 (MSS, TM), Landsat-7 +ETM sensors and census demographic data were utilized. The supervised classification results were assessed for accuracy using Google Earth archived images, and counter checked with prior land cover map, obtaining reasonable moderate to high accuracy levels in overall accuracy, user accuracy, producer accuracy and Kappa statistic. Post classification change detection enabled identification of localities of change, amount and type of change and the rate of change from one use to another between the periods of study.

From the results, both study areas have undergone notable changes in LULC in the 25-26 years of study. Agriculture and settlement/urban centers increased, and more so in Athi

River, with land transformation advancing towards more marginalized semi-arid areas of the sub-watersheds, that used to be pastoral grounds/ranches and wildlife habitats. Concurrently, forest cover declined tremendously and more-so in the upper north zones of the Athi River basin, a likely result of increased intensive horticulture and population expansion. Expansion of Nairobi city and the connecting infrastructure development is good for economic growth. For horticulture growers, the city provides a closer and ready market for the produce, and also faster access to cargo freights to international markets. However, inability to balance the social – economics with the environmental needs makes such expansion chaotic and unsustainable.

From an environmental management stand point, the rapid and vast transformation of land within the fragile unstable arid to semi-arid (ASALs) sub-watersheds in the study area is unsettling. This is because LULC changes in such areas pose increased vulnerability to climate variations and related impacts on resources, people etc. ASALs are dominated by grasslands and woodlands, which support a high diversity of wildlife, promoting local and international tourism and therefore the need for better management. Conserving forested areas, controlling encroachment into fragile landscapes and monitoring rates of LULC transformation are necessary precautions towards improving overall health of the watersheds. This understanding will aid development of policy and regulatory measures that address the challenges in watershed resource use and management. Efficient management strategies allow delivery of multiple ecosystem services, (e.g. through better land use policies), while conserve threatened biodiversity (Mt. Kenya and the grasslands ecosystems). This is important and very crucial given increasing human induced pressures on habitats, and the apparent effects of climate variability in the region.

5.5 References

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CHAPTER 6

Coupled Effects on Kenyan Horticulture following the 2008/2009 Post-election Violence, and the 2010 Volcanic eruption of Eyjafjallajökull

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Abstract

In chapters 2, 3, 4 and 5, the research established the spatial extent of intensive greenhouse horticulture farming, and assessed the impacts on environmental resources (surface water, vegetation). There are numerous socio economic benefits of the sub sector. This prompts a need to develop methods that seeks to balance horticulture production and the sustainable use of resource to minimize the environmental cost. This chapter demonstrates that despite the positive growth in horticultural exports; the sub-sector is vulnerable to external effects (such as political instability and natural calamities) which can cause significant economic impacts, impeding growth and development of the sub- sectors. We evaluated the impacts of two events, 1) the 2008 post-election violence, and 2) the 2010 Icelandic volcanic eruption, on the Kenyan horticultural exports. The findings showed a positive increase in exports until 2008/2009, where the trend declined continuously hitting lowest volume in 2010, particularly the month of December which coincided with a rainy, low production season. There were significant differences in export volumes between the groups, where cut-flowers lead in export, followed by vegetables and fruits. Interestingly, unlike cut-flowers and vegetables, the fruit exports increased after the two events. Plausible explanation s included changes in farmer

preferences to fruit production (less labor and less nutrient applications comparative to cut-flower and vegetables); and improved local and regional markets. The findings of the current study present important lessons that can help initiate a discussion on suitable needed changes within the horticulture sub-sector, to aid sustainable development of the local economies.

Keywords: Post-election violence, Volcano eruption, Cut-flowers, Vegetables, Horticulture, Kenya.

6. Introduction

The Icelandic volcano eruption of Eyjafjallajokull in March 2010 had instantaneous unforeseen effects on the horticulture sub-sector in Kenya, significantly reducing the volume of local exports. The volcano is located at the southern tip of the Eastern Volcanic Zone in Iceland, and historically, has been active experiencing two major eruptions in 1994 and 1999 (Sturkell, Sigmundsson, & Einarsson, 2003). This volcano and over 30 active volcanic systems and eruptions in the region pose a threat to the local people and the aviation industry (Thordarson & Larsen, 2007; Webley et al., 2012). The 2010 event had far reaching effects on horticulture exports due to flight cancellations mainly to the European nations, which are the main importers of Kenya’s horticultural produce. Fresh produce such as cut-flowers, vegetables and fruits are intensively produced primarily for export to overseas markets such as Netherlands, UK and Germany (Dolan, Opondo, & Smith, 2003). The sub-sector has experienced rapid growth and vitality in the last two decades following the underperformance of traditional cash crops such as coffee, tea or tobacco in the world market. Other Sub-Saharan economies participating in high value horticulture include; Zambia and Zimbabwe (Barrientos, Dolan, & Tallontire, 2003), Ethiopia, South Africa (Smith et al., 2004).

While the sub-sector is hailed as extraordinary owing to creation of jobs and market opportunities, and improved Gross Domestic Product (GDP), there is growing debate on the environmental and social concerns (Hale & Opondo, 2005). Debatable concerns question the sustainability of the industry owing to the unintended side effects that may be levied on the environment and human wellbeing. For example, the carbon footprint resulting from miles of air travel by produce; the sustainable use and management of natural and capital resources employed in production; corporate social responsibility among other non-trivial issues.

Current high ranking issues of global environmental concern include intensive farming, water pollution, dams and the impact of dams on the environment, land use changes and ecosystem destruction (UNDP, 2010; WorldBank, 2010). Interestingly, these environmental problems surround intensive commercial horticulture farming in many developing nations including; Kenya (Nyakundi et al., 2011; Owiti & Oswe, 2007); Spain (Pulido et al., 2000); Ethiopia (Ali, 2014).

Research points to resource degradation and unsustainable long term impact of production activities on natural resources and ecosystems generally. Geographically, the issues seem local-regionally spread, but are gradually becoming critical issues to the global environment. Production of fresh produce is primarily driven by demand at overseas markets, with minimal local/domestic consumption. Market prices are volatile, fluctuating rapidly as dictated by the global international markets.

The volatility of the industry is a key point of discussion due to increasing changes in global climate, which increases the occurrence and severity of natural calamities such as drought and famine. These events can influence local and regional climatic conditions negatively impacting agricultural production. Reports also link changes in global climate to political instability and increased social political unrest in developing nations with serious economic consequences (Muhammad, D'Souza, & Amponsah, 2013). In the recent past, political unrest affects up to 25% of elections in Sub-Saharan Africa (Bekoe, 2010), negatively impacting established regimes, social structures, and curtailing developmental progress (Neumayer, 2004).

In the current study, the timing of the 2008/2009 post-election violence followed by the unexpected 2010 Icelandic volcanic eruption present a unique research case. Some recent studies have tried to examine the impact of these events (individually), on cut-flower export (Ksoll et al., 2009, 2010; Leipold & Morgante, 2013). However, the horticulture sub-sector in Kenya is comprised of cut-flowers, vegetables and fruits exports, all which have contributed to the rapid rise of the sub-sector. The current work is the first to examine the coupled impacts of the highlighted events on all three groups of exports, using raw long term export data records. The violence broke out in early 2008 following the December 27, 2007 national election results. Fighting lasted over a three month period, affecting several regions in Kenya including: Nakuru, Eldoret, and Naivasha, which are also regions of high horticulture production.

There was little recovery period between the violence event and the 2010 volcanic event, presenting a double blow to investors, stakeholders, workers, and the Kenyan economy. The impacts were pronounced in regions where the conflicts occurred (Ksoll et al., 2009). The transportation of workers to the farms in the conflict zones was hampered, in turn affecting produce harvesting, processing, and transportation from the farms to market. Reports also indicate that majority of workers fled the regions of unrest, limiting availability of semi-skilled and skilled labor. These are some of the social problems directly linked to political unrest and of significant impact to the sub-sector.

Both events present environmental and social concerns that threaten the sustainable future of the horticulture sub-sector in Kenya. The volcanic eruption of Eyjafjallajökull in 2010, affected the aviation industry (Webley et al., 2012), directly impacting transportation of fresh produce to market, causing huge economic losses as tons of produce decayed. Kenya's chief cut flower export market is the Netherlands, (from which the goods are distributed to other European nations through an auction system), followed by the UK and in third position is Germany. The local and regional markets are not strong, and they lack most of the horticultural produce. Currently, there is a growing criticism and call for a paradigm shift in so far as increased dependency of Kenya's horticulture sub-sector to foreign global markets is concerned (Leipold & Morgante, 2013). Critics highlight a need for the industry to reduce over-dependency on foreign global market, and diversify into local and regional alternative market outlets. Such outlets may provide a shorter term market cushion for the highly vulnerable sub-sector.

It is apparent that high value horticulture farming faces important challenges that require a paradigm change in production and marketing trends as well as how environmental and social issues are addressed. Scholars argue that Sub-Saharan Africa is socially and environmentally most vulnerable to climate change (Burke et al., 2009; Dyer, 2011; Hsiang, Burke & Miguel, 2013; Maystadt & Ecker, 2014). For example, Dyer (2011) hypothesizes that climate change will place growing pressure on fresh water and food over the coming century, triggering social disorder, mass migration and violent conflict.

It is a controversial topic of debate, and recent work (Buhaug, 2010) strongly disagrees with the Dyer's hypothesizes indicating that there is essentially no correlation between climate-change indicators such as temperature and rainfall variability, and the frequency of civil wars over the past 50 years in Sub-Saharan Africa. In Somalia (neighboring Kenya), evidence points to a strong general casuality between increasing civil war and a climate related drought in the region (Hsiang et al., 2013).

Besides the debate, the rapid expansion of the horticulture sub-sector in Kenya is accompanied by high level use of external inputs such as fertilizers, herbicides, fungicides, insecticides (termed here as agrochemicals). Imports, and use of agrochemicals at the farm level increased with the rapid rise of horticulture (Nyakundi et al., 2011), raising questions on the environmental and social impact of intensive use of high value inputs on farm by large-scale firms. In the Netherlands, a similar situation necessitated the nation to adopt environmental restrictions and conditions under which horticulture development could proceed with aims of promoting environment-friendly agricultural production systems. In contrast, many Sub-Saharan economies embracing high value horticulture are struggling to admit that there exists a down side of the intensive production activities. Additionally, they are slow to take leading roles in forging the stringent conditions and restrictions necessary towards sustainable horticulture farming.

This study intends to contribute to the ongoing discussion on the need for a paradigm shift in view of the above highlighted significant events and the plight of horticulture sub-sector. The study examines export data (volume) for the three commodities(cut-flowers, vegetables and fruits) that comprise export cluster (1995-2013), to evaluate the impacts of the two events on export trends using the long term data (19 years) compiled by Horticultural Crops Development Authority (HCDA). We compare the explained variability between the three main groups of exports to statistically determine dominant groups characterizing Kenyan export horticulture.

6.1 Methods and Data analysis

Raw data on volume exports for cut flowers, vegetables and fruits from 1995 - 2013 were obtained from the Horticultural Crops Development Authority (HCDA, 2014) available at http://www.hcda.or.ke/. HCDA is the main regulatory body with authority to facilitate the development, promotion, facilitation and regulation of the horticultural sub-sector in Kenya (Rikken, 2011). The study focused on volume of exports, even though the value statistics can also be obtained from the public portal. Prices of horticultural exports are highly volatile, and market dependent with no specific set standard.

Data processing and analysis was carried out in MS Excel and CoDaPack 2.0 © (Comas & Thio-Henestrosa, 2011). Linear trends of export volumes (kgs) were computed for the three clusters of horticultural produce (cut flowers, vegetables and fruits) over 19 year time period and for the months January-December to establish trend (sign), strength. From the trend lines, the obtained R squares for each month for cut-flowers, vegetables and fruits were used in ANOVA to determine the dominant export cluster over the years. A bi-plot of R squares (which explain observed variability in export data) was generated in CoDaPack 2.0, and used to draw comparisons underlying monthly variation/differences in exported quantity. CoDaPack is a powerful tool used in compositional data analysis i.e. data comprising up to 1, and since the r sq. values range between 0-1, its application in this step was useful. Bi-plots are considered a standard tool to present multivariate data (Filzmoser & Hron, 2008). In this study, bi-plot provides a meaningful investigation and deeper understanding into existing variation and spread in monthly exports from the three groups of horticulture produce. The arrangement and display of rays is based on the overall correlation matrix (Reimann, 2008). This is more advantageous compared to bivariate scatterplot which fails to provide an overall planar view of the participating groups (flowers, vegetables and fruits) and their relationships (monthly) (Filzmoser, Hron, & Reimann, 2012). The dependent variables were months (January to December) and the corresponding monthly r square for each export cluster. Thus, the matrix array comprised 12 (months) *3 (cut-flower, vegetables, fruits) independent groups.

6.2 Results and discussion

The results highlight important characteristics of the horticulture sub-sector in Kenya. Figure 6-1A-C, illustrate the general growth in volume of horticultural exports to overseas, which has led to the rapid expansion of the horticulture industry in Kenya.

6.2.1 Trends in export volumes over years

From the results, there has been a steady increase in amount of horticultural produce exported from Kenya.

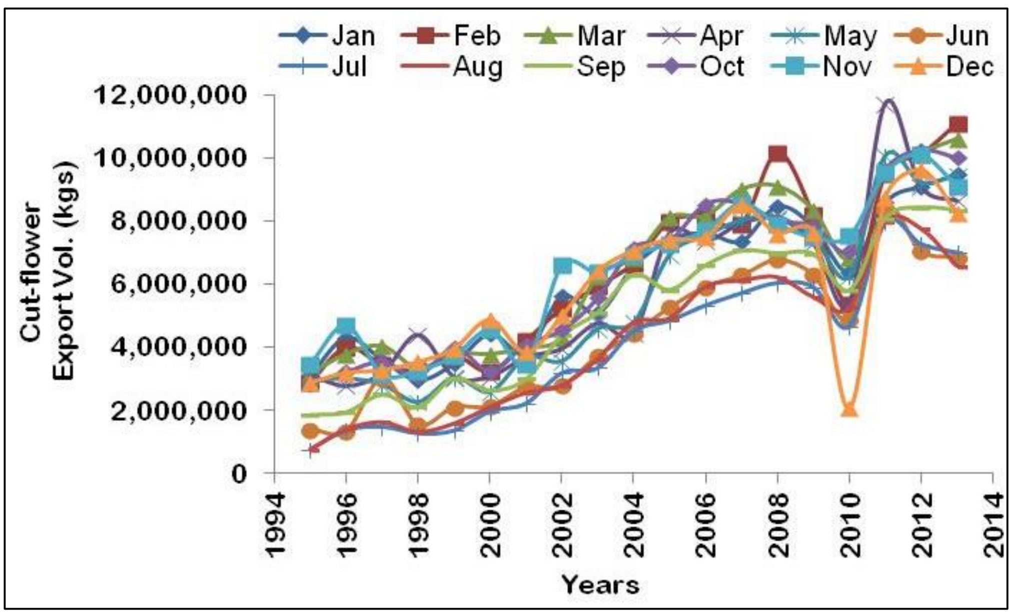

Figure 6-1A: Positive trend in export volume (kgs) of cut-flowers 1995 to 2013; the trend decline in 2009-2010 due to post- election unrest, and a further decline in 2010 due Icelandic volcanic eruption. December 2010 had record breaking lowest export volume for cut-flowers.

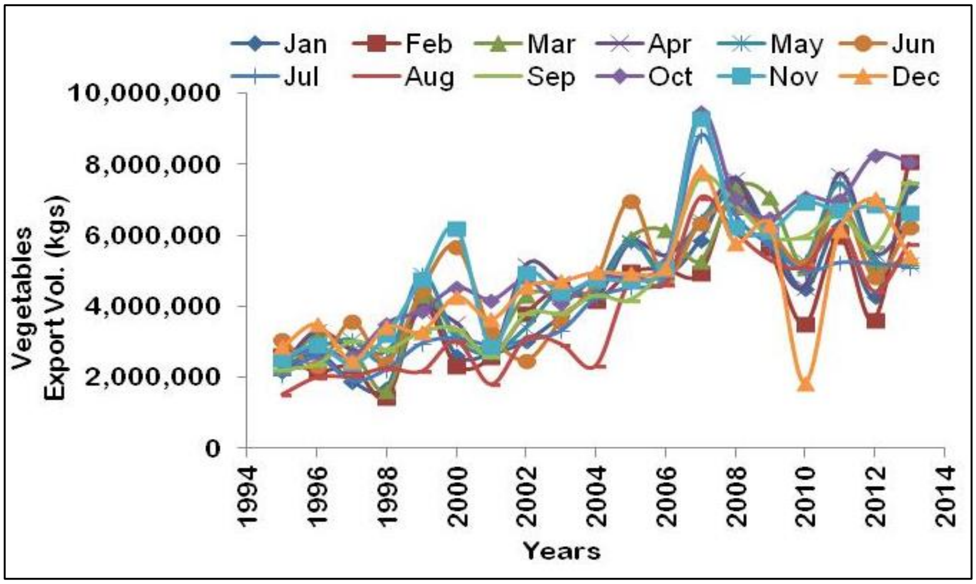

Figure 6-1B: Positive trend in export volume (kgs) of vegetables 1995 to 2013; the trend declines in 2009-2010 due to post- election unrest, and is worst in 2010 due Icelandic volcanic eruption. December 2010 had record breaking lowest export volume for vegetables.

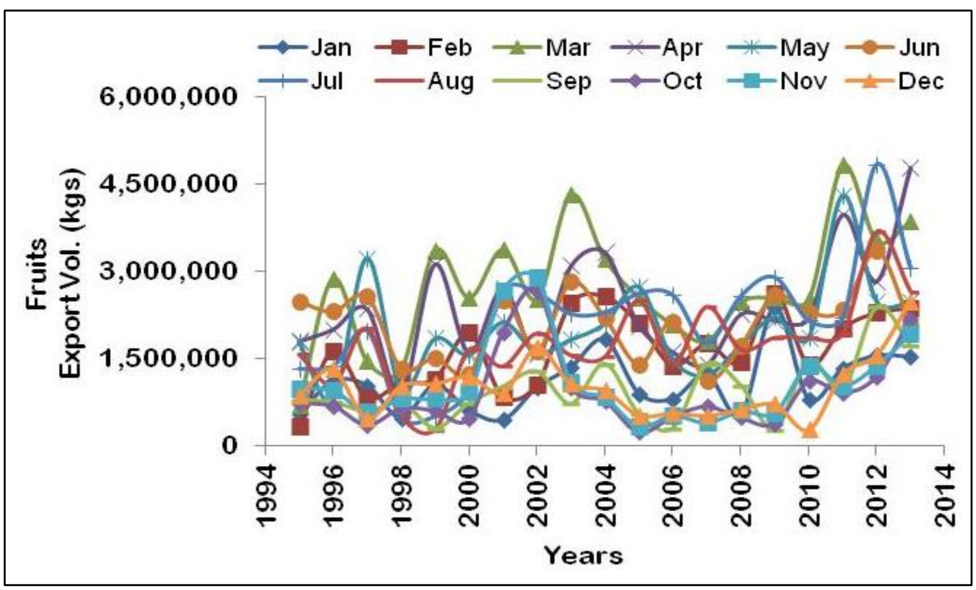

Figure 6-1C: Temporal variation in fruit export (kgs) 1995 to 2013. Compared to cut-flowers and vegetables, fruit exports do not show a severe decline in trend in the period 2008-2009, and 2010.

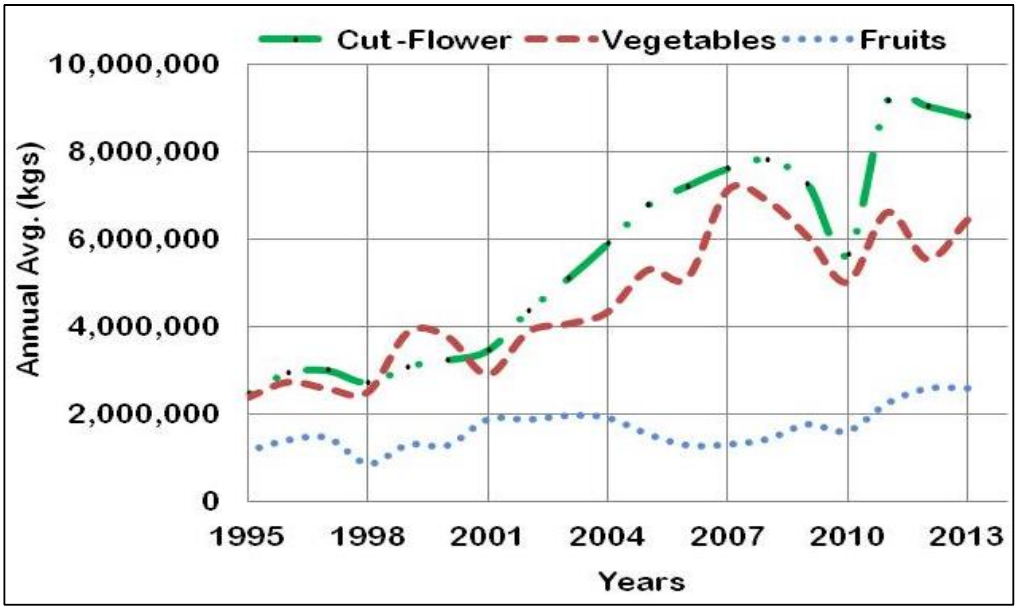

Figure 6-2: Annual average exports of cut-flowers, vegetables and fruits. There is a sharp decline in 2008/2009 for cut-flowers and vegetables, prior to a rapid decline in 2010. From 2010, the annual average fruit exports have increased beyond the 2 million (kgs) mark.

In Figure 6-2, the annual average exports for cut-flowers, fruits and vegetables rose after 2010, with flowers showing a greater recovery margin than vegetables, whose trend declined again in 2012. The vegetable trend shows a slow recovery post 2010, raising questions as to whether there are other likely factors besides political instability and Icelandic volcanic ash that could be affecting stability of vegetable trends. For instance, the annual average in 2012 is slightly lower than 2011 and 2013. This is a question that needs further investigation given the changes in global climate and its effect on rainfall, and agriculture in general. Additionally, occurrence of drought in the region may have had a direct effect on production of vegetables.

Another interesting observation from Figure 6-2 is the temporal switch in the leading export group between vegetables and cut-flowers which occurred from 1998-2000, and since then, cut-flower exports dominate the Kenyan horticulture sub-sector.

6.2.2 Monthly variability in export clusters

In general cut-flowers have a higher explained R. square in all months. Vegetable variability though higher than that of fruits, illustrate peak months (March to May, and September to October), and lows (February, June, and December). This is a likely indication of seasonal rainfall influence on production activities, and therefore quantity exported.

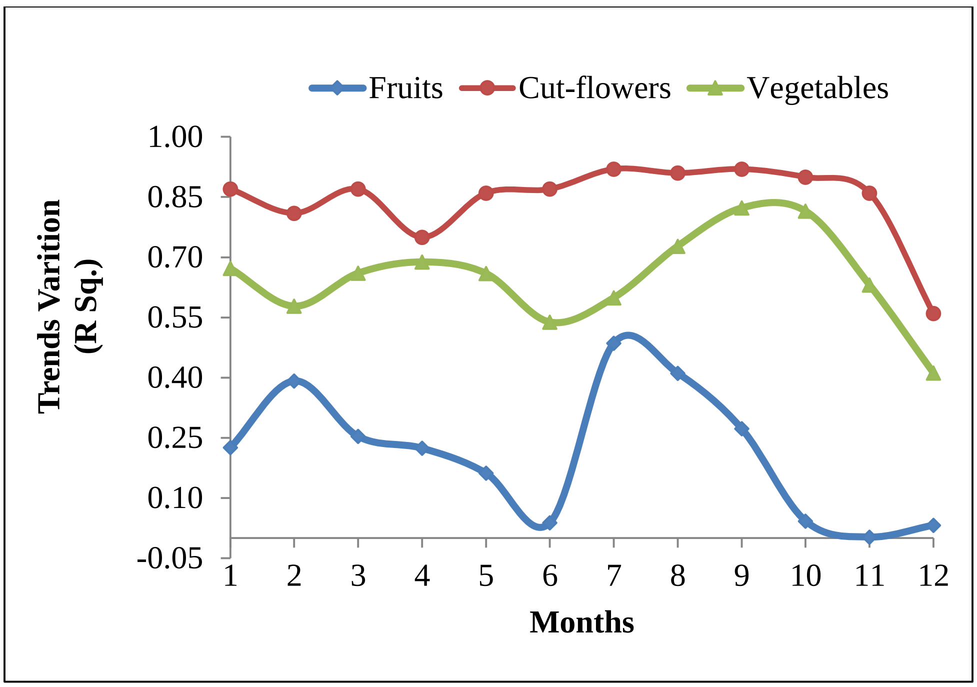

Figure 6-3A: Monthly variability in exports of cut flowers, vegetables and fruits, 1995-2013

The bi-plot (Figure 6-3B) further illustrates the relationship between the monthly variability and the three export groups. There is close association between cut-flowers and vegetables exports (close rays), which declines in June, October, November and December, hence low variability. This may indicate production behavior of exporting firms, where they combine flower and vegetable production targeting different markets. Such behavior may allow for price risk aversion if one commodity does not price well at the market.

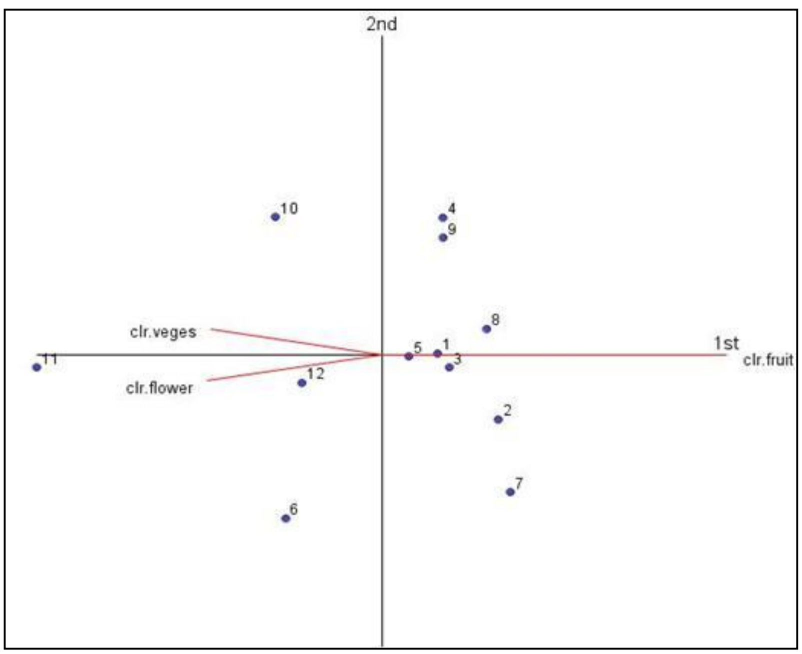

Figure 6-3B: Bi-plot visualization of explained variability between the 3 groups

Fruit R. square is low, and with no close relationship to the other two groups (Figure 6-3B, see long ray), and attains distinct peaks in specific months i.e. February, July, and August unlike vegetable whose peak months are spread (Figure 6-3A). This behavior is not surprising, and is plausible because unlike vegetables and flowers that go through shorter production periods, fruit tree and shrubs are mostly perennial. They flower and form fruits at particular times of the year. Moreover, all year round cut-flower production is carried out under climate controlled greenhouses overriding the aspect of seasonality portrayed by fruits.

6.2.3 Testing differences in export group volumes

Results (Table 6-1) show a statistically significant difference between the groups, (*F* ratio = 63.08) larger than the ($F_{critical}$ = 3.316), with cut-flowers dominating exports in the last 19 years (~2 decades), followed by vegetables, and fruits, respectively.

Table 6-1. ANOVA between export groups

SUMMARY

	Count	*Sum*	***Average***	***Variance***
Fruits	11	2.317	0.211	0.029
Cut-flowers	11	*9.230*	0.839	0.011
Vegetables	11	7.133	0.648	0.014

ANOVA

Source of Variation	*SS*	*df*	*MS*	***F***	*P-value*	***F crit***
Between Groups	2.285	2.000	1.142	**63.080**	*0.000*	**3.316**
Within Groups	0.543	30.000	0.018			
Total	2.827	32				

6.3 Discussion and conclusions

From the analysis, both the Icelandic volcanic eruption and 2008 post-election violence in conflict zones in Kenya had significant negative impacts on the horticulture sub-sector. The positive trend in exports (Figure 6-1A to C and Figure 6-2) declined following the 2008 post-election violence, and later declined further following the Icelandic volcanic eruption in 2010. The discussions focus on these two factors, and choose to start with the eruption effect because these were much felt globally than the regional political unrest.

6.3.1 Icelandic eruption effects on Horticulture sub-sector

The positive trends in horticultural export volumes was severely affected in 2008 and worse-off in 2010 (Figure 6-2) following Eyjafjallajökull volcanic eruption that limited flight activity. Cargo flights to the European markets, the main consumers of Kenya's horticultural produce were cancelled, leading to huge losses as a result of the global phenomenon. Our findings (Figure 6-1A-C and Figure 6-2) show that the event brought cut-flower and vegetable export volume to the lowest level for all months in 2010, and especially the month of December (i.e. less than 2 million kgs in export, a quantity observed in early 1990s). The volcanic eruption event occurred in March 2010, however, the lowest exports of the year were observed in December 2010, several months after eruption. This is due to the fact that December is a rainy and low season month, and therefore, a combination of the volcanic impact and a low production month temporarily affected the positive linear trend in cut flower volume.

Vegetable average annual trend (Figure 6-2) is very variable after 2010, a finding that opens the discussion of how long might it take for the trend to stabilize? This question may take a few more years of export data monitoring to respond to. However, compounded effects, such as the recent prolonged drought in the region (Funk, 2010) which has affected water availability for farming, and high temperatures generally may have an effect on vegetable farming. Cut-flowers are commonly grown under climate controlled greenhouses, unlike production of vegetables which mainly proceed in open fields, and face harsh weather conditions, which could limit production activities.

Globally large volcanic eruptions have far-reaching effects on global climate (Scientific American, 2005). The eruptions produce enormous amounts of carbon dioxide, a greenhouse gas that helps trap radiated heat arising from earth surface. The resulting insulation affects global temperatures since it tends to push the system beyond a balanced state required for planet habitation. The Icelandic eruption had a direct effect on local-regional horticulture sub-sector as seen in the abrupt decline in export to overseas market. The volcanic ash and aerosol clouds injected into the atmosphere limited cargo flights and the aviation industry in general. Fine particles resulting from volcano eruptions limit visibility, affecting movement of planes and can incur huge repair and mechanical losses, limiting air travel. Other than such direct effect, large volcanic eruption affects planet temperatures (Stenchikov et al., 2002). For example Mt. St. Helens eruption in 1982 lowered global temperatures by about 0.1^0 C (Robock, 2000), and when the much smaller eruption of El Chichón occurred, its impact on global temperature (cooling) were higher due to voluminous sulfur- rich gases emitted.

Such environmental hazards leading to changes in global temperatures (cooling or warming) are reported to be of significance effect on crop production (Atkinson, Brennan, & Jones, 2013). For example, prolonged cooler seasons cause chilling and frost-injury on produce especially those grown in open field (fruits, vegetables, some outdoor flowers) leading to massive losses. Although cut-flower production may still prevail under such circumstance, the cost of production may possibly increase due to a need for extra cooling or warming of the greenhouse, humidity adjustments *etc.* aspects of production that increase energy consumption.

While the 2010 eruption may not be the last of the large global volcanic eruption with local effects, how to plan for action (locally and globally) in the event of such catastrophes' is a question of debate. A good example is the case of Vesuvius in Europe, in which scientists believe could be more dangerous than previously assumed (Barnes, 2011) prompting a strong debate about the risk and scale of future disasters. Emergency planning for disaster is not trivial in current changing planet. Although local authorities can lay plans and strategies of emergency actions, it is pretty difficult to do the same for market oriented sectors. How can the global horticulture market prepare for poor quality or lack of goods, due to far reaching effects of global environmental hazards that curtail produce travel to markets?

Based on our finding, this is a debate worth engaging in because the horticulture sub-sector in Kenya has high economic returns and that has promoted the overall economic growth of the country, besides the international recognition. What level of precaution can the firms employ so as to keep secure and proceed as before? Though businesses can suffer a certain percentage of uncertainty and risks, those presented by natural disasters, can thwart progress in a blink of an eye. Given the price volatility of the sub-sector, horticulture growers and exporters face risks whose impacts can thwart production in a flash. Growing criticism highlights the need for horticultural firms to consider and investigate regional outlets of the goods, which may provide short term relieve in event of natural hazards, as the farms strategize for solutions.

6.3.2 Effect of the 2008 post-election violence

The political and ethnic chaos that followed the 2007 presidential election in Kenya (CIPEV, 2008; Dercon & Gutiérrez-Romero, 2012) severely affected the horticulture sub-sector particularly in areas of conflict (Ksoll et al., 2010). Our results (Figure 6-2) show that the positive trend in export, mainly cut-flowers and vegetables) declined in 2008, and 2009. This finding is verified by Macchiavello and Morjaria (2011) highlighting that only a few (16) of the 94 export firms of flower producers in violence-affected areas survived to the following growing season (2008/09). Displacement of workers in conflict regions (most of which house clusters of horticulture farms), lack of transport means to work places resulted in poor turnouts at work places, and this reduced overall efficiency and output. Besides, other reports indicate that the overall investor confidence declined (IMF, 2010), and this seems to have affected the 2009 volume. The extent and state of spread of the post-election violence was not anticipated by many flower firms (Ksoll et al., 2010), majority of whom had the perception of Kenya as a stable regional economy to invest in, which has since been compromised (Kimani, 2008).

Interestingly, during the unrest period, and after the 2010 event, results show a surge in the average annual fruit export (Figure 6-2), up to 2013. This might be an indication of changes in production strategies towards more risk averse crops, which are not very sensitive to market prices. Moreover, compared to cut-flower and vegetable production, fruits may require less production costs in terms of labor, crop management etc. However, the market value is lower compared to the other two clusters, and is highly seasonal, which imply that capturing an all-year round market may not be forthcoming. Also, dependence on rainfall may limit fruit yield. The slight decline in average annual vegetable exports in 2012 may perhaps signify a "pre-election phobia", with the 2012 elections that were underway. The election campaigns were not smooth, fueling speculations of unrest.

Though it might be implausible to single out this as a reason, reports indicate that political instability linked to election violence can limit the number of investors, forcing them to reassess the investment climate (BEBA, 2013). Dercon and Romero (2012) indicate that following post-election violence in many regions, distrust builds among communities which limit economic exchanges and ability to do business, an issue that many horticultural companies, and primarily those located in conflict zones might struggle with until stability regain.

6.3.3 Leading export clusters

The study analysis confirms that cut-flower exports (Table 6-1) dominate the Kenyan horticulture industry, forming a high valued cluster. This finding is corroborated by a body of literature (Dolan & Opondo, 2005; Rikken, 2011). Our findings show a significant dominant trend of this group over vegetables and fruits (Figure 6-3). The explained month to month variability in export quantities over decades is pretty smooth compared to the other two groups. This observation is attributed to the all year round cut flower production under the greenhouse environment, which provide a controlled climate (Justus & Yu, 2014). The overall value from cut flower supersedes that of vegetables and fruits, explaining why cut-flower production and export has continuously dominated the horticulture sub-sector.

However, the 2010 volcanic eruption and the 2008 ethnically-fuelled political unrest in the country significantly and negatively impacted the horticulture export volume leading to huge losses. The monthly export volume for cut flowers and vegetables declined rapidly, and were further affected by the December-rainfall season recording a historically low average for the month (Figure 6-1 A and B). The annual average fruit exports were not affected by the two events, and in fact, fruit export rose since 2009. A plausible explanation is that fruits have attained a local or regional market demand, that is less volatile in comparison to cut-flower and vegetables, or farmers could perhaps be changing their preference towards fruit production. Moreover, increased concerns over health and a proper diet have increased the demand for healthy fruit and vegetables (Wismer, 2014). This may well stir a continued demand for these commodities, despite underlying production and marketing challenges.

What we gather from the study is that the horticulture sub-sector has undergone major milestones in attaining a global recognition, through the process of export upgrading. The growth has been positive, taking advantage of geographical location, climate, labor, mature technologies, advanced skills and knowledge intensive products. More so, the use of farm management software such as Farmsoft (http://www.farmsoft.com/), Muddyboots (http://en.muddyboots.com/) that ease data entry, supervision and management has proved critical in both large and small scale production systems.

Despite these milestones, horticulture farming under current changing global environment will require continued sustainable adjustments in order to overcome impeding challenges. A growing body of literature notes that changing climate will affect rainfall, temperature and the general agricultural climate. Prolonged droughts in the Horn of Africa –including Kenya, Tanzania, Uganda, Sudan and Ethiopia will accelerate land degradation (Funk 2010), an important environmental sustainability concern. Under these conditions, positive economic growth by the sub-sector might be tricky, necessitating immediate discussions between the government, firms, and stakeholder, on achievable goals to keep the business thriving but also prepared for unseen events.

Unlike the highlighted issues, generally horticulture in Kenya has been a success story. However, like the majority of Sub-Saharan economies, it should be able to take commendable steps and tactics towards a more sustainable and competitive global stage. Strict international export standards and codes of practice such as European Retailers Producers Working Group for Good Agricultural Practice (EUREGAP), the British Retail Consortium (BRC), Milieu Project Sierteelt (Barrientos et al., 2003; Dolan & Opondo, 2005) have put pressure on exporting firms, however, there is need for more stringent national policies and involvement. Such a step might have better control in regulating environmental protection and sustainable resource utilization.

Policy measures that hold firms accountable for long term environmental impacts resulting from productions activities are necessary. This may compel the firms to feel "permanent" and not sojourner investors who exploit the social and environmental conditions of countries (Blowfield & Frynas, 2005). Due to increased resource degradation linked to intensive production activities, local measures that seek to preserve and protect the best agricultural soils are necessary. Recently, an increasing number of companies in Kenya have embraced corporate social responsibility (CSR), an attempt to improve their reputations and a move benefitting both the firms and the communities (Blowfield & Dolan, 2008). Better agricultural education, outreach and low-level investment in water infrastructure can perhaps help to improve rain-dependency by farmers' and improve crop yields, cushioning against adverse effects of climate. As drought frequency rises, the regional consequences of agricultural production may become unbearable for farmers without new policies to assist them to cope with climatic changes. Criticism highlight needs for developing regional and local markets and minimize reliance on overseas markets.

In summary, the present findings show that the 2008 post-election violence in Kenya and the 2010 Icelandic volcano eruption had a negative impact on the long-term trends of horticultural produce exports in Kenya. Although the study did not evaluate the economic value of produce lost, reports indicate that farmers lost as much as $ 1.3M a day (Wadhams, 2010). These unexpected events occurred consecutively limiting economic recovery time by investors and the nation from one event to another. The findings show that cut-flower and vegetable exports were severely affected, more so by the 2010 volcanic eruption event, with the average annual quantities declining to > 6 million kgs in 2010. Interestingly, the annual average exports of fruits have since increased, setting a historical record (> 2 million kgs annually in the last 3 years). Fruit farming seems more sustainable at the long-run due to reduced labor requirements, disease resistant and also lower fertilizer application, but further investigation can verify why the fruit exports were not affected as did cut-flowers and vegetables. Cut-flowers dominate the horticultural produce exports, closely followed by vegetables. This is plausibly explained by a significant use of climate controlled green-houses for flower production, which enables all year production. Vegetable production is mainly in open fields which may introduce seasonality and monthly variation in quantities exported as seen in the results. In the aftermath of the highlighted events, the findings of the present study suggest that the cut-flower annual trends appear to stabilize faster than the vegetables, a concern for future investigation. The study speculates that the ongoing drought in East Africa may be impacting the weather patterns in the region, limiting outdoor farming activities and hence vegetable production. Discussions on climate change preparedness and sustainable horticulture farming are necessary, in effort to build capacity and work towards strengthening existing initiatives so that the farmers and stakeholders are informed. The study also identifies a need to rebuild investor confidence in the country, putting effort towards stable social-political governance. This may be challenging but organizations such the Horticultural Crops Development Authority

(HCDA), Kenya Plant Health Inspectorate Service (KEPHIS), the Kenya Flower Council (KFC), the Fresh Produce Exporters Association of Kenya (FPEAK) bodies that work with the horticultural industry, and the government can come together and explore different strategies to regain trust of investors and stakeholder. This is an important step towards strengthening and revitalizing the horticulture sub-sector.

6.4 References

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CONCLUSION

This dissertation evaluated the extent and spread of commercial horticulture in Kenya, and its implications on two primary environmental resources employed in production. The work adopted an integrated approach that combined desk work, field study, remote sensing data and geographical information system tools to address four main research questions relevant to horticulture production. We examined: 1) the spatial spread and dynamics of farming activities within sub-watersheds, 2) the impact on surface water quality characteristics, 3) the vegetation response to increasing intensive farming and anthropogenic disturbances, and 4) the role of this type of farming on land cover and land use changes. The work illustrates that understanding the impacts of increased intensive farming activities on environmental resources, is an important agenda that can contribute to their sustainable use and an improved production culture. We have generated new data that fill existing knowledge gaps, while providing critical information useful towards drafting and streamlining better watershed resource management policies.

The study is based in central highlands of Kenya, a region of high agricultural potential that is experiencing increased land fragmentation due to increase in population, urban sprawl, soil erosion and deforestation. The region also partially portrays semi-arid to arid climatic conditions, which makes it highly vulnerable to climate changes.

The horticulture sub-sector in Kenya is more than two decades old. It has evolved to be a significant socio-economic engine to the nation. Even so, existing literature on the spatial extent and dynamics of production is overly generalized. It depicts production activities as occurring at wider geographical scales, enhanced by factors such as better trade terms, wider international markets, diversification and increased fresh produce demand. This is often not the case as we show in this work. There is need for accurate records that shed light on growth patterns, including number of farms and area under production. Moreover, increasing lines of evidence associate intensive horticulture production to numerous effects on the environment, with broad consequences to the ecosystems (water, land, and soil resources, human).

The first chapter therefore, establishes the current spatial distribution of greenhouse horticulture in central Kenya (by mapping the farm location), derives the area under green-house cultivation, and also determines the significant predicting factors to such farming. We show that large-scale horticulture production is heterogeneously concentrated in specific watersheds, where capital resources of production are available.

Based on our findings, the statically significant factors that accurately predict our observed spatial spread of horticulture across the study area and therefore influence choice of location for such include: population density (for labor needs), the average rainfall (irrigation purposes), average slope (siting of greenhouses) and dams (water storage). While topo-edaphic factors such as soil pH, average cation exchange capacity (CEC), exchangeable potassium (exK), exchangeable sodium (exNa) are elements critical in determining soil productivity and ability to support agriculture, current advances in horticulture are shifting towards the use of soilless media technologies. Soilless media include peat moss, wood chips, vermiculite, hydroponics, *etc*. Such media enable easier manipulation of plant-soil needs providing consistent results, a sterile environment for production, and preferable alternative to the natural soils. This may affect the investors/farmers preference and choice of a region for greenhouse siting. The finding underscores the mainstream perception that the country's good climatic condition and soils, as reasons explaining the vibrant growth and spread of production activities. It is still a debatable question. We have generated a map of farms distribution within sub-watersheds in the study area using Google Earth visualization tools. This information is useful in formulating policies that will enable equal resource utilization/allocation and mobilization of infrastructures such as roads, municipal water, health facilities, schools, for use by growing communities in highly crowded watersheds.

In the third chapter , we seek to understand surface water quality characteristics in relationship to land use type, focusing on sub-watershed in hot spot areas of intensive horticulture farming (small-scale and large-scale-farming). Agrochemicals, which include fertilizers, pesticides, herbicides, soil enhancements, that are intensively used in horticulture production are harmful to human, plants, animals and the environment at large. In aquatic environments, excess nutrients and pollutants are harmful to aquatic communities, as they deplete oxygen supply in the water. Where water resources are used for domestic needs, watering livestock, and urban and industrial uses, elevated pollutant levels can be harmful. This chapter therefore seeks to determine the general surface water quality status and likely key processes that explain the situation. Our results indicate prevalence of cadmium, phosphate, and zinc elements across study area. This are linked to the rigorous use of phosphate fertilizers and copper based agrochemicals mainly by large-scale commercial farmers. The discriminate analyses of the field data show four significant discriminant functions, ($p < 0.05$). These functions separate water quality indicators into five land-use types, with 89.5% correct assignment enabling association of land use type with observed water quality. We also observe high concentrations of dissolved solids (TDS), electro-conductivity (EC) and salinity that spike at locations proximate to intensive small-scale and large-scale horticulture production. Interestingly, we find that nitrate is prevalent in mixed agriculture (MAG) due to increased use of animal manure.

The results in this chapter enhance our current knowledge on the implications of intensive commercial horticulture and land-use practices on water quality in the region. We strongly consider these findings critical to formulating ecologically-sound watershed management and pollution abatement plans. Conversely, the onetime field sampling of surface water may present a limitation to the study findings. We understand that surface water characteristics are dynamic and highly variable in time and space, which can affect our results. It is desirable to have multiple sampling events distributed over different season to provide a more accurate representation of the river systems. However, in our case, a financial constraint restricted amount of field work, chemicals and reagents to a single sampling event at each location.

In order to reduce the sampling bias and likely margin of error, we have examined multiple parameters (14) per site, while exercising a high degree of accuracy. Even so, we believe that in a region where very little consistent water quality data exist, our work has generated baseline information, upon which future studies can reference. Future research identifies a need for follow-up sampling that includes biological assessments of benthic communities along the same study sites. The diversity and abundance of benthic populations or prevalence of specific types of macro–invertebrates may indicate pollution stress or, pristine habitat condition. The presence, absence or abundance of specific benthos in the water will provide reliable information which, when used alongside sampled water quality parameters, can indicate the prevailing environmental conditions of stream habitats, and therefore help validate our current findings. It will expand our knowledge and understanding of the interactions between intensive horticulture farming, land-use changes, and surface water quality and river ecosystems.

In chapter four, we have used extensive records of remote sensing data on vegetation condition (NDVI) to illustrate its applicability in monitoring terrestrial habits for early warning signs of environmental stress on vegetation. Thirty three (33) sub-watersheds that have shown increased clusters of farms and production activities are used in this chapter. Overall, the results capture considerable variations in vegetation condition largely attributed to mixed factors, including drought, intensive farming activities, and rainfall variation. The Normalized Difference Vegetation Index in hot spot sub-watersheds declined (negative) significantly after 1990. This is a period associated with rapid growth and expansion of horticulture production, and anthropogenic disturbances on land cover in the region. Our statistical analysis indicate significant differences in slopes before-1990 and after-1990 ($p < 0.05$; $p < 0.1$ respectively). Like we had hypothesized, we observe a decline in vegetation over densely populated sub-watersheds, although low NDVI values in 1984 and 2000 was the effect of severe droughts. The results from this chapter provided very interesting results, supporting the hypothesis that: 1) there are changes in the sub-watersheds, and the vegetation is responding at varying levels to these changes, and 2) human disturbances play important role in observed changes. We hope that this information will assist natural resource managers in designing effective conservation measures. The findings from this chapter closely resonate with the results in chapter five, where we highlight how increased horticulture farming impact land use and land cover (LULC) dynamics in hot spot production areas. In chapter six, we highlight effects of a natural disaster and political instability on horticultural export. Despite the rapid growth of the sub-sector, it is vulnerable to unexpected natural events and factors such as war, which occurred in areas of high horticulture production affecting labor availability in the farms, transportation of goods to the market etc.

Broadly speaking, agriculturally productive watersheds are experiencing important land transformations with consequences on environmental resources. This challenges the effort towards sustainable watershed resource management. We have utilized multi-temporal Landsat data in LULC classification and change detection analysis to quantify rate of LULC transformation. We show that in the last 25 years (1984-2009/2010) the selected case study regions (both horticultural hotspots) have experienced intense land transformation at varying magnitudes. The changes are largely attributed to socio-economic drivers including increased human migration into the region fueling growth of settlement, increased irrigation farming (and therefore increased area under water-dams), and the growth of cities and industries. LULC has broad impacts on ecosystems, and currently linked to global, regional and local climate variability and change. Due to prevailing diverse agro-climatic characteristics of the central highlands of

Kenya, from very productive zones to semi-arid to arid regions, there is need for sustainable measures to curtail the rapid LULC. Results from this chapter indicate that vast areas are covered by woody grasslands that primarily support wildlife and pastoral communities. For this reason, the rapid expansion of farming and settlement into these marginalized areas may increase level of resource vulnerability to changes and variability in climate limiting the resources available for use. Interestingly, we find that in Laikipia, the highest percentage annual rate of change is towards settlement /urban use (20.2%), whereas in Athi River, the highest annual percentage rate of change is towards agriculture use (37.7%). From this observation, we infer that even though both regions are highly involved in horticulture production, there are underlying differences in local drivers and types of land use transformations. Effective mitigation strategies are therefore limited to the regions. It is also evident from this chapter that archives of remote sensing data can highly facilitate large scale monitoring of terrestrial environments by means not attainable through ground work.

From our multifaceted study and body of literature, there is surmounting detail that the growth and proliferation of commercial horticulture production has positive and negative imprints on the environment and the society. The widely known success story of Kenyan horticulture is often captured in phrases such as, "the flying flowers and vegetables" from Kenya. Conversely, the story is not exhilarating when we factor in the unintended costs of production to the environmental resources applied in production, and their sustainable use (which is what we focus on in this work).

In the end of the dissertation, we have included a chapter which examines trends in export volumes of horticulture produce. It also examines the volatility of the sub-sector when faced with unexpected natural calamities and instabilities in political climate. We draw attention to the fact that most of the high valued fresh commodities are exported to international markets, and therefore a breakdown in marketing channels/ arrangements due to diverse reasons can incur devastating loss to stakeholder and the sub-sector. Analysis of the raw export data archived by HCDA, show a fairly steady export trend of cut-flowers, vegetables and fruits since 1995. However, following the post-election violence in the country in 1997/1998, the main horticultural production regions were affected, leading to remarkable decline in flower and vegetable exports. The annual average fruit exports were not affected during this period, which was attributed to a presence of a wider local and regional market, likely difference major international markets for fruits (Russia, UAE) and also different mode of transport to market (shipping). Additionally, the Icelandic volcano eruption Eyjafjallajökull in March 2010 caused further damage on the sub-sector. It significantly reduced the volume of cut-flower and vegetable exports (and therefore loss) due to flight cancellations to Europe, the main buyer of Kenya's fresh produce.

These two events strongly point to the volatility of the subsector, partly due to its overdependence on foreign markets. Future research can seek ways to build and strengthen local and regional market outlets for horticultural produce, as precautions in the event of future calamities. On a broader note, there is an urgent need for discussions on climate change preparedness and sustainable horticulture farming in the region. This is in effort to build capacity and work towards strengthening existing initiatives that inform farmers and stakeholders. Following the political instability, several investors lost confidence in the Kenya's horticulture business. Rebuilding investor confidence may be challenging, but it is an important step towards strengthening and revitalizing the horticulture sub-sector. Organizations such the Horticultural Crops Development Authority (HCDA), Kenya Plant Health Inspectorate Service (KEPHIS), the Kenya Flower Council (KFC), the Fresh Produce Exporters Association of Kenya (FPEAK) bodies that work with the horticultural industry and the government can come together and explore different strategies to regain trust of investors and stakeholder.

Other than the environmental and social concerns we have highlighted in this work, there are commendable advances towards best management practices (BMPs) in the field of horticulture. For instance, the use of integrated pest management (IPM), as a sustainable approach to managing agricultural pests has been widely adopted. IPM combines biological, cultural, physical/mechanical, and chemical tools to keep pests below their economic injury levels thereby minimizing economic, health and environmental risks. Adoption of IPM approaches may be financially stressful to small-scale farmer; however, large-scale farmers (e.g. Finlays-Naivasha) report a significant reduction in the use of synthetic pesticides as a result of using biological control agents.

Additionally, there has been notable progress in biotechnology and plant engineering approaches that produce plant varieties that are able resist pest and disease invasion, hence a reduction in the use of pesticides on farms. Never the less there are critics to the likely impacts of genetically modified crops on the environment, and therefore a debatable approach.

Also, due to the huge waste stream generated by horticultural farm practices, the Ministry of Environment has partnered with a handful growers on a pilot scheme to convert farm waste into biogas (e.g. Simbi Roses in Thika and PJ Dave in Kitengela) that will cut down on electricity use. Successful implementation of the project is projected to be a major milestone since the farms can be used as models replicable by other growers.

The increasing drought episodes in the country affect water resources available for farming. It is therefore recommendable that the industry sets policies that promote collection and use of rain water collected from greenhouse roofs. Such effort would reduce storm run-off, and concurrently reduce on-farm erosion and nutrient wash-off to water bodies.

What we learn from this work is that the horticulture sub-sector has several milestones to overcome in order to equilibrate the socio-economic gains and the negative environmental impacts. The milestones are achievable through proper regulatory frameworks and policies that are developed in consultation with farmers, stakeholders, communities and the responsible government bodies.

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LIST OF APPENDICIES

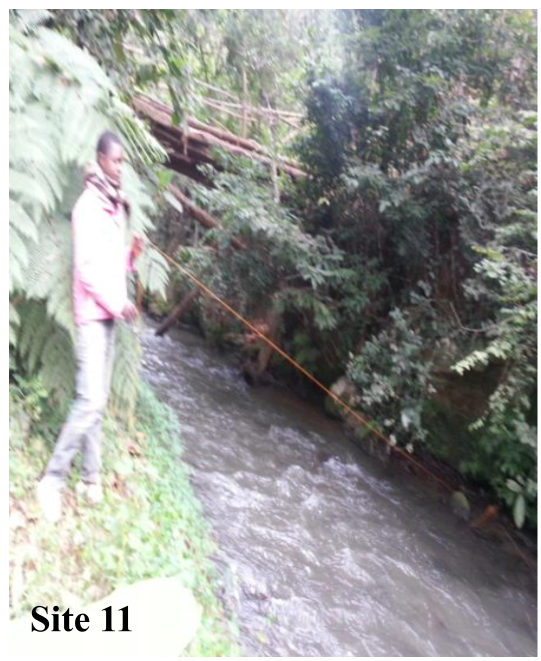
Appendix A

A.1: A picture of rose plants growing directly on slightly raised soil beds in a greenhouse. The vegetative bending forms a base from which upright shoots grow to stems, and are harvested as cut flowers.

A.2: A picture of hypericum plants directly growing in the ground, on low beds that are covered by plastic under a greenhouse. At the foreground is support for drip line used for irrigation.

Appendix B

B.1: Pictures from field surface water.



Pictures taken by Faith Muriithi (author)

Site 18 and Site 8: Healthy forest aquatic environment

Site 22 and Site 11: Pristine waters exiting forest

Appendix B

B.2: Pictures from field surface water study – Erosion of river banks

Pictures taken by Faith Muriithi (author)

Site 2: A totally disturbed stream bank environment

Site 4 and site 10: River banks erosion

Site 35: High erosion on banks of Burguret River

Appendix B

B.3: Pictures from field surface water study- Sources of pollution

Pictures taken by Faith Muriithi (author)

Site 14: Mixed subsistence farming, little riverine vegetation

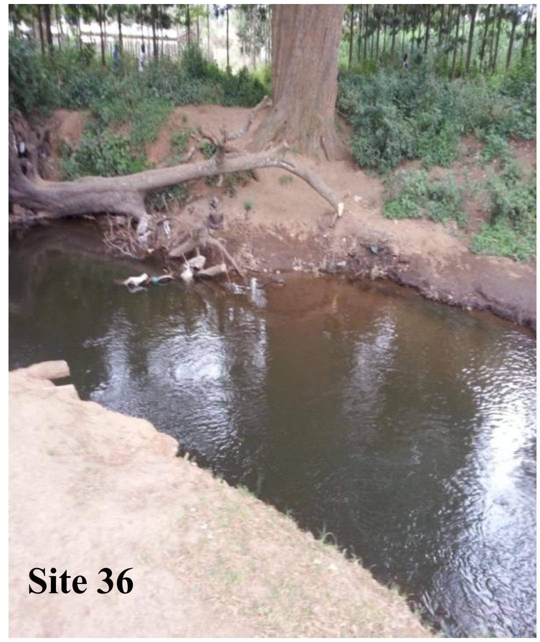
Site 17: Very turbid river, and hot dusty environments

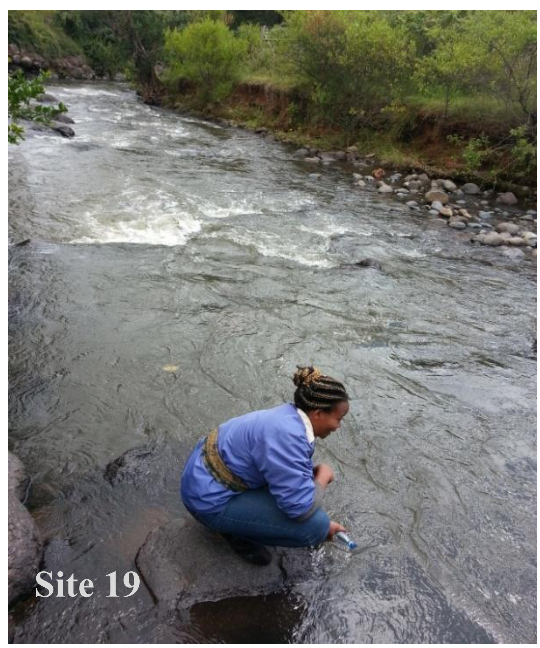
Site 23: Full vegetation cover but point source pollution is an issue

Site 29: Very turbid, mucky water exiting one of the flower farms

Appendix B

B.4: Pictures from field surface water study - stream bank modification



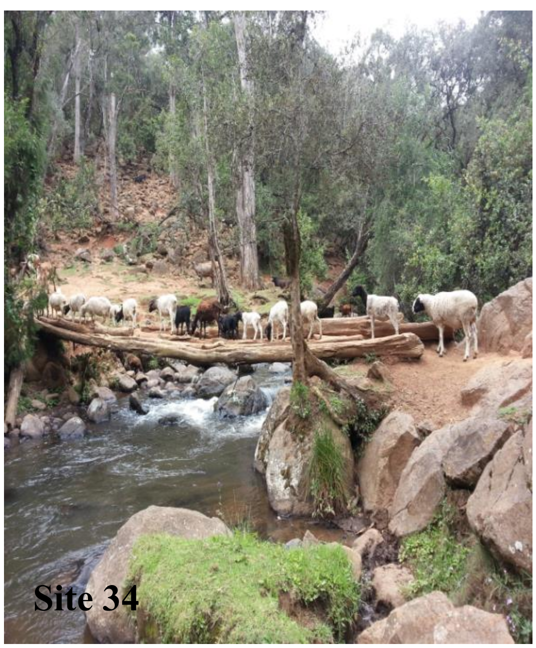


Pictures taken by Faith Muriithi (author)

Site 7: Lack of riparian cover, man-made cravats'
Site 36: Urban River, garbage on river banks
Site 19: Field sampling and sampling materials

Appendix B

B.5: Pictures from the field study - domestic and animal use of the surface



Pictures taken by Faith Muriithi (author)

Site 30: Fetching water for domestic use
Site 34: Livestock drinking and crossing the river
Site 38: Measurement – channel width measure

Appendix C

C.1: Data for chapter four. Averaged annual NDVI data for sub-watersheds derived from GIMMS AVHRR NDVI data

Sub-watersheds / Year	5BD	2EF	1FD	4FA	2EA	2ED	1GB	1GA	2EC	1GG	1GC	1GD	4EA	5BB	5BA	2EG1	4EB	2GB	3AA	3AB	3BC
1982	0.45	0.52	0.68	0.54	0.51	0.62	0.63	0.65	0.52	0.62	0.64	0.62	0.54	0.59	0.53	0.61	0.55	0.53	0.36	0.29	0.50
1983	0.48	0.53	0.69	0.52	0.49	0.63	0.63	0.67	0.50	0.61	0.64	0.64	0.54	0.56	0.53	0.63	0.53	0.53	0.36	0.31	0.51
1984	0.35	0.41	0.67	0.48	0.40	0.63	0.64	0.67	0.41	0.58	0.63	0.64	0.52	0.53	0.42	0.59	0.52	0.51	0.35	0.28	0.47
1985	0.49	0.54	0.69	0.51	0.62	0.61	0.65	0.68	0.57	0.66	0.65	0.65	0.56	0.59	0.46	0.60	0.52	0.58	0.37	0.38	0.57
1986	0.40	0.51	0.68	0.50	0.47	0.59	0.64	0.65	0.51	0.61	0.62	0.62	0.54	0.52	0.41	0.55	0.52	0.51	0.33	0.35	0.51
1987	0.41	0.47	0.69	0.53	0.51	0.59	0.65	0.70	0.50	0.61	0.63	0.65	0.55	0.57	0.49	0.57	0.50	0.52	0.37	0.34	0.53
1988	0.42	0.51	0.71	0.51	0.58	0.63	0.64	0.69	0.56	0.62	0.67	0.65	0.54	0.56	0.49	0.62	0.52	0.55	0.37	0.34	0.49
1989	0.42	0.55	0.70	0.52	0.51	0.65	0.64	0.66	0.52	0.57	0.64	0.64	0.55	0.56	0.51	0.60	0.51	0.51	0.43	0.38	0.54
1990	0.50	0.53	0.71	0.55	0.53	0.64	0.65	0.69	0.53	0.63	0.64	0.64	0.59	0.60	0.53	0.59	0.57	0.52	0.42	0.39	0.54
1991	0.48	0.54	0.68	0.53	0.52	0.63	0.64	0.68	0.52	0.60	0.62	0.62	0.57	0.57	0.53	0.58	0.52	0.48	0.43	0.33	0.50
1992	0.44	0.55	0.72	0.52	0.49	0.62	0.63	0.70	0.51	0.63	0.65	0.61	0.54	0.54	0.47	0.61	0.51	0.50	0.40	0.34	0.51
1993	0.39	0.47	0.70	0.52	0.47	0.59	0.60	0.65	0.46	0.58	0.61	0.61	0.56	0.56	0.47	0.57	0.53	0.48	0.30	0.31	0.53
1994	0.44	0.55	0.74	0.54	0.52	0.59	0.67	0.68	0.53	0.63	0.64	0.66	0.57	0.59	0.53	0.63	0.57	0.50	0.41	0.37	0.56
1995	0.46	0.58	0.72	0.52	0.54	0.67	0.67	0.70	0.53	0.63	0.67	0.64	0.55	0.56	0.50	0.62	0.54	0.52	0.41	0.33	0.51
1996	0.44	0.57	0.70	0.53	0.54	0.63	0.65	0.67	0.53	0.62	0.64	0.63	0.59	0.53	0.46	0.61	0.53	0.54	0.39	0.34	0.53
1997	0.40	0.50	0.70	0.50	0.49	0.59	0.60	0.67	0.51	0.54	0.62	0.59	0.53	0.56	0.49	0.59	0.51	0.50	0.30	0.33	0.46
1998	0.50	0.56	0.71	0.53	0.56	0.65	0.64	0.68	0.55	0.61	0.64	0.64	0.56	0.61	0.55	0.62	0.55	0.55	0.40	0.42	0.50
1999	0.43	0.55	0.71	0.50	0.53	0.64	0.64	0.70	0.52	0.63	0.64	0.62	0.54	0.53	0.47	0.61	0.50	0.52	0.34	0.29	0.51
2000	0.38	0.46	0.68	0.50	0.49	0.56	0.62	0.66	0.45	0.60	0.63	0.62	0.52	0.55	0.44	0.53	0.48	0.48	0.26	0.24	0.48
2001	0.40	0.55	0.71	0.43	0.58	0.61	0.65	0.69	0.55	0.64	0.64	0.65	0.47	0.54	0.44	0.59	0.43	0.54	0.37	0.32	0.44
2002	0.44	0.51	0.71	0.53	0.51	0.61	0.64	0.69	0.49	0.60	0.63	0.62	0.55	0.56	0.50	0.56	0.53	0.49	0.33	0.31	0.49
2003	0.48	0.54	0.68	0.51	0.54	0.65	0.62	0.66	0.56	0.60	0.63	0.62	0.56	0.59	0.53	0.61	0.53	0.53	0.36	0.34	0.51
2004	0.41	0.46	0.70	0.50	0.50	0.60	0.60	0.67	0.50	0.57	0.63	0.60	0.52	0.55	0.43	0.58	0.49	0.50	0.28	0.26	0.49
2005	0.38	0.45	0.72	0.50	0.53	0.66	0.64	0.71	0.47	0.61	0.65	0.62	0.55	0.54	0.44	0.60	0.52	0.49	0.29	0.25	0.50
2006	0.39	0.42	0.68	0.48	0.48	0.57	0.62	0.69	0.43	0.60	0.63	0.62	0.53	0.56	0.49	0.54	0.51	0.51	0.30	0.30	0.45

APPENDIX C

C.1 (*continued*): Data for chapter four. Averaged annual NDVI data for sub-watersheds derived from GIMMS AVHRR NDVI data

Sub-watersheds / Year	2CB	5DC	5DA	5DB	1CB	2EK	5AC	2EE	2EG2	5AD	1CC	2EB	5BC	5BE	1FC	5AA	1FA	5AB	3AC	3EA	3BA
1982	0.53	0.35	0.40	0.41	0.58	0.51	0.41	0.41	0.45	0.37	0.59	0.52	0.49	0.49	0.67	0.51	0.65	0.50	0.34	0.41	0.37
1983	0.56	0.32	0.40	0.42	0.59	0.52	0.40	0.43	0.44	0.39	0.60	0.49	0.51	0.47	0.70	0.49	0.65	0.47	0.35	0.41	0.42
1984	0.49	0.28	0.36	0.37	0.56	0.43	0.31	0.37	0.33	0.27	0.57	0.42	0.39	0.43	0.68	0.46	0.62	0.39	0.32	0.41	0.38
1985	0.56	0.35	0.41	0.43	0.60	0.59	0.45	0.44	0.49	0.43	0.61	0.59	0.51	0.46	0.69	0.54	0.67	0.52	0.37	0.43	0.43
1986	0.52	0.31	0.36	0.38	0.55	0.50	0.36	0.40	0.43	0.33	0.56	0.47	0.44	0.43	0.68	0.46	0.61	0.44	0.33	0.40	0.37
1987	0.52	0.32	0.39	0.39	0.56	0.49	0.34	0.39	0.42	0.29	0.58	0.52	0.47	0.42	0.70	0.46	0.63	0.42	0.32	0.39	0.42
1988	0.53	0.34	0.36	0.37	0.57	0.52	0.37	0.41	0.47	0.34	0.60	0.55	0.48	0.45	0.72	0.48	0.67	0.44	0.31	0.42	0.39
1989	0.55	0.35	0.38	0.40	0.59	0.54	0.40	0.43	0.44	0.36	0.59	0.51	0.47	0.45	0.70	0.49	0.62	0.46	0.38	0.42	0.43
1990	0.56	0.38	0.43	0.43	0.59	0.53	0.43	0.40	0.42	0.44	0.60	0.52	0.52	0.48	0.71	0.52	0.67	0.53	0.38	0.43	0.44
1991	0.54	0.31	0.41	0.40	0.55	0.51	0.37	0.43	0.46	0.38	0.58	0.49	0.47	0.43	0.66	0.50	0.63	0.47	0.36	0.43	0.41
1992	0.54	0.30	0.38	0.33	0.59	0.52	0.35	0.40	0.43	0.35	0.58	0.49	0.46	0.45	0.69	0.49	0.66	0.48	0.34	0.41	0.38
1993	0.51	0.27	0.40	0.37	0.57	0.49	0.31	0.34	0.35	0.29	0.57	0.46	0.46	0.43	0.68	0.44	0.60	0.42	0.31	0.36	0.37
1994	0.50	0.31	0.40	0.37	0.56	0.50	0.34	0.41	0.44	0.39	0.56	0.49	0.49	0.45	0.73	0.46	0.63	0.45	0.38	0.43	0.44
1995	0.57	0.37	0.40	0.41	0.60	0.54	0.44	0.46	0.48	0.41	0.61	0.54	0.50	0.45	0.70	0.53	0.64	0.50	0.37	0.43	0.43
1996	0.55	0.30	0.40	0.38	0.58	0.55	0.36	0.39	0.46	0.33	0.60	0.53	0.48	0.45	0.70	0.51	0.63	0.48	0.36	0.42	0.40
1997	0.53	0.32	0.38	0.36	0.55	0.50	0.36	0.40	0.43	0.32	0.56	0.49	0.45	0.42	0.68	0.49	0.58	0.45	0.32	0.35	0.36
1998	0.57	0.42	0.44	0.46	0.58	0.57	0.46	0.48	0.50	0.43	0.59	0.56	0.52	0.50	0.69	0.53	0.63	0.51	0.37	0.42	0.41
1999	0.56	0.32	0.38	0.39	0.60	0.53	0.35	0.45	0.46	0.35	0.62	0.52	0.45	0.45	0.69	0.48	0.67	0.47	0.30	0.37	0.38
2000	0.50	0.25	0.37	0.37	0.57	0.50	0.32	0.37	0.39	0.30	0.57	0.47	0.41	0.42	0.68	0.47	0.61	0.41	0.30	0.38	0.34
2001	0.56	0.28	0.33	0.35	0.63	0.57	0.40	0.42	0.47	0.34	0.66	0.54	0.42	0.45	0.71	0.51	0.67	0.45	0.30	0.36	0.39
2002	0.53	0.34	0.39	0.40	0.57	0.51	0.38	0.40	0.41	0.36	0.59	0.51	0.47	0.46	0.71	0.48	0.64	0.45	0.32	0.38	0.36
2003	0.56	0.39	0.42	0.43	0.56	0.55	0.43	0.47	0.49	0.42	0.57	0.54	0.52	0.48	0.66	0.52	0.61	0.51	0.35	0.41	0.39
2004	0.55	0.32	0.37	0.34	0.58	0.52	0.37	0.42	0.40	0.34	0.56	0.50	0.43	0.44	0.68	0.48	0.63	0.45	0.28	0.34	0.34
2005	0.57	0.29	0.33	0.37	0.61	0.53	0.35	0.43	0.41	0.30	0.60	0.52	0.42	0.46	0.70	0.47	0.64	0.46	0.26	0.34	0.35
2006	0.52	0.27	0.33	0.31	0.59	0.47	0.32	0.35	0.36	0.31	0.57	0.48	0.44	0.44	0.68	0.44	0.61	0.45	0.29	0.33	0.32

APPENDIX C

C.1 *(continued*): Data for chapter four. Averaged annual NDVI data for sub-watersheds derived from GIMMS AVHRR NDVI data

Sub-watersheds / Year	4BC	2GC	1JB	1LB1	4ED	4BA	2KA	4AD	4DD	4BD	2GD	4CA	4BE	1JE	4CB	4BF	4BG	2H	4CC	4DE	3BD	3CB
1982	0.51	0.54	0.76	0.52	0.41	0.57	0.45	0.63	0.44	0.59	0.39	0.59	0.52	0.61	0.52	0.53	0.44	0.29	0.46	0.31	0.47	0.48
1983	0.52	0.57	0.76	0.57	0.39	0.50	0.47	0.58	0.43	0.56	0.43	0.57	0.50	0.62	0.57	0.52	0.44	0.32	0.44	0.27	0.52	0.51
1984	0.47	0.55	0.75	0.55	0.38	0.49	0.43	0.55	0.38	0.52	0.35	0.57	0.44	0.61	0.51	0.42	0.35	0.28	0.40	0.26	0.45	0.41
1985	0.56	0.65	0.74	0.56	0.38	0.60	0.50	0.59	0.47	0.60	0.47	0.63	0.54	0.63	0.57	0.51	0.44	0.35	0.46	0.33	0.54	0.47
1986	0.48	0.54	0.72	0.51	0.36	0.49	0.43	0.48	0.40	0.50	0.40	0.58	0.50	0.61	0.48	0.46	0.40	0.33	0.42	0.30	0.51	0.40
1987	0.50	0.56	0.76	0.58	0.39	0.50	0.49	0.60	0.44	0.57	0.42	0.59	0.49	0.64	0.54	0.44	0.41	0.31	0.41	0.32	0.49	0.44
1988	0.51	0.58	0.76	0.57	0.37	0.50	0.47	0.55	0.44	0.53	0.43	0.58	0.45	0.63	0.52	0.48	0.42	0.34	0.42	0.29	0.47	0.42
1989	0.50	0.56	0.74	0.57	0.39	0.57	0.47	0.62	0.46	0.57	0.41	0.60	0.52	0.63	0.55	0.51	0.43	0.35	0.42	0.34	0.54	0.50
1990	0.50	0.59	0.76	0.58	0.42	0.51	0.50	0.58	0.47	0.57	0.44	0.61	0.53	0.62	0.59	0.50	0.45	0.37	0.46	0.35	0.52	0.49
1991	0.52	0.54	0.74	0.58	0.40	0.50	0.48	0.62	0.48	0.59	0.44	0.60	0.53	0.60	0.57	0.50	0.46	0.31	0.46	0.33	0.51	0.48
1992	0.47	0.51	0.75	0.57	0.34	0.49	0.46	0.57	0.40	0.53	0.42	0.59	0.50	0.62	0.55	0.47	0.42	0.34	0.40	0.29	0.51	0.50
1993	0.48	0.52	0.76	0.52	0.37	0.46	0.42	0.61	0.41	0.55	0.36	0.55	0.52	0.60	0.51	0.51	0.42	0.29	0.42	0.31	0.47	0.46
1994	0.47	0.53	0.75	0.57	0.39	0.44	0.46	0.54	0.50	0.61	0.40	0.57	0.55	0.62	0.56	0.54	0.47	0.31	0.49	0.32	0.53	0.55
1995	0.50	0.56	0.73	0.59	0.40	0.51	0.49	0.60	0.46	0.57	0.44	0.59	0.52	0.65	0.57	0.52	0.42	0.32	0.45	0.33	0.52	0.53
1996	0.48	0.57	0.76	0.58	0.39	0.47	0.47	0.66	0.46	0.56	0.43	0.60	0.53	0.64	0.58	0.49	0.42	0.32	0.45	0.29	0.49	0.50
1997	0.39	0.53	0.75	0.53	0.38	0.42	0.43	0.62	0.39	0.53	0.37	0.57	0.49	0.61	0.50	0.43	0.37	0.32	0.40	0.29	0.45	0.43
1998	0.44	0.56	0.74	0.57	0.43	0.49	0.49	0.60	0.46	0.54	0.43	0.60	0.49	0.62	0.54	0.45	0.40	0.40	0.44	0.40	0.49	0.46
1999	0.47	0.55	0.75	0.56	0.36	0.55	0.45	0.60	0.39	0.55	0.40	0.58	0.51	0.64	0.54	0.45	0.39	0.32	0.40	0.28	0.48	0.44
2000	0.41	0.48	0.74	0.51	0.36	0.41	0.40	0.58	0.36	0.49	0.33	0.50	0.44	0.60	0.49	0.40	0.37	0.24	0.38	0.27	0.41	0.41
2001	0.38	0.55	0.74	0.57	0.31	0.42	0.46	0.56	0.31	0.47	0.40	0.49	0.42	0.62	0.46	0.39	0.32	0.32	0.36	0.24	0.44	0.40
2002	0.46	0.53	0.73	0.54	0.41	0.53	0.44	0.61	0.44	0.56	0.39	0.59	0.50	0.62	0.54	0.47	0.43	0.33	0.44	0.35	0.47	0.46
2003	0.47	0.54	0.74	0.56	0.39	0.50	0.47	0.59	0.43	0.55	0.43	0.58	0.50	0.64	0.51	0.44	0.39	0.34	0.41	0.34	0.47	0.44
2004	0.39	0.53	0.75	0.52	0.35	0.44	0.41	0.58	0.36	0.51	0.37	0.61	0.46	0.60	0.52	0.41	0.37	0.26	0.37	0.29	0.45	0.42
2005	0.45	0.55	0.76	0.53	0.35	0.49	0.41	0.63	0.39	0.55	0.36	0.62	0.50	0.63	0.55	0.45	0.39	0.27	0.39	0.29	0.48	0.44
2006	0.43	0.54	0.72	0.52	0.33	0.43	0.41	0.58	0.35	0.50	0.38	0.58	0.46	0.59	0.50	0.41	0.36	0.31	0.35	0.27	0.44	0.42

APPENDIX C

C.1 *(continued)*: Data for chapter four. Averaged annual NDVI data for sub-watersheds derived from GIMMS AVHRR NDVI data

Sub-watersheds / Year	2FB	2GA	4DC	4AB	2FA	2FC	4DB	4AA	1GE	4DA	1JA	4BB	1JC	1JD	4EC	1JF	1LA1	4AC	2KB	3BB	3DA
1982	0.55	0.54	0.51	0.52	0.46	0.53	0.52	0.56	0.64	0.48	0.67	0.46	0.69	0.75	0.50	0.67	0.64	0.60	0.41	0.40	0.41
1983	0.52	0.53	0.54	0.56	0.45	0.53	0.53	0.59	0.66	0.48	0.69	0.55	0.69	0.77	0.48	0.69	0.66	0.55	0.39	0.44	0.40
1984	0.49	0.49	0.54	0.49	0.39	0.51	0.50	0.54	0.62	0.44	0.68	0.57	0.69	0.74	0.45	0.68	0.64	0.55	0.38	0.39	0.42
1985	0.57	0.60	0.52	0.51	0.48	0.56	0.49	0.67	0.65	0.49	0.69	0.58	0.66	0.75	0.48	0.68	0.64	0.61	0.45	0.45	0.44
1986	0.50	0.49	0.48	0.45	0.42	0.49	0.45	0.52	0.64	0.46	0.64	0.52	0.64	0.74	0.46	0.68	0.63	0.49	0.41	0.41	0.40
1987	0.55	0.51	0.53	0.51	0.44	0.51	0.48	0.62	0.65	0.48	0.68	0.59	0.66	0.74	0.47	0.68	0.65	0.55	0.43	0.43	0.42
1988	0.55	0.52	0.54	0.56	0.47	0.53	0.53	0.61	0.64	0.46	0.69	0.58	0.69	0.75	0.47	0.69	0.65	0.55	0.43	0.38	0.40
1989	0.55	0.52	0.55	0.53	0.45	0.52	0.56	0.58	0.66	0.52	0.67	0.58	0.67	0.74	0.50	0.68	0.67	0.55	0.41	0.45	0.41
1990	0.56	0.55	0.55	0.55	0.45	0.52	0.54	0.60	0.65	0.51	0.69	0.55	0.68	0.75	0.53	0.68	0.68	0.53	0.46	0.47	0.45
1991	0.55	0.53	0.55	0.52	0.41	0.52	0.54	0.59	0.62	0.51	0.67	0.55	0.65	0.75	0.51	0.67	0.65	0.55	0.41	0.39	0.43
1992	0.52	0.51	0.46	0.47	0.45	0.53	0.48	0.55	0.62	0.44	0.69	0.51	0.67	0.76	0.44	0.68	0.66	0.56	0.41	0.41	0.42
1993	0.44	0.45	0.57	0.52	0.43	0.51	0.53	0.60	0.63	0.50	0.67	0.54	0.70	0.74	0.49	0.68	0.64	0.58	0.36	0.42	0.38
1994	0.53	0.46	0.56	0.56	0.42	0.53	0.58	0.57	0.63	0.52	0.68	0.51	0.68	0.74	0.55	0.69	0.67	0.57	0.40	0.47	0.46
1995	0.55	0.53	0.56	0.52	0.48	0.54	0.55	0.61	0.64	0.51	0.67	0.51	0.65	0.75	0.49	0.69	0.68	0.54	0.42	0.44	0.44
1996	0.56	0.54	0.54	0.50	0.45	0.53	0.53	0.55	0.64	0.48	0.69	0.58	0.70	0.75	0.48	0.71	0.67	0.55	0.43	0.42	0.42
1997	0.52	0.48	0.52	0.49	0.44	0.51	0.48	0.53	0.60	0.41	0.68	0.53	0.67	0.74	0.46	0.67	0.66	0.52	0.37	0.35	0.37
1998	0.54	0.52	0.56	0.56	0.48	0.53	0.56	0.59	0.64	0.47	0.67	0.54	0.70	0.75	0.50	0.68	0.67	0.57	0.43	0.43	0.44
1999	0.55	0.51	0.56	0.53	0.46	0.53	0.47	0.57	0.64	0.45	0.70	0.61	0.69	0.75	0.45	0.69	0.65	0.57	0.40	0.39	0.38
2000	0.50	0.44	0.47	0.51	0.37	0.47	0.45	0.54	0.63	0.41	0.66	0.54	0.67	0.74	0.43	0.66	0.62	0.58	0.34	0.41	0.37
2001	0.57	0.50	0.46	0.47	0.45	0.51	0.42	0.54	0.65	0.38	0.68	0.52	0.67	0.74	0.38	0.68	0.66	0.55	0.40	0.38	0.35
2002	0.52	0.48	0.56	0.53	0.42	0.50	0.54	0.60	0.62	0.47	0.66	0.63	0.65	0.75	0.50	0.69	0.64	0.59	0.40	0.38	0.41
2003	0.56	0.53	0.53	0.55	0.48	0.55	0.51	0.59	0.64	0.47	0.67	0.57	0.67	0.75	0.48	0.67	0.65	0.56	0.40	0.41	0.40
2004	0.53	0.48	0.53	0.52	0.40	0.50	0.51	0.54	0.61	0.42	0.67	0.56	0.68	0.74	0.43	0.68	0.64	0.56	0.34	0.37	0.37
2005	0.51	0.47	0.54	0.52	0.42	0.49	0.54	0.55	0.63	0.47	0.69	0.59	0.69	0.75	0.45	0.68	0.65	0.60	0.36	0.39	0.35
2006	0.48	0.50	0.51	0.51	0.43	0.46	0.50	0.56	0.63	0.43	0.67	0.57	0.67	0.72	0.42	0.66	0.63	0.58	0.38	0.34	0.33

Appendix D

D.1: Horticultural export data compiled from HCDA for chapter 6. Volume of cut-flowers exported in kilograms (Kgs) 1995-2013.

Year	2013	2012	2011	2010	2009	2008
January	9,486,854	9,125,556	8,607,248	6,415,006	7,842,900	8,494,942
February	11,109,495	10,126,758	9,516,110	5,397,336	8,204,708	10,178,518
March	10,611,652	10,177,754	9,608,279	6,827,041	8,360,115	9,116,370
April	8,648,768	9,092,465	11,742,090	5,438,125	7,317,019	8,100,433
May	9,470,873	9,200,838	10,066,661	6,251,385	7,478,172	8,120,990
June	6,853,264	7,058,228	8,405,295	4,912,215	6,305,651	6,785,265
July	7,030,427	7,297,942	7,987,898	4,681,899	5,926,346	6,066,317
August	6,592,111	7,772,025	7,998,325	5,283,998	5,611,363	6,239,225
September	8,364,296	8,448,884	8,103,724	5,829,626	6,971,035	6,994,054
October	10,019,802	10,248,297	9,626,065	7,079,424	7,864,568	8,028,538
November	9,104,865	10,111,234	9,533,511	7,536,311	7,498,734	7,909,337
December	8,261,520	9,646,213	8,755,124	2,078,577	7,660,400	7,604,690

Year	2007	2006	2005	2004	2003	2002
January	7,380,320	7,639,490	7,439,649	6,587,111	5,104,881	5,632,625
February	7,908,086	8,128,270	8,001,786	6,678,808	5,938,082	5,244,659
March	9,016,285	8,177,564	8,128,654	6,830,930	6,282,126	4,311,085
April	7,944,455	7,376,655	7,637,096	4,449,128	4,781,390	3,972,238
May	8,020,160	7,541,049	6,926,425	4,786,081	4,588,617	3,553,955
June	6,291,878	5,927,850	5,274,428	4,455,802	3,749,301	2,787,609
July	5,741,009	5,353,742	4,869,158	4,539,071	3,365,902	3,206,463
August	6,136,117	5,942,273	4,939,260	4,811,498	3,654,666	2,808,621
September	7,087,944	6,619,744	5,839,102	6,327,349	5,129,537	4,400,565
October	8,570,848	8,550,923	7,400,169	7,173,514	5,579,497	4,560,242
November	8,580,292	7,725,087	7,291,723	6,941,935	6,381,435	6,617,803
December	8,515,316	7,497,356	7,426,017	7,085,033	3,851,011	4,890,470

Year	2001	2000	1999	1998	1997	1996	1995
January	3,824,958	4,446,160	3,498,868	2,976,695	3,622,113	4,327,022	3,127,312
February	4,212,891	3,230,278	3,749,687	3,283,390	3,461,519	4,011,112	2,902,470
March	3,993,881	3,799,403	3,802,532	3,340,240	4,051,211	3,804,225	3,170,470
April	3,703,557	3,091,223	3,081,073	4,410,968	3,197,936	2,787,801	3,130,231
May	3,674,914	2,578,366	3,040,658	2,257,085	2,814,720	3,003,067	2,935,471
June	2,746,185	2,131,462	2,111,849	1,549,333	3,039,712	1,352,347	1,408,457
July	2,234,665	1,984,083	1,377,394	1,285,780	1,495,140	1,382,072	777,399
August	2,575,081	2,120,350	1,600,099	1,336,317	1,640,578	1,420,249	780,720
September	3,014,560	2,659,358	3,035,462	2,128,060	2,533,403	1,968,314	1,886,000
October	4,100,487	3,261,359	4,001,486	3,113,911	3,558,882	3,229,033	2,866,542
November	3,463,820	4,564,150	3,720,762	3,272,499	3,144,782	4,715,480	3,484,887
December	3,851,011	4,890,470	3,972,275	3,559,107	3,293,012	3,211,524	2,903,580

D.2: Horticultural export data compiled from HCDA for chapter 6. Volume of vegetables exported (Kgs) 1995-201

Year	2013	2012	2011	2010	2009	2008
January	7,377,742	4,297,014	6,293,511	4,499,258	6,046,509	7,522,536
February	8,099,704	3,638,912	5,990,439	3,497,697	5,650,139	7,290,145
March	5,344,514	5,260,571	6,854,471	5,115,801	7,084,753	7,333,601
April	6,363,775	5,488,096	7,732,375	4,559,719	5,716,995	7,603,797
May	5,190,760	5,345,951	7,473,896	5,277,253	5,927,030	7,089,862
June	6,232,137	4,851,028	6,987,621	5,177,564	6,114,911	6,807,456
July	5,113,572	5,212,342	5,234,212	4,990,952	5,723,016	6,602,687
August	5,766,102	4,421,007	6,210,273	5,116,290	5,306,681	6,101,919
September	7,512,305	5,675,823	6,588,570	5,961,331	5,977,275	6,902,423
October	8,090,701	8,266,395	7,016,536	7,103,181	6,494,644	7,067,110
November	6,662,141	6,854,649	6,706,757	6,933,869	6,140,875	6,227,651
December	5,418,881	7,040,374	6,156,997	1,857,330	6,316,774	5,796,129

Year	2007	2006	2005	2004	2003	2002
January	5,889,406	4,934,717	5,885,988	4,522,528	3,728,706	3,038,944
February	4,941,002	5,055,472	4,981,570	4,193,339	4,520,374	3,816,177
March	5,293,645	6,157,110	5,955,461	4,430,299	4,348,716	4,326,978
April	6,310,190	5,436,222	5,803,325	4,253,790	4,697,649	5,168,442
May	6,427,076	4,888,438	5,837,341	4,396,460	4,484,790	3,419,480
June	6,358,883	4,809,840	6,993,778	4,716,118	3,596,266	2,485,971
July	8,805,250	4,808,625	4,538,454	4,239,098	3,320,660	3,059,102
August	7,058,623	4,633,447	4,730,572	2,329,756	2,939,211	3,100,577
September	7,610,319	5,234,789	4,194,172	4,310,321	3,817,514	3,793,268
October	9,480,673	5,211,780	4,838,310	4,807,859	4,106,566	4,753,889
November	9,307,214	5,075,086	4,726,882	4,770,212	4,395,979	4,949,274
December	7,840,956	5,102,078	4,941,189	4,971,726	4,717,732	4,567,365

Year	2001	2000	1999	1998	1997	1996	1995
January	2,678,425	2,634,420	4,365,734	1,723,661	1,902,392	2,687,248	2,172,924
February	2,573,719	2,349,665	4,059,796	1,462,203	2,327,164	2,175,500	2,613,513
March	2,890,415	3,188,546	4,324,289	1,634,374	2,791,685	3,203,122	2,293,614
April	2,644,136	3,534,928	3,874,324	2,762,045	2,773,873	3,315,866	2,334,442
May	2,685,407	3,103,456	4,896,122	2,500,994	3,067,445	2,828,836	2,280,741
June	3,278,072	5,686,336	4,478,054	2,420,589	3,569,238	2,345,101	3,062,955
July	2,910,082	3,115,735	2,967,912	2,241,616	1,919,949	2,562,859	2,090,188
August	1,807,118	3,016,586	2,169,621	2,267,482	2,034,358	2,004,986	1,524,895
September	2,593,042	3,371,677	3,288,764	2,791,849	3,024,377	2,376,022	2,228,668
October	4,187,938	4,535,486	3,873,438	3,531,449	2,598,128	2,815,635	2,516,466
November	2,870,071	6,215,918	4,781,643	3,210,244	2,392,498	2,920,547	2,524,598
December	3,652,458	4,285,970	3,296,895	3,443,448	2,481,194	3,506,309	2,875,612

D.2: Horticultural export data compiled from HCDA for chapter 6. Volume of fruits exported in kilograms (Kgs) 1995-2013

Year	2013	2012	2011	2010	2009	2008
January	1,534,619	1,551,414	1,330,290	799,935	2,382,744	533,399
February	2,367,215	2,287,684	2,024,580	1,393,886	2,624,700	1,431,750
March	3,858,698	3,528,648	4,823,829	2,517,724	2,548,678	2,476,795
April	4,780,724	2,827,103	3,973,358	2,199,178	2,162,588	2,263,940
May	2,473,409	2,480,114	4,298,797	1,864,977	2,217,669	1,727,727
June	2,095,448	3,361,833	2,337,418	2,296,474	2,591,748	1,718,463
July	3,049,394	4,838,504	2,197,643	2,145,595	2,895,301	2,573,049
August	2,647,152	3,675,851	1,919,348	1,850,681	1,852,910	1,653,692
September	1,712,308	2,381,009	965,411	1,474,167	274,183	1,031,313
October	2,181,229	1,193,671	910,055	1,107,454	382,691	484,620
November	1,922,275	1,381,371	1,036,926	1,380,317	573,842	602,773
December	2,484,995	1,562,913	1,233,277	282,810	715,994	625,401

Year	2007	2006	2005	2004	2003	2002
January	1,224,929	805,843	899,178	1,833,189	1,355,320	1,001,833
February	1,753,774	1,379,481	2,112,620	2,563,759	2,454,412	1,058,882
March	1,798,526	2,082,442	2,545,672	3,216,520	4,326,048	2,525,944
April	1,399,787	1,614,174	2,068,497	3,329,629	3,091,928	1,577,991
May	1,219,966	1,485,921	2,734,976	2,103,677	1,829,264	1,615,533
June	1,126,854	2,138,583	1,399,142	2,203,263	2,823,766	1,631,646
July	1,759,631	2,587,442	2,614,486	2,289,130	2,262,850	2,628,124
August	2,386,135	1,411,558	2,494,739	1,523,779	1,549,655	1,929,016
September	1,400,323	298,418	539,718	1,404,987	716,668	1,274,066
October	675,458	505,334	234,618	771,849	1,003,441	2,670,698
November	401,301	528,539	338,186	832,182	1,097,268	2,881,289
December	524,766	567,603	529,981	957,100	1,064,849	1,687,211

Year	2001	2000	1999	1998	1997	1996	1995
January	441,889	603,808	1,044,659	479,495	1,035,872	1,108,528	537,936
February	850,868	1,940,469	1,152,115	1,081,876	825,497	1,632,806	327,975
March	3,378,937	2,549,949	3,364,569	1,302,268	1,454,288	2,878,494	695,985
April	2,714,309	1,602,082	3,122,922	897,670	2,355,143	2,003,507	1,798,805
May	2,125,729	1,566,979	1,847,294	973,769	3,224,679	804,886	1,782,927
June	2,505,273	1,224,594	1,501,436	1,330,988	2,573,788	2,307,097	2,483,375
July	2,672,277	955,825	505,562	489,563	1,978,717	1,366,510	1,320,068
August	1,361,056	1,646,021	276,499	525,598	2,014,817	1,053,268	1,567,846
September	1,014,547	730,225	299,174	747,147	582,457	750,190	784,044
October	1,949,993	474,504	602,844	644,271	358,282	686,002	728,911
November	2,667,282	930,244	808,563	812,905	577,904	958,855	980,548
December	913,294	1,191,096	1,069,570	1,033,564	473,292	1,319,223	857,579

Appendix E

PREFACE

"This Doctoral Dissertation was produced in accordance with guidelines which permit the inclusion as part of the Doctoral Dissertation the text of an original paper, or papers, submitted for publication. Doctoral Dissertation must still conform to all other requirements explained in the "Guide for the Preparation of the Doctoral Dissertation at The Montclair State University." It must include a comprehensive abstract, a full introduction and literature review, and a final overall conclusion. Additional material (procedural and design data as well as descriptions of equipment) must be provided in sufficient detail to allow a clear and precise judgment to be made of the importance and originality of the research reported.

It is acceptable for this Doctoral Dissertation to include as chapters authentic copies of papers already published, provided these meet type size, margin, and legibility requirements. In such cases, connecting texts, which provide logical bridges between different manuscripts, are mandatory. Where the student is not the sole author of a manuscript, the student is required to make an explicit statement in the introductory material to that manuscript describing the student's contribution to the work and acknowledging the contribution of the other author(s). The signatures of the Supervising Committee which precede all other material in the Doctoral Dissertation attest to the accuracy of this statement."

Justus, F., Yu, D., 2014. Spatial Distribution of Greenhouse Commercial Horticulture in Kenya and the Role of Demographic, Infrastructure and Topo-Edaphic Factors. *ISPRS International Journal of Geo-Information*, Vol. 3 No.1,p. 274-296.

Justus, K. F., 2014. Coupled effects on Kenyan horticulture following the 2008/2009 post-election violence and the 2010 volcanic eruption of Eyjafjallajökull. *Natural Hazards*, Vol. 76, No.2, p. 1205-1218.

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