DYNAMICS OF FOREST COVER EXTENT, FOREST FRAGMENTATION AND THEIR DRIVERS IN THE LAKE VICTORIA CRESCENT, UGANDA FROM 1989 TO 2009

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ABSTRACT

Despite the important values forests play in the tropics, sustainable forest management still remains a challenge as manifested through continued forest loss. The objective of this study was to provide information on the dynamics of forest cover and their drivers vital for enhancing sustainable forest management in the Lake Victoria crescent, Uganda. Several methodologies including remote sensing and Geographic Information Systems techniques, analysis of landscape patterns and various social science techniques were integrated in working towards the stated goal. Results showed that the Lake Victoria crescent, Uganda covering an area of about 1,509,228 ha, experienced a decline in forest cover from 9.0% in 1989 to 4.4% in 2009. This was in comparison with non-forest cover which increased from 58.7% in 1989 to 63.5% in 2009 while open water coverage generally remained unchanged averaging 32.3% from 1989 to 2009. Mean annual deforestation rate from 1989 to 2009 decreased with a weighted mean rate of 2.56%. Both deforestation and afforestation declined between 1989 and 2009 although deforestation still exceeded afforestation. In addition to deforestation, the Lake Victoria crescent also experienced forest fragmentation from 1989 to 2009. Forests greater than 100 ha in size were the most vulnerable to forest fragmentation yet they still constituted a big proportion of forest cover in 2009. Deforestation was a consequence of proximate causes which were triggered by a number of underlying drivers acting singly or in combination, with underlying drivers being more influential. In a bid to promote sustainable forest management, there is a need to continue with efforts to curb deforestation and forest fragmentation, especially amongst forests greater than 100 ha. This could be achieved through empowerment of local communities to take a core role in sustainable management of forest resources.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Forest resources are a mainstay in the three pillars of sustainable development namely economy, society and environment (Kayanja and Byarugaba, 2001). Many world economies including Uganda are wholly or partly dependent on forest resources (FAO, 1997). Uganda covers an area of about 24 million ha (UNEP, 2008) of which approximately 4.9 million ha (20%) are under forest cover (MWLE, 2003a).

Uganda's forest resources contribute 6% of the national gross domestic product and employ millions of people (MWLE, 2001; Kayanja and Byarugaba, 2001) in addition to acting as raw materials for various industries. Most of Uganda's population (85.1%) is in rural areas (UBOS, 2008) and generally poor, thus heavily dependent on natural resources like forests for meeting its basic needs (Mwavu and Witkowski, 2008). These include medicine, crafts and furniture, food and flavoring, firewood and charcoal, building materials and timber (Oryem-Origa *et al.*, 2001; UNEP, 2008; MWLE, 2001; Kayanja and Byarugaba, 2001). Forests also act as a catchment for water bodies including Lake Victoria, the second largest fresh water lake in the world. Other environmental services provided by forests include maintenance of high biodiversity (Kayanja and Byarugaba, 2001; UNEP, 2008) and protection of globally important carbon sinks that currently sequester carbon dioxide from the atmosphere thus being critical to future climate stabilization (Stephens *et al.,* 2007).

In developing countries such as Uganda where a large proportion of the human population depends almost entirely on natural resources for their livelihoods, there are increasing competing demands for utilization, development and sustainable management of the land resources (e.g. natural vegetation), resulting in land-use and land-cover changes (Mwavu and Witkowski, 2008). Such land-use and land-cover changes including forest cover change in the tropics are mostly manifested through deforestation (FAO, 2006) and forest fragmentation. Uganda has suffered serious deforestation (Kayanja and Byarugaba, 2001). Because of the important roles played by forests, the threat posed by forest cover loss especially through deforestation and forest fragmentation needs to be addressed so as to avoid negative ecological, environmental, social and economic impacts (Kupfer, 2006).

Although not a panacea, sustainable forest management, if promoted in Uganda, could avert this forest cover loss. Sustainable forest management is defined by the Food and Agriculture Organization of the United Nations (FAO) as "the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems." In spite of the many reforms in management of forest resources in Uganda including policy and legislation such as the Uganda Forestry Policy (MWLE, 2001), the National Forestry and Tree Planting Act (Republic of Uganda, 2003) and the Land Act (Republic of Uganda, 1998), sustainable forest management remains a challenge. This is manifested through illegal forest activities notably pit sawing, charcoal burning, grazing, cultivation and settlement among others (Namaalwa, 2008).

Promotion of sustainable ecosystem management including forests requires detailed accurate and up-to-date resource information (Coppin *et al.*, 2004; Odada *et al.*, 2009). This information is useful in monitoring ecosystem changes to establish linkages between policy decisions, regulatory actions and subsequent ecosystem-use activities (Lunetta *et al.*, 2006). This information among others might include spatial and quantitative information about forest cover dynamics (Odada *et al.*, 2009; Li *et al.*,2009). This is in addition to information about forest landscape patterns which is reported to be vital in addressing a wide range of critical issues such as sustainability, global climate change and carbon budgets (Li *et al.*, 2009). Furthermore, a comprehensive understanding of the drivers of forest cover dynamics is also necessary (Odada *et al.*, 2009).

Some forest cover information about Uganda does exist. For example, according to FAO (2005), Uganda lost about 26.3% of its forest cover between 1990 and 2005. Uganda was also reported to be losing an estimated 55,000 ha per year of forest cover (NEMA, 2001; MWLE, 2002). Most of these estimates of forest cover dynamics are based on regional, continental and or global assessments (Mayaux *et al*., 2005; Nagendra, 2007). Although these estimates are very useful in evaluating long-term trends, their shortcomings include their potential to hide very dramatic local scale situations in addition to their usually being inaccurate due to insufficient ground validation of remotely sensed information (Mayaux *et al*., 2005). There is therefore inadequate detailed and accurate local scale information about forest cover dynamics in Uganda's Lake Victoria crescent which acts a hindrance to promotion of sustainable forest management.

Forest landscape patterns are usually characterized through forest fragmentation. Forest fragmentation refers to a landscape-level process in which forest tracts are progressively sub-divided into smaller, geometrically more complex and more isolated forest fragments as a result of both natural processes and human land-use activities (McGarigal and Marks, 1995). Patterns of forest fragmentation are used to show the condition or trends of forest loss in a particular area or region (Abdullah and Nakagoshi, 2007). Additionally, properties of forested landscapes such as patch size, the amount of edge, the distance between habitat areas, and the connectedness of habitat patches have a direct influence on the flora and fauna (Ripple *et al*., 1991). Despite such implications of forest landscape patterns on forest sustainability, most national and other forest assessments focus solely on the extent of forest loss without concern for forest spatial patterns (Kupfer, 2006). And Uganda is no exception to this trend where assessments focus mainly on forest cover extents. This therefore results in unavailability of information about forest landscape patterns thus presenting another hindrance to promotion of sustainable forest management.

In recognition of the fast disappearance of forests in the tropics, many interventions aimed at either conserving or sustainably managing forest resources ranging from government-owned protected areas to private conservation parks and community reserves have been implemented over time (Nagendra, 2007). However, outcomes of these interventions have been mixed in addition to their variation from one place to the other. The undesirable outcomes are mostly manifested through continuing deforestation. Most of the interventions are based on dominant paradigms or theories specifically about drivers of forest change (deforestation or reforestation) or land-use and land-cover change in general such as population growth leading to deforestation (Nagendra, 2007; Vogt *et al*., 2006). However, most of these paradigms or theories are a result of studies conducted at regional, national, continental or global scales (e.g. Geist and Lambin, 2002; Nagendra, 2007). Other interventions are based on knowledge about drivers of forest change obtained from local scale studies which usually consist of a single study (e.g. Mwavu and Witkowski, 2008). Apart from this single case scenario making the study scale too narrow, it hinders comparison necessary for developing generalizations at the local scale. Therefore, the too broad or too narrow scale at which dominant paradigms or theories about drivers of forest cover change were developed in addition to their variations with geographical context might be accounting for the inadequacy of some of the interventions developed to promote sustainable forest management.

1.2 GOALS OF THE STUDY

The goal of this study was to contribute to promotion of sustainable forest management in the Lake Victoria crescent, Uganda. To achieve this goal, it was deemed important to address identified knowledge gaps that were hindering promotion of sustainable forest management that arose out of the lack of or inadequacy of information about forest cover dynamics, forest fragmentation, and drivers of forest cover dynamics.

1.3 OBJECTIVES OF THE STUDY

1.3.1 Objective 1: Assess forest cover dynamics in the Lake Victoria crescent from 1989 to 2009

It was hypothesized that forest and other land-cover in the Lake Vicroria crescent had been changing since 1980s. It was therefore necesssary to assess forest and other land-cover change as a way of acquiring information about its dynamics. This assessment was aimed at answering the following questions: (i) What was the composition of forest and other land-cover in the Lake Victoria crescent at different times from 1989 to 2009?, (ii) What was the trend of changes in forest and other land-cover in the Lake Victoria crescent from 1989 to 2009?, and (iii) What was the spatial distribution of forest and other land-cover dynamics in the Lake Victoria crescent from 1989 to 2009? This was implemented through standard remote sensing and Geographic Information Systems techniques which have been widely used in addressing a wide variety of resource management problems including assessment of forest cover change and its causes (Gautam *et al*., 2004) at different scales. The resulting information was hoped to play a vital role in creating an understanding of the dynamics of local forest and other land-cover among forest stakeholders upon which the design of locally innovative and sustainable forest management interventions would be based, thus enhancing sustainable forest management. This objective is the focus of chapter two.

1.3.2 Objective 2: Characterize forest fragmentation in the Lake Victoria crescent from 1989 to 2009

Because of the heavy dependency of the human population on forest resources, it was hypothesized that changes in forest landscape patterns in the form of forest fragmentation occurred in the Lake Victoria crescent from 1989 to 2009. Due to the absence of a single universal measure of forest fragmentation, a number of landscape metrics which included number of patches, total area, patch size, shape index, largest patch index, aggregation index and contagion index were evaluated using Fragstats software (McGarigal and Marks, 1995) to determine their variability from time to time. The variability of landscape metrics was then used in assessing forest fragmentation. Knowledge of the trends of forest fragmentation was hoped to help forest protection efforts in identifying which forests were most at risk of being converted to non-forest. This knowledge might also act as a baseline upon which other decisions with regard to promotion of sustainable forest management would be made. This objective is the focus of chapter three.

1.3.3 Objective 3: Determine key drivers of deforestation in the Lake Victoria crescent from 1989 to 2009

In view of the loss of forest cover in the Lake Victoria crescent from about 9.0% in 1989 to 4.4% in 2009 despite several interventions, it was deemed necessary to acquire a comprehensive theoretical understanding of the drivers of deforestation. This was to be achieved through a case study approach with a multiple-case design (Yin, 2009; Eisenhardt, 1989) because of its ability to test and generate theory (Eisenhardt, 1989). Understanding drivers of deforestation was hoped to act as a basis for development of useful policy interventions to curb forest cover loss (Nagendra, 2007), especially occurring in the form of deforestation. This objective is the focus of chapter four.

1.4 STUDY AREA

The study area is located between 0˚8´S and 0˚42´N and between 32˚5´and 33˚32´E. It encompasses all or parts of Mayuge, Iganga, Jinja and Kamuli districts in eastern Uganda and all or parts of Kayunga, Mukono, Luwero, Kampala, Wakiso, Mpigi, Mityana, Nakaseke and Kiboga districts in central Uganda. The study area measures about 162 by 94 km, an equivalent of 1,509,328 ha (Fig.1.1). This area is referred to as Lake Victoria crescent.

Uganda lies astride the equator and thus has a climate typical of equatorial regions. However the climate in the southern part of Uganda including the Lake Victoria crescent is modified by maritime conditions due to closeness to Lake Victoria in addition to altitudinal effects as this area is over 1,000 m asl. The temperatures range between 15 ºC and 30 ºC. The rainfall has a bimodal distribution with two fairly well marked seasons which are March-June and October/November-December/January. The rainfall averages 1,200 to 1,500 mm and is well distributed (NEMA, 2006/07; NEMA, 2008).

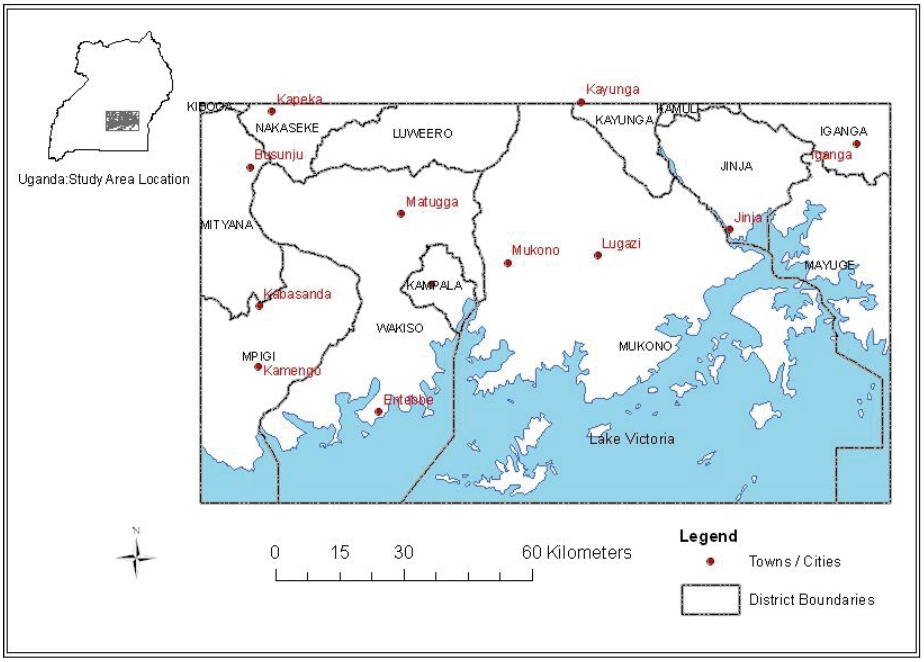

Figure 1.1 Study Area

Of Uganda's forests and woodlands covering 4.9 million hectares (NEMA, 2006/07), a substantial portion of them, including both natural forests (Namaalwa, 2008; UNEP, 2008) and plantation forests of different sizes, lie within the Lake Victoria crescent (NEMA, 2004/05). Since most forests on private land have been heavily degraded and about 1.9 million ha of natural forest are protected areas, only Central and Local Forest Reserves remain available for various uses (NEMA, 2006/07). Indeed, the human population in this densely populated area is heavily dependent on forest resources for human livelihood needs (Mwavu and Witkowski, 2008; Oryem-Origa *et al*., 2001). The area's economy is majorly dependent on agriculture, both small and large scale. However, other economic activities associated with urbanization do exist.

This area was therefore selected for this study because of the presence of many types of forests of different sizes and management profiles in a densely populated area with the human population known to depend on forest resources for its livelihood. Additionally, this area possessed Landsat imagery with less cloud cover for at least two points in time since 1989 that could facilitate time series analysis.

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CHAPTER TWO

FOREST COVER DYNAMICS IN THE LAKE VICTORIA CRESCENT, UGANDA

2.1 ABSTRACT

Massive forest cover loss continues to occur especially in the tropics. In order for interventions to address forest cover loss to be developed, quantitative and spatial information about forest and other land-cover dynamics is required. Unfortunately, this information is usually unavailable as processes of forest cover loss have not been sufficiently studied in parts of the tropics. This study therefore sought to investigate forest and other land-cover dynamics in the Lake Victoria crescent since 1980s. Landsat Thematic Mapper and Enhanced Thematic Mapper Plus images for 1989, 1995, 2002 and 2009 each covering an area of 1,509,328 ha were pre-processed and classified using the unsupervised technique. This was followed by post-classification comparison change detection. The three land-cover classes which were clearly discriminated include open water, forest and non-forest. Mean overall accuracy for all classifications was 98.0% while mean kappa statistic was 0.96. Forest cover declined from 9.0% in 1989 to 4.4% in 2009 while non-forest cover increased from 58.7% in 1989 to 63.5% in 2009. Open water coverage generally remained unchanged with a mean coverage of 32.3%. Estimates of mean annual rates of deforestation from 1989 to 2009 exhibited a declining trend with a weighted mean of 2.56%. Land-cover conversion from non-forest to forest and vice-versa generally declined. A visual assessment showed deforestation to have a clustered spatial distribution. The revealed forest and other land-cover dynamics demonstrate the continued forest loss and need for sustainable forest management interventions in the Lake Victoria crescent.

Key Words: Landsat, Deforestation, Land-cover Inter-conversions, Sustainable Forest Management, Uganda

2.2 INTRODUCTION

Forest resources are a mainstay in the three pillars of sustainable development namely economy, society and environment (Kayanja and Byarugaba, 2001). Many world economies including Uganda are wholly or partly dependent on forest resources (FAO, 1997). Uganda covers an area of about 24,000,000 ha (UNEP, 2008) of which approximately 4,900,000 ha (20%) are forested (MWLE, 2003).

Uganda's forest resources contribute 6% of the national gross domestic product and employ many people (Kayanja and Byarugaba, 2001; MWLE, 2001) in addition to acting as raw materials for various industries. Most of Uganda's population (85.1%) is in rural areas (UBOS, 2008) and generally poor, thus heavily dependent on natural resources like forests for meeting its basic needs (Mwavu and Witkowski, 2008). These include medicine, crafts and furniture, food and flavoring, firewood and charcoal, building materials and timber (Kayanja and Byarugaba, 2001; MWLE, 2001; Oryem-Origa *et al.*, 2001; UNEP, 2008). Forests also act as a catchment for water bodies including Lake Victoria, the second largest fresh water lake in the world. Other environmental services provided by forests include maintenance of high biodiversity (Kayanja and Byarugaba, 2001; UNEP, 2008) and protection of globally important carbon sinks that currently sequester carbon dioxide from the atmosphere and thus are viewed as critical to future climate stabilization (Stephens *et al*., 2007).

In developing countries such as Uganda where a large proportion of the human population depends almost entirely on natural resources for their livelihoods, there are increasing competing demands for utilization, development and sustainable management of the land resources (e.g. natural vegetation), resulting in land-use and land-cover changes (Mwavu and Witkowski, 2008). The resulting land-use and land-cover change is best exemplified in deforestation (FAO, 2006; Odada *et al.*, 2009). Massive deforestation continues to occur in the tropics (Nagendra, 2007) including Uganda (Kayanja and Byarugaba, 2001; MWLE, 2002; NEMA, 2001). Forest cover loss through deforestation therefore poses a threat that needs to be addressed if forests are to continue providing goods and services important for sustaining human livelihoods.

Although not a panacea, sustainable forest management, if promoted in Uganda, could avert this forest cover loss. In spite of the many reforms regarding management of forest resources in Uganda, sustainable forest management remains a challenge (Namaalwa, 2008).

Promotion of sustainable ecosystem management requires accurate and up-to-date resource infomation (Coppin *et al.*, 2004; Odada *et al.*, 2009) useful in monitoring ecosystem changes to establish linkages between policy decisions, regulatory actions and subsequent land-use (ecosystem-use) activities (Lunetta *et al.*, 2006). However, this information is not readily available especially in Africa due to insufficient studies about processes of deforestaion (Lung and Schaab, 2010). Indeed, Africa has the lowest known rates of forest conversion despite having the second largest amount of rainforest in the world (Baccini *et al*., 2008).

This study investigated forest and other land-cover dynamics in the Lake Victoria crescent since the 1980s. The study objectives were to: (i) Stratify forest and other land-cover in the Lake Victoria crescent since the 1980s, (ii) Assess forest and other land-cover dynamics in the Lake Victoria crescent since the 1980s, and (iii) Map the spatial distribution of forest and other land-cover dynamics in the Lake Victoria crescent since the 1980s. The resulting information would be vital in creating an understanding of the dynamics of local forest and other land-cover among forest stakeholders upon which locally innovative and sustainable forest management interventions to benefit both people and nature would be designed, thus enhancing sustainable forest management.

2.3 MATERIALS AND METHODS

2.3.1 Study Area

The study area is located between 0˚8´S and 0˚42´N and between 32˚5´and 33˚32´E. It encompasses all or parts of Mayuge, Iganga, Jinja and Kamuli districts in eastern Uganda and all or parts of Kayunga, Mukono, Luwero, Kampala, Wakiso, Mpigi, Mityana, Nakaseke and Kiboga districts in central Uganda. The study covers an area of 1,509,328 ha (Fig.2.1). This area is referred to as Lake Victoria crescent. This area was selected because of being one of the most forested areas in Uganda (NEMA, 2005/05). It was characterized by high population densities with the local population heavily dependent on forest resources for human livelihood needs. It was also an area for which imagery with less cloud cover since 1989 could be obtained.

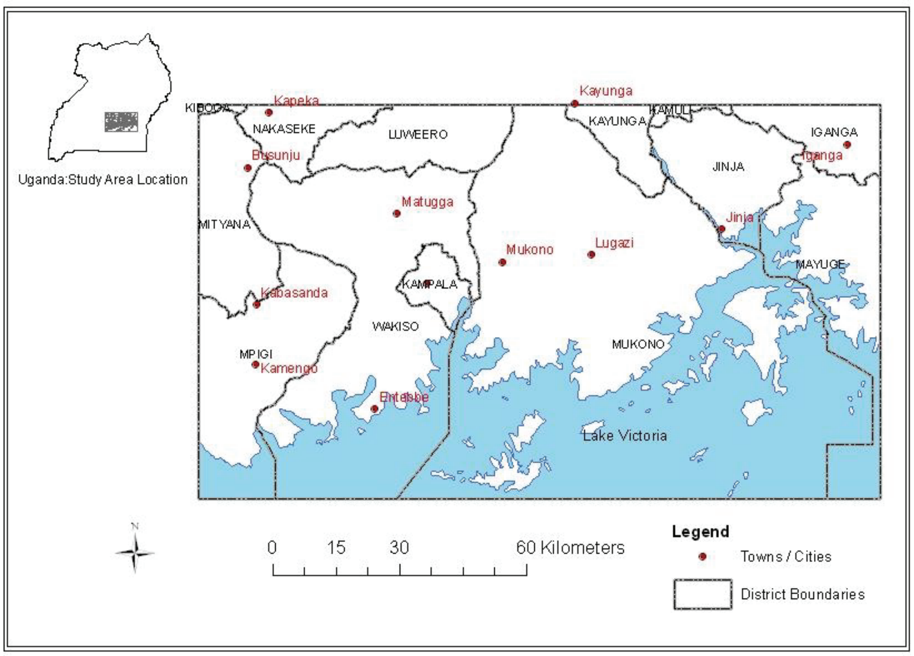

Figure 2.1 Study Area

2.3.2 Image Data Acquisition, Pre-processing and Classification

Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) imagery (Table 2.1) corresponding to Path 171 Row 060 (p171r060) which covers the study area (Fig.2.1) were obtained from United States Geological Survey (USGS). Efforts were made to obtain images with as low cloud cover as possible in addition to obtaining images from one season to reduce seasonal effects. Although some of the scenes exhibited high cloud cover, the scene portions corresponding to the study area were either clear or low in cloud cover.

Table 2.1 Landsat TM/ETM+ image dates used in the study

Satellite Sensor	Date	Cloud Cover (%)
Landsat 4 TM	27 February 1989	0
Landsat 5 TM	19 January 1995	0
Landsat 7 ETM+	27 November 2001	4
Landsat 7 ETM+	09 July 2002	5
Landsat 7 ETM+	17 January 2009	01
Landsat 7 ETM+	28 July 2009	13
Landsat 7 ETM+	01 January 2009	15
Landsat 7 ETM+	29 August 2009	26
Landsat 7 ETM+	27 September 2008	10
Landsat 7 ETM+	16 December 2008	43
Landsat 7 ETM+	16 February 2008	23

The processing of the time-series data (1989, 1995, 2002 and 2009) generally followed the outline in Fig.2.2. Pre-processing involved reprojection of the 1995 image from WGS 1984 UTM Zone 36S to WGS 1984 UTM Zone 36N, the coordinate system for all the other images. The 2002 time-series dataset was created by subsetting 27 November 2001 and 09 July 2002 images to extract cloud-free subsets which were then mosaicked. The 2009 time-series data exhibited data gaps manifested as strips as a result of the failure of the Landsat 7 scan-line corrector (SLC) on May 31, 2003. Hence, the 2009 time-series data were SLC-off. It was therefore necessary to perform gap-filling before any other processing could be performed on the 2009 image. This was done using NASA's Frame_and_Fill_win32 program (Irish, 2009). The 17 January 2009 image was used as the anchor (base) image for the 2009 time-series with the 28 July 2009, 27 September 2008, 16 February 2008, 16 December 2008, 01 January 2009 and 29 August 2009 images as fill scenes 1, 2, 3, 4, 5 and 6 respectively. All the fill scenes exhibited relatively high cloud cover. However, most of the cloud cover was outside the study area and therefore was not expected to greatly affect the output 2009 filled scene. The 1989, 1995, 2002 and 2009 time series images were then subset or clipped to conform to the extent of the study area. Additionally, the 09 July 2002 image was also subset to conform to the study area.

Unsupervised classification (Jensen, 1996) was performed on each time-series image including the 09 July 2002 image. Unsupervised classification utilizing the Iterative Self-Organizing Data Analysis Techniques (ISODATA) was deemed appropriate because of the inaccessibility of ground and or reference data such as aerial photographs that would aid in the selection of training points, a prerequisite for supervised classification. This was implemented using ERDAS IMAGINE software version 9.2. The number of spectral classes was set to 30 with a convergence threshold of 0.95. Spectral classes were labeled and recoded to generate classified images with 3 classes (open water, forest and non-forest) and 2 classes (forest and non-forest). A majority statistical filter (3 by 3 pixels) was applied to the recoded images to reduce "salt and pepper" effect of scattered isolated pixels to create the final time-series classified images with exception of 2002 image. The filter also ensured that areas classified as forests conformed with the acceptable definition of forest as covering a minimum of 0.5 ha (FAO, 2000).The 2002 final time series classified image was created by mosaicking the 2002 classified and filtered image with a subset of the classified and filtered 09 July 2002 image which further minimized cloud cover effects.

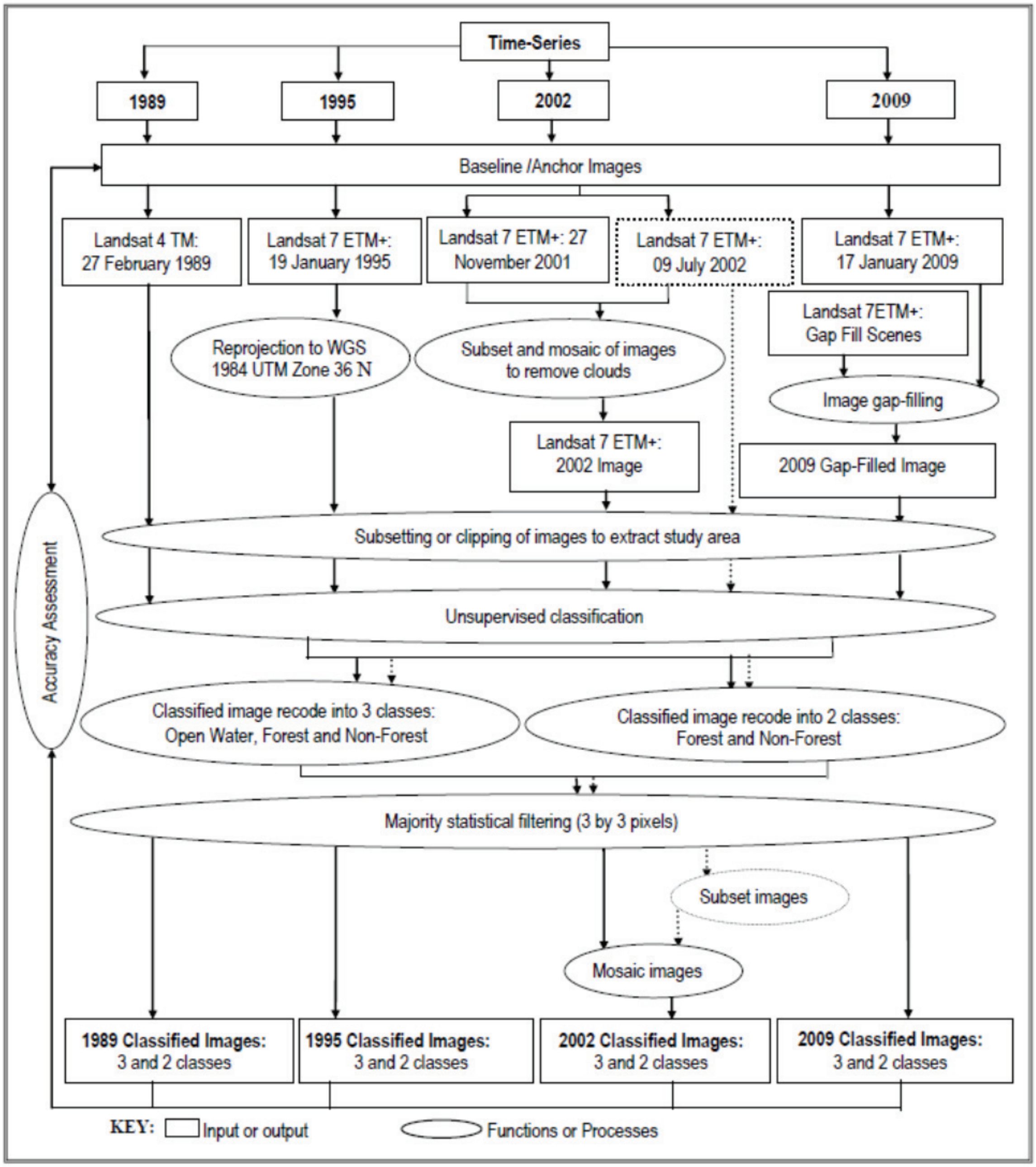

Figure 2.2 Processing methodology for Landsat satellite time series data

2.3.3 Accuracy Assessment

Due to limitations with collecting in-situ field data for accuracy assessment, reference data was extracted from the four original time series unclassified images i.e. 1989, 1995, 2002 and 2009 (Wynne *et al*., 2007). This involved randomly locating 699 points within the study area. Each point was visually (manually) classified as open water, non-forest or forest with respect to each of the five original unclassified 432 false color composite images to create a classification accuracy assessment reference dataset (Lung and Schaab, 2010). High resolution historical imagery from Google Earth was used in verifying the reliability of the visual accuracy assessment. This involved importing the 699 random points into Google Earth. Using the historical imagery time slider in Google Earth to select imagery that corresponded with the time series imagery, a sub-sample of the 699 points was interpreted as open water, non-forest or forest to create another reference dataset. However, only Google Earth images for 2002 and 2009 were available, and hence the only images utilized for accuracy assessment.

In conformance with standard accuracy assessment techniques, error matrices were produced and used to compute user's accuracy, producer's accuracy and overall accuracy for each classification. In addition, for each classification, kappa (κ) was computed using equation (i) to determine how much better the classification was than chance alone (Campbell, 2007).

$$\kappa = \frac{Observed - Expected}{1 - Expected} \qquad \text{(i)}$$

where: Observed = Overall value for percent correct and

Expected = Estimate of the contribution of chance agreement to the observed percent correct

In order to determine the reliability of each of the computed kappa statistic, a Z-score based on kappa variance was computed using equation (ii) (Congalton and Green, 1999).

$$z_{\kappa} = \frac{\kappa}{\sqrt{(var(\kappa)}} \qquad \text{(ii)}$$

where: κ = kappa statistic

var (κ) = kappa variance

2.3.4 Land-cover Class Area Estimation

One of the aims of this analysis was to determine temporal variations in area estimates associated with the various land-cover classes in the Lake Victoria crescent. These estimates had to be obtained from the maps obtained through image classification through counting pixels corresponding to each land-cover type. However, these area estimates would be unreliable as they would not have any indication of error (Switzer, 1969 cited in

Card, 1982). Landsat Thematic Mapper classification maps, which have been used as a basis for computing reliable forest area estimate that include error estimates (Wynne *et al.*, 2000) were deemed appropriate in this endeavor. Taking into consideration that the accuracy assessment dataset used in this study consisted of a simple random sample of points, methods specifically designed for this type of dataset in Card (1982) were adopted. Using the error matrices (Appendix A) and marginal proportions (Appendix B and C), acquisition of reliable or corrected area estimates involved a determination of true marginal proportions for each land-cover category based on the known map marginal proportions. This was followed by calculation of the variance of each estimate of true marginal proportion and finally the 95% confidence intervals for each estimate of the true marginal proportion.

In implementing the above, the following terms were used:

γ_{f} = True marginal proportion for forest class

γ_{nf} = True marginal proportion for non-forest class

γ_{ow} = True marginal proportion for open water class

$ß_{f}$ = Map marginal for forest class

$ß_{nf}$ = Map marginal for non-forest class

$ß_{ow}$ = Map marginal for open water class

α_{f_f} = Percent forest pixels that were forest

α_{f_nf} = Percent forest pixels that were non-forest

α_{f_ow} = Percent forest pixels that were open water

μ_{nf_nf} = Percent non-forest pixels that were non-forest

μ_{nf_f} = Percent non-forest pixels that were forest

μ_{nf_ow} = Percent non-forest pixels that were open water

$þ_{ow\_ow}$ = Percent open water pixels that were open water

$þ_{ow\_f}$ = Percent open water pixels that were forest

$þ_{ow\_nf}$ = Percent open water pixels that were non-forest

δ_{pf} = Variance of percent forest

δ_{pnf} = Variance of percent non-forest

δ_{pow} = Variance of percent open water

ϕ = Total number of ground plots

Equations (iii) to (v) were used for calculating true marginal proportions while equations (vi) to (viii) were used for calculating variances of the true marginal proportions. Equation (ix) was used to compute the 95 percent interval estimates of percent area.

$$\gamma_f = ((ß_f)(\alpha_{f\_f})) + ((ß_{nf})(\mu_{nf\_f})) + ((ß_{ow})(þ_{ow\_f})) \quad \text{(iii)}$$

$$\gamma_{nf} = ((ß_{nf})(\mu_{nf\_nf})) + ((ß_f)(\alpha_{f\_nf})) + ((ß_{ow})(þ_{ow\_nf})) \quad \text{(iv)}$$

$$\gamma_{ow} = ((ß_{ow})(þ_{ow\_ow})) + ((ß_f)(\alpha_{f\_ow})) + ((ß_{nf})(\mu_{nf\_ow})) \quad \text{(v)}$$

$$\delta_{pf} = \frac{((ß_f)-(ß_f)(\alpha_{f\_f}))(ß_f)(\alpha_{f\_f})}{ß_f*\phi} + \frac{((ß_{nf})-(ß_{nf})(\mu_{nf\_f}))(ß_{nf})(\mu_{nf\_f})}{ß_{nf}*\phi} + \frac{((ß_{ow})-(ß_{ow})(þ_{ow\_f}))(ß_{ow})(þ_{ow\_f})}{ß_{ow}*\phi} \quad \text{(vi)}$$

$$\delta_{pnf} = \frac{((ß_{nf})-(ß_{nf})(\mu_{nf\_nf}))(ß_{nf})(\mu_{nf\_nf})}{ß_{nf}*\phi} + \frac{((ß_f)-(ß_f)(\alpha_{f\_nf}))(ß_f)(\alpha_{f\_nf})}{ß_f*\phi} + \frac{((ß_{ow})-(ß_{ow})(þ_{ow\_nf}))(ß_{ow})(þ_{ow\_nf})}{ß_{ow}*\phi} \quad \text{(vii)}$$

$$\delta_{pow} = \frac{((ß_{ow})-(ß_{ow})(þ_{ow_{ow}}))(ß_{ow})(þ_{ow_{ow}})}{ß_{ow}*\phi} + \frac{((ß_{nf})-(ß_{nf})(\mu_{nf_{ow}}))(ß_{nf})(\mu_{nf_{ow}})}{ß_{nf}*\phi} + \frac{((ß_f)-(ß_f)(\alpha_{f_{ow}}))(ß_f)(\alpha_{f_{ow}})}{ß_f*\phi} \quad \text{(viii)}$$

95% Area Interval estimate = Estimate of true marginal proportion ± 2√ (variance) (ix)

2.3.5 Rates of Deforestation

Using corrected area estimates of forest cover, mean annual deforestation rates between different image dates were computed using equation (x). The deforestation rates that were computed covered the periods 1989 to 1995, 1989 to 2002 and 1989 to 2009.

$$Mean\ Annual\ Deforestation\ Rate\ from\ T_1\ to\ T_2\ (\%) = \frac{T_1\ Forest\ Area - T_2\ Forest\ Area}{T_1\ Forest\ Area * (T_2 - T_1)} * 100 \quad \text{(x)}$$

where: T_1 = the baseline year (1989)

T_2 = the acquisition year for the second image

A weighted mean annual rate of deforestation from the three deforestation estimates (1989 to 1995, 1989 to 2002 and 1989 to 2009) was subsequently computed to obtain an independent estimate of mean annual deforestation for the period 1989 to 2009.

2.3.6 Change Detection

The aim of change detection was to obtain spatial and quantitative information about periodic conversions of land-cover from forest to non-forest and vice-versa. Although many methods for change detection using satellite imagery exist including univariate image differencing, composite analysis, post-classification comparison and image ratioing among other approaches (Coppin *et al.*, 2004), post-classification comparison change detection was selected. This was because post-classification comparison also referred to as delta classification is the most commonly used quantitative method of change detection with the major advantage of providing 'from-to' change class information (Coppin *et al.*, 2004; Jensen, 1996).

Post-classification comparison change detection on a pixel by pixel basis was therefore implemented using the binary (forest and non-forest) time series classification images. The generated matrix enabled identification of periodic conversions of land-cover from forest to non-forest and vice-versa. The time series comparisons were 1989 to 1995, 1995 to 2002 and 2002 to 2009. Area statistics associated with the changes were computed based on number of pixels in each change category. The time series change detection maps were overlaid to determine the spatial distribution of land-cover inter-conversions.

2.4 RESULTS

2.4.1 Forest and other Land-cover Stratification

Three land-cover classes namely open water, non-forest and forest were discriminated through unsupervised classification of the Landsat imagery for 1989 (Fig. 2.3), 1995 (Fig. 2.4), 2002 (Fig. 2.5) and 2009 (Fig. 2.6).

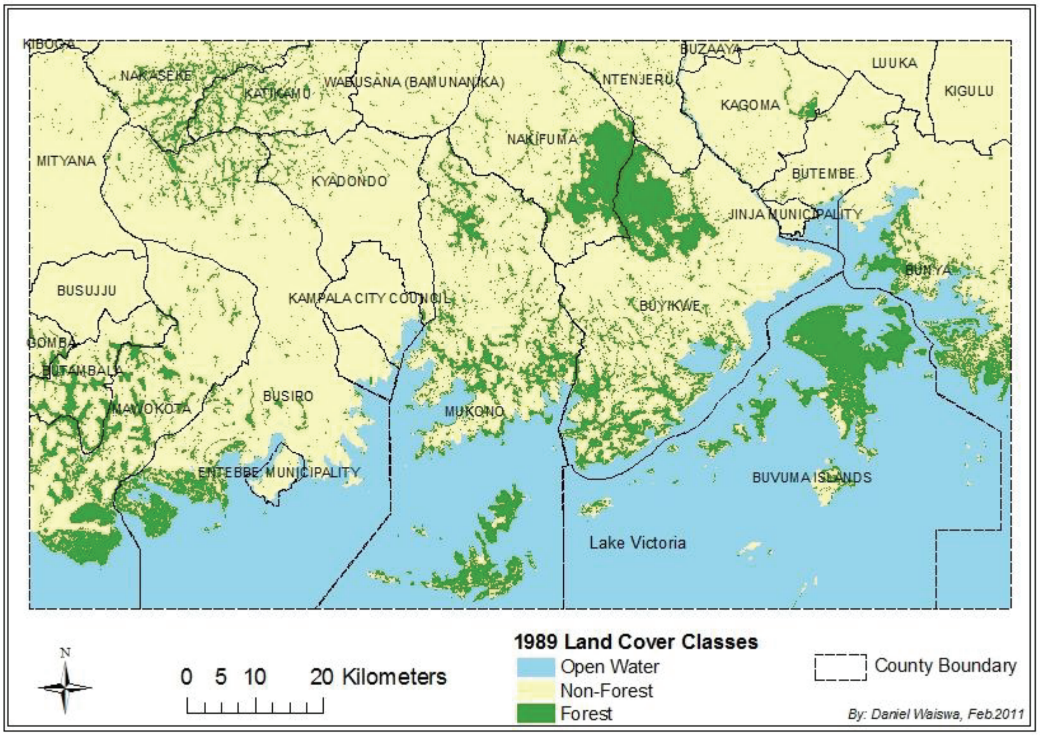

Figure 2.3 Land cover categorical map of the Lake Victoria crescent, Uganda in 1989 showing open water, non-forest and forest land-cover classes

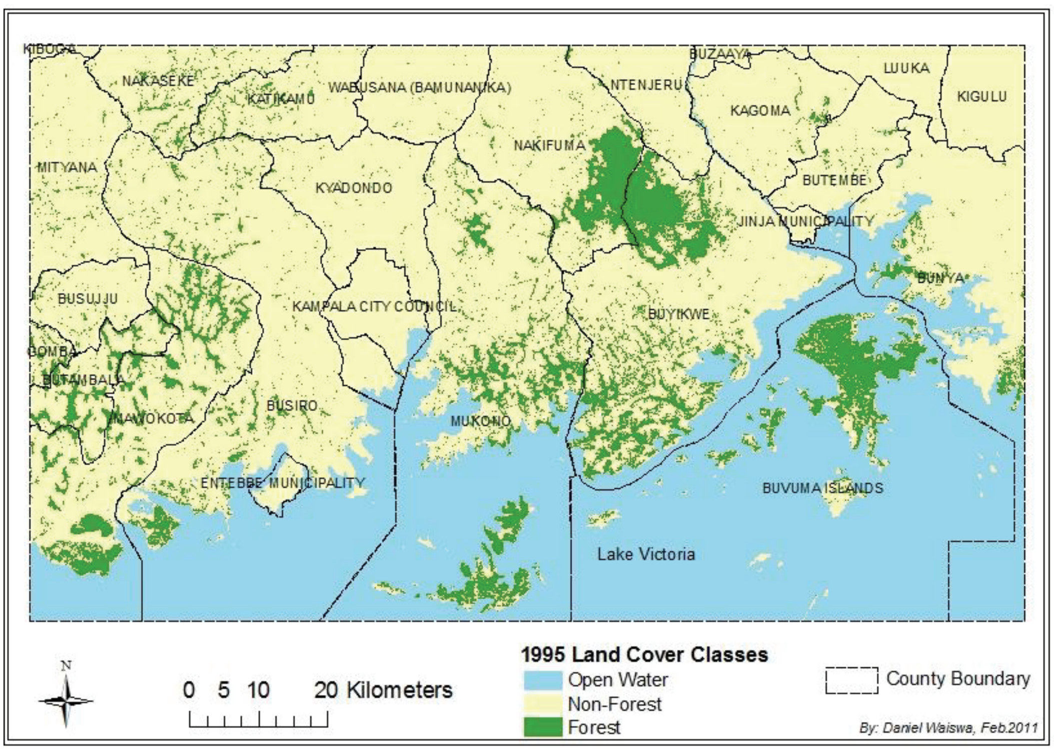

Figure 2.4 Land-cover categorical map of the Lake Victoria crescent, Uganda in 1995 showing open water, non-forest and forest land-cover classes

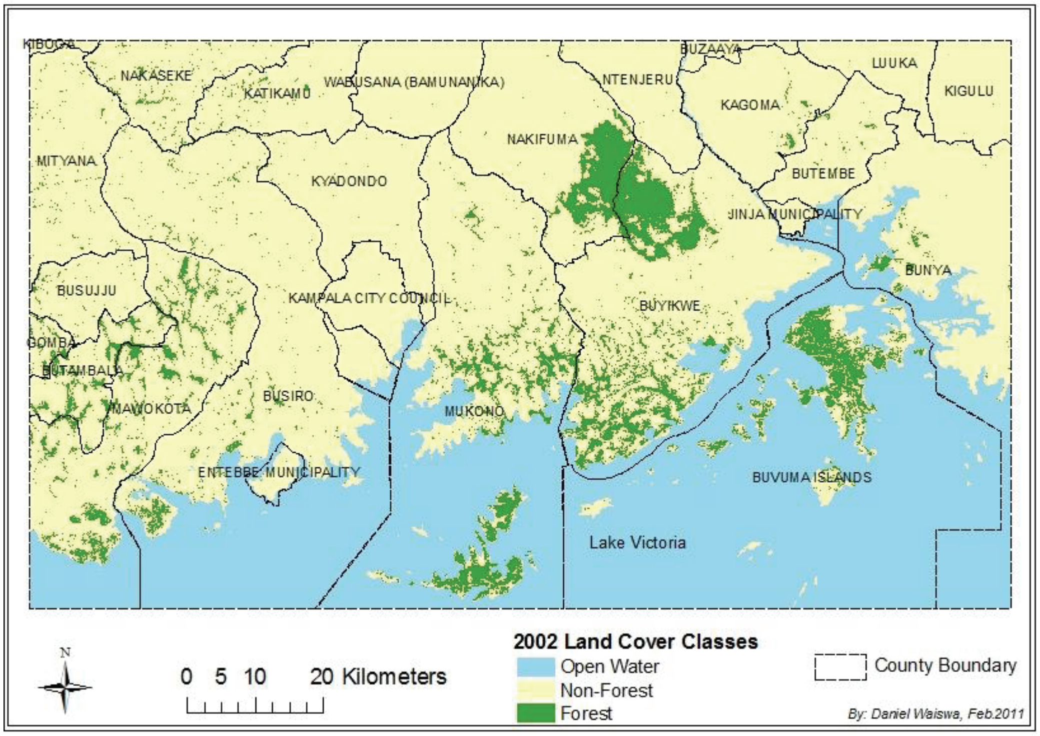

Figure 2.5 Land-cover categorical map of the Lake Victoria crescent, Uganda in 2002 showing open water, non-forest and forest land-cover classes

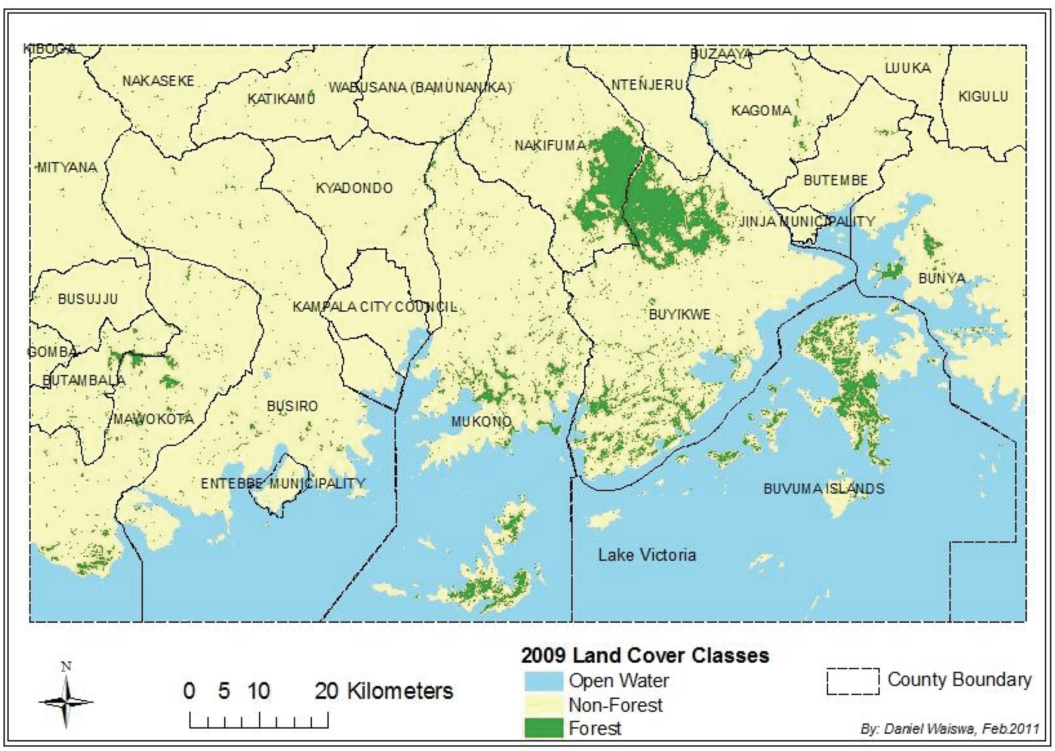

Figure 2. 6 Land-cover categorical map of the Lake Victoria crescent, Uganda in 2009 showing open water, non-forest and forest land-cover classes

2.4.2 Accuracy Assessment

Based on a visual comparison of the same 699 random points in the study area between the classified images and their corresponding original satellite images, producer's accuracy for forest class averaged 84.5% while user's accuracy averaged 89.1% for all classifications. This was in comparison with producer's accuracy for non-forest and open water classes which averaged 98.3% and 99.9% while their user's accuracy averaged 98.0% and 99.1% respectively. Overall accuracy ranged from 97.1% to 98.1%.The kappa statistic ranged from 0.95 to 0.96 for all classifications with all associated Z-scores greater than 1.96 (Table 2.2).

Using the Google Earth interpreted points as a reference dataset, overall accuracy for the 2002 image classification was 97.7% with a kappa statistic of 0.97 and Z-score of 7.45. The overall accuracy, kappa statistic and Z-score for the 2009 image classifications was 91.7%, 0.91 and 4.84 (Table 2.3).

Table 2.2 Producer's and user's accuracies with associated overall accuracy, kappa and Z-scores for each classification based on visually interpreted reference dataset

Image Date	Forest		Non-Forest		Open Water		Overall Accuracy (%)	Kappa	Z-Score
	Producer's Accuracy (%)	User's Accuracy (%)	Producer's Accuracy (%)	User's Accuracy (%)	Producer's Accuracy (%)	User's Accuracy (%)			
1989	83.8	91.2	98.0	97.1	100	99.1	97.1	0.95	32.44
1995	86.4	91.1	98.1	98.1	100	98.7	97.7	0.96	31.92
2002	84.3	93.5	98.8	98.1	100	99.1	98.1	0.95	31.50
2009	83.3	80.6	98.4	98.6	99.6	99.6	98.1	0.96	29.76

Table 2.3 Overall accuracy and kappa statistics for each classification based on Google Earth reference dataset

Image Date	Overall Accuracy (%)	Kappa Statistic	Z-Score
2002	97.7	0.97	7.45
2009	91.7	0.91	4.84

2.4.3 Forest and other Land-cover Change Analysis

Land-cover change analysis focused on quantifying the composition of land-cover types in the study area and assessing inter-conversions between forest and non-forest land-cover types since the 1980s. Additionally, rates of deforestation were determined as deforestation was the most visible form of land-cover change.

A quantitative examination of the composition of each discriminated land-cover class in the entire study area encompassing about 1,509,328 ha revealed that forest cover varied from 9.0 ± 0.5% in 1989 to 4.4 ± 0.5% in 2009. Meanwhile, non-forest cover varied from 58.7 ± 0.6% in 1989 to 63.5 ± 0.5% in 2009. Open water varied from 32.3 ± 0.2% in 1989 to 32.1 ± 0.2% in 2009 (Table 2.4).

Table 2.4 The 95 percent interval estimate of percent land-cover class area

Land-cover Class	**Image Dates**			
	1989	**1995**	**2002**	**2009**
	Area Interval Estimate (%)	Area Interval Estimate (%)	Area Interval Estimate (%)	Area Interval Estimate (%)
Forest	9.0 ± 0.5	7.6 ± 0.5	6.0 ± 0.4	4.4 ± 0.5
Non-forest	58.7 ± 0.6	59.9 ± 0.5	61.7 ± 0.5	63.5 ± 0.5
Open Water	32.3 ± 0.2	32.5 ± 0.3	32.3 ± 0.2	32.1 ± 0.2

With the 1989 forest cover as the baseline, the mean annual deforestation rate from 1989 to 1995 was 2.59%. This was in comparison with the mean annual deforestation rate of 2.56% from 1989 to 2002 and remained unchanged from 1989 to 2009. The weighted mean annual deforestation rate from 1989 to 2009 was 2.56%.

A quantitative assessment of land-cover conversions from forest to non-forest and vice-versa determined through post-classification change detection on the binary (forest/non-forest) classified images revealed varying trends of land-cover change dynamics (Table 2.5). In the entire study area measuring 1,509,328 ha, 26,447 ha (1.75%) underwent conversion from non-forest to forest while 62,248 ha (4.12%) changed from forest to non-forest from 1989 to 1995. From 1995 to 2002, 11,035 ha (0.73%) converted from non-forest to forest compared with 53,000 ha (3.51%) from forest to non-forest. From 2002 to 2009, 15,151 ha (1.00%) converted from non-forest to forest compared with 49,768 ha (3.30%) from forest to non-forest. The general trend as manifested by the net change in land-cover inter-conversions shows continued forest cover loss.

Table 2.5 Land-cover inter-conversions between forest and non-forest classes

Land-cover Conversion	**Image Dates**		
	1989 to 1995	**1995 to 2002**	**2002 to 2009**
	Area (ha)	Area (ha)	Area (ha)
Non-Forest to Forest	26447	11035	15151
Forest to Non-Forest	62248	53000	49768
Net Change [a]	-35801	-41965	-34617

[a] Negative (-) sign depicts forest cover loss

2.4.4 Spatial Distribution of Forest and other Land-cover Change Dynamics

Mapping of land-cover class conversions from forest to non-forest and vice-versa for the periods 1989 to 1995, 1995 to 2002 and 2002 to 2009 revealed a spatial distribution of inter-conversions. Although conversions from non-forest to forest existed, conversions from forest to non-forest indicating deforestation were prominently visible. An overlay of all the conversion maps on both the 1989 land-cover classification map and county administrative boundaries map of the study area (Fig.2.7) revealed that deforestation mostly affected the eastern, south western, western, north western and central parts of the Lake Victoria crescent. On the other hand, conversion from non-forest to forest cover (afforestation) was widely dispersed.

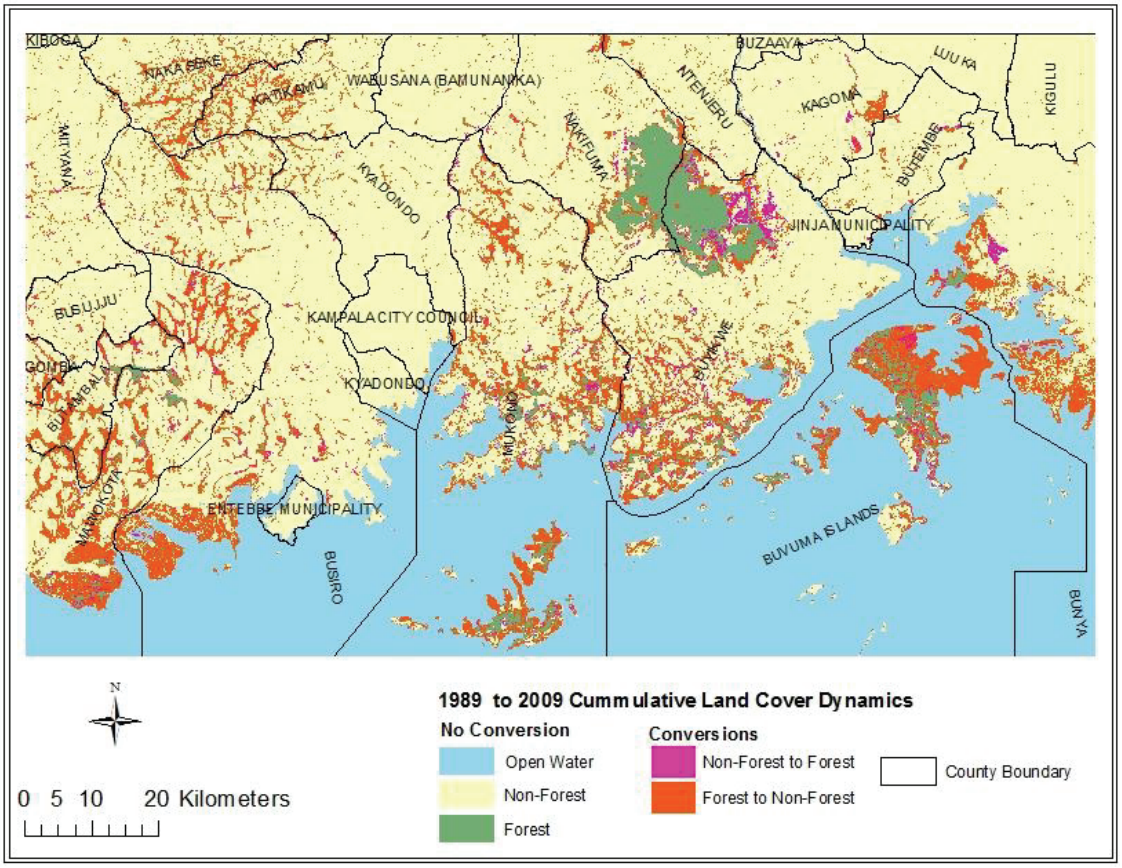

Figure 2.7 Distribution of cumulative land-cover inter-conversions between forest and non-forest from 1989 to 2009 overlaid on the 1989 land-cover map

2.5 DISCUSSION

2.5.1 Forest and other Land-cover Stratification

In order to acquire land-cover stratification information since 1980s, image classification was deemed necessary. Although many classification approaches exist, the ISODATA unsupervised approach was used. This was because there was inadequate information to aid selection of training samples for supervised classification. Hence, unsupervised classification enabled generation of spectral classes which were then converted into informational classes with the help of both a posteriori knowledge of the study area and existing secondary data (Jensen, 1996).

2.5.2 Accuracy Assessment

Considering the three land-cover classes that were discriminated i.e. open water, non-forest and forest, the average overall accuracy of over 97% for all classifications based on visual accuracy assessment is a good indicator of the reliability of the classifications as there was near complete agreement between the classified images and reference dataset. The reliability of all classifications is further supported by the high kappa values ranging from 0.95 to 0.96 indicative of near complete agreement and their associated Z-scores which were all significant at the 95% level. The observed high classification accuracy could be attributed to the fact that two of the classification classes, forest and non-forest, usually result into higher classification accuracies of over 85% (Olander *et al.*, 2008). Additionally, open water class usually exhibits very high classification accuracies as it is easily distinguishable from other land-cover classes.

Similar findings were obtained with Google Earth interpreted points on the 2002 and 2009 images. Overall accuracies of 97.7% and 91.7% were an indicator of the reliability of classifications as there was near complete agreement between the classified images and reference dataset. This claim of reliable classifications was also supported by the high kappa values ranging from 0.91 to 0.97 indicative of strong or near complete agreement and their associated Z-scores which were all significant at the 95% level. These accuracy assessment results are closely consistent with the findings of Lung and Schaab (2010) in a study around Mabira Central Forest Reserve involving land-cover classification in which the overall classification accuracy was 80.80% with a kappa statistic of 0.79. It can therefore be asserted that the image classifications were reliable as both visual classification and Google Earth-based accuracy assessments were consistent.

2.5.3 Forest and other Land-cover Change Analysis

Unsupervised classification of the satellite imagery facilitated discrimination of forest, non-forest and open water land cover types upon which a quantitative analysis of land-cover dynamics was based. Forest cover in the Lake Victoria crescent declined from about 9.0% in 1989 to 4.4% in 2009. This reduction was also demonstrated by the reduction in number of forest validation points from 74 (10.6%) in 1989 through 59

(8.4%) in 1995, 51 (7.3%) in 2002 to 30 (4.3%) in 2009. Furthermore, forest cover loss was also reflected in the mapped forest area. These findings showing decreasing forest cover in the Lake Victoria crescent are in agreement with Uganda's national forestry cover statistics from Global Forest Resources Assessment data which showed that Uganda lost an average of 86,400 ha of its forest cover per year between 2000 and 2005 (FAO, 2005). Similarly, Lung and Schaab (2010) analyzing land-cover dynamics in and around Mabira Forest between 1973 and 2003 reported deforestation associated with agricultural encroachment and population increase. It is also reported that Uganda accumulated a deforestation deficit of about 1,400,000 ha between 1990 and 2005 (Mugumya, 2010). Conversely, non-forest cover increased from 58.7% in 1989 to 63.5% in 2009 while open water coverage generally remained constant averaging 32.3% from 1989 to 2009.

In order to obtain results suitable for monitoring trends in land-cover dynamics, it was necessary to obtain detailed periodically-based changes showing the nature of changes instead of a binary change/no change detection associated with many change detection approaches (Coppin *et al.*, 2004). And post-classification comparison change detection was deemed appropriate as it facilitated comparison of the classified maps on a pixel-by-pixel basis providing a change detection matrix (Coppin *et al.*, 2004; Jensen, 1996) from which "from – to" change class information was extracted. The high classification accuracies of the individual date classifications used as inputs ensured that the outputs of post-classification comparison change detection were accurate (Coppin *et al.*, 2004; Foody, 2001; Jensen, 1996).

There was a general decline in land-cover conversion from non-forest to forest from 1989 to 2009. Similarly, conversions from forest to non-forest also declined. The implication was that afforestation and deforestation were on the decline. Furthermore, the difference in land-cover area between land that changed from non-forest to forest and vice-versa in the period 1989 to 1995, 1995 to 2002 and 2002 to 2009 generally declined, an indicator that deforestation exhibited a declining trend from 1989 to 2009. Indeed, mean annual rates of deforestation declined from 1989 to 2009 with a weighted mean annual deforestation rate of 2.56%. The declining rates of deforestation from 1989 to 2009 signaled a positive trend in forest management and could be an indicator that deforestation was halted or reached its peak in the Lake Victoria crescent between 1989 and 2009. However, forest utilization remained unsustainable as deforestation still exceeded afforestation. This therefore underscores the continued need to combat deforestation.

This study's weighted mean annual rate of deforestation of 2.56% from 1989 to 2009 is different from FAO (2005) estimates which reported mean annual deforestation at 1.76% between 1990 and 2000 and 2.13% between 2000 and 2005. This difference could be attributed to differences in methodology used in generating the estimating. However, this disparity could also be attributed to differences in scale at which assessments are implemented with FAO operating at national or even global levels (Nagendra, 2007) while this study was at local or regional level. Operating at small scales such as national and global levels which are usually associated with utilization of coarse resolution data tend not to capture detailed information at large scales such as local, regional or sub-national levels. Therefore, issues under consideration such as deforestation are either overestimated or underestimated due to scale at which the information (such as forest cover dynamics) that aided decision making was obtained. Hence, the need to pay attention to choice of appropriate scale.

2.5.4 Spatial Distribution of Forest and other Land-cover Change Dynamics

Conversion from forest to non-forest cover occurred in many counties within the Lake Victoria crescent. It was spatially concentrated in counties that are known to be forested. This finding reinforces the assertion of classification consistency. On the other hand, with exception of a few large afforestation and or reforestation patches in Buyikwe and Bunya counties, most of the afforestation and or reforestation occurred in small and scattered patches.

2.5.5 Implications of Results

Since the 1980s, sustainable forest management remains a challenge in Uganda's Lake Victoria crescent as manifested by the continued decline in forest cover. However, there is a gradual decrease in rates of deforestation. It is therefore important to understand why despite the continued forest cover loss, deforestation rates are declining. This understanding could go a long way in design of interventions for promotion of sustainable forest management. Furthermore, the need for accurate and reliable information about forest cover dynamics to inform debates, discussions and decision making on forest management and conservation in Uganda still exists (Obua *et al.*, 2010). And since this study reveals the potential of the widely reported national forest cover statistics either under- or over-estimating sub-national (local) forest cover dynamics, it is important that focus be extended to acquisition and reporting of sub-national (local) forest cover statistics. Making decisions with knowledge of local forest cover dynamics could potentially enhance sustainable forest management.

2.6 CONCLUSION

This study demonstrated the potential of utilizing time series Landsat imagery in generating information about forest and other land-cover dynamics over time using the techniques of unsupervised image classification and post-classification comparison change detection. Forest cover in the Lake Victoria crescent decreased from 9.0% to 4.4% in comparison with non-forest cover which increased from 58.7% to 63.5% while open water coverage generally remained constant at about 32.3% from 1989 to 2009. From 1989 to 2009, mean annual deforestation rates declined with a weighted mean annual deforestation rate estimated at 2.56%. Similarly, land-cover conversion from non-forest to forest and vice-versa generally declined. Therefore, deforestation in the Lake Victoria crescent either peaked or was halted as manifested by its declining rates despite the continued decline in forest cover from 1989 to 2009. Land-cover conversion from forest to non-forest (deforestation) was spatially more visible with a clustered distribution while conversions from non-forest to forest generally exhibited a random spatial distribution. The dynamics of forest and other land cover in this study demonstrated the continued loss of forest cover thus necessitating development of approaches to curb the forest loss. This may involve research focused on understanding drivers of observed land-cover dynamics to facilitate design of interventions for promotion of sustainable forest management at local scales.

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CHAPTER THREE

CHARACTERIZATION OF FOREST FRAGMENTATION IN THE LAKE VICTORIA CRESCENT, UGANDA

3.1 ABSTRACT

Forest fragmentation continues to be a major threat to forest sustainability especially in the tropics. However, most assessments focus on forest extents with little emphasis placed on forest fragmentation thus leaving knowledge gap which acts as a hindrance to promotion of sustainable forest management. This objective of the study was to characterize forest fragmentation in the Lake Victoria crescent at different temporal scales since the 1980s. The methodology involved computation of several forest landscape metrics which included number of patches, total area, patch size, shape index, largest patch index, aggregation index and contagion index at both patch and class levels using Fragstats software. The input datasets were temporal land-cover categorical maps of 1989, 1995, 2002 and 2009. Results showed the occurrence of forest fragmentation in the Lake Victoria crescent from 1989 to 2009, although more prevalent from 1989 to 1995. Forests whose area was greater than 100 ha experienced greater fragmentation than smaller forests thus pointing to the great risk forests greater than 100 ha face with regard to fragmentation. Forest fragmentation also occurred simultaneously with deforestation from 1989 to 2009.More focus should be put on sustainably managing forests that are greater than 100 ha as they are very susceptible to forest fragmentation; yet their fragmentation into smaller forests has the potential of exacerbating deforestation as small forests are easily lost through deforestation. Research aimed at understanding the impacts of forest fragmentation on the functioning of forests in the Lake Victoria crescent should be conducted as it is will play a vital role in planning for sustainable management of forests not only in the Lake Victoria crescent but also in other areas with similar habitats.

Key Words: Lake Victoria Crescent-Uganda, Landsat, Forest Fragmentation, Landscape Metrics, Sustainable Forest Management

3.2 INTRODUCTION

Forest resources are a mainstay in the three pillars of sustainable development namely economy, society and environment (Kayanja and Byarugaba, 2001). Many world economies including Uganda are wholly or partly dependent on forest resources (FAO, 1997). Uganda covers an area of about 24 million hectares (UNEP, 2008) of which approximately 4.9 million hectares (20%) are under forest cover (MWLE, 2003a).

Uganda's forest resources contribute 6% of the national gross domestic product and employ millions of people (MWLE, 2001; Kayanja and Byarugaba, 2001) in addition to acting as raw materials for various industries. Most of Uganda's population (85.1%) is in rural areas (UBOS, 2008) and generally poor, thus heavily dependent on natural resources like forests for meeting its basic needs (Mwavu and Witkowski, 2008). These include medicine, crafts and furniture, food and flavoring, firewood and charcoal, building materials and timber (Oryem-Origa *et al.*, 2001; UNEP, 2008; MWLE, 2001; Kayanja and Byarugaba, 2001). Forests also act as a catchment for water bodies including Lake Victoria, the second largest fresh water lake in the world. Other environmental services provided by forests include maintenance of high biodiversity (Kayanja and Byarugaba, 2001; UNEP, 2008) and protection of globally important carbon sinks that currently sequester carbon dioxide from the atmosphere thus being critical to future climate stabilization (Stephens *et al.*, 2007).

In developing countries such as Uganda where a large proportion of the human population depends almost entirely on natural resources for their livelihoods, there are increasing competing demands for utilization, development and sustainable management of land resources (e.g. natural vegetation), resulting in land-use and land-cover changes (Mwavu and Witkowski, 2008). Such land-use and land-cover changes including forest cover change in the tropics are mostly manifested through deforestation (FAO, 2006) and forest fragmentation.

Forest fragmentation refers to a landscape-level process in which forest tracts are progressively sub-divided into smaller, geometrically more complex and more isolated forest fragments as a result of both natural processes and human land-use activities (McGarigal and Marks, 1995). Forest fragmentation results into either the forested landscape getting reduced in the size because of pressure from the peripheries or the forest habitat within a landscape getting replaced by another type of land-cover, thereby leading to permanent loss of forest habitat. The resulting human-perceived biotypes are viewed as patches or matrices in the heterogeneous landscape (Lele *et al.*, 2008).

Forest landscape patterns such as forest fragmentation are used to show the condition or trends of forest loss in a particular area or region (Abdullah and Nakagoshi, 2007). Properties of forested landscapes such as patch size, amount of edge, distance between habitat areas, and connectedness of habitat patches have a direct influence on the flora and fauna (Ripple *et al.*, 1991). Additionally, there are concerns about the impact of forest fragmentation on conservation planning (Schwartz, 1997 cited in Butler *et al*., 2004). All these arise because landscape patterns determine the functional integrity of the landscape by influencing critical ecological processes such as land-atmosphere interactions (Lele *et al*., 2008).

Forest fragmentation caused by changes in human land-use activities is a major concern for forest sustainability in many tropical countries (Abdullah and Nakagoshi, 2007). In Uganda, the heavy dependence of the human population on forest resources for its basic needs (Mwavu and Witkowski, 2008) has the potential of contributing to forest fragmentation, thus posing a threat to forest sustainability. Yet forest sustainability is needed to avoid negative ecological, environmental, social and economic impacts associated with forest loss. However, most national and other forest assessments focus solely on the extent of forest loss without concern for forest spatial patterns such as forest fragmentation (Kupfer, 2006). This therefore results into unavailability of information about forest landscape patterns thus presenting another hindrance to promotion of sustainable forest management. It was therefore important to assess forest landscape patterns in Uganda's Lake Victoria crescent to acquire information vital for promotion of sustainable forest management. Additionally, information about forest fragmentation is vital for addressing a wide range of critical issues such as global climate change and carbon budgets (Li *et al*., 2009).

The objective of this study was to characterize forest fragmentation in the Lake Victoria crescent at different temporal and spatial scales since 1980s. The underlying hypothesis was that forest fragmentation in the Lake Victoria crescent increased with time since 1980s. Landscape metrics which are usually used in describing forest fragmentation, have been proven to be effective in measuring forest fragmentation (McGarigal and Marks, 1995; Abdullah and Nakagoshi, 2007; Midha and Mathur, 2010) and were adopted for the characterization of forest fragmentation. Knowledge of the trends of forest fragmentation will help forest protection efforts in identifying which forests are most at risk of being lost. This knowledge might also act as a baseline upon which other decisions with regard to promotion of sustainable forest management can be based.

3.3 MATERIALS AND METHODS

3.3.1 Study Area

The study area is located between 0˚8´S and 0˚42´N and between 32˚5´and 33˚32´E. It encompasses all or parts of Mayuge, Iganga, Jinja and Kamuli districts in eastern Uganda and all or parts of Kayunga, Mukono, Luwero, Kampala, Wakiso, Mpigi, Mityana, Nakaseke and Kiboga districts in central Uganda. The study area measures about 162 by 94 km, an equivalent of 1,509,328 ha (Fig.3.1). This area is referred to as the Lake Victoria crescent.

Uganda lies astride the equator and thus has a climate typical of equatorial regions. However the climate in the southern part of Uganda including the Lake Victoria crescent is modified by maritime conditions due to closeness to Lake Victoria in addition to altitudinal effects as this area is over 1,000 m asl. The temperatures range between 15 ºC and 30 ºC. The rainfall has a bimodal distribution with two fairly well marked seasons which are March-June and October/November-December/January. The rainfall averages

1,200 to 1,500 mm and is well distributed (NEMA, 2006/07; NEMA, 2008).

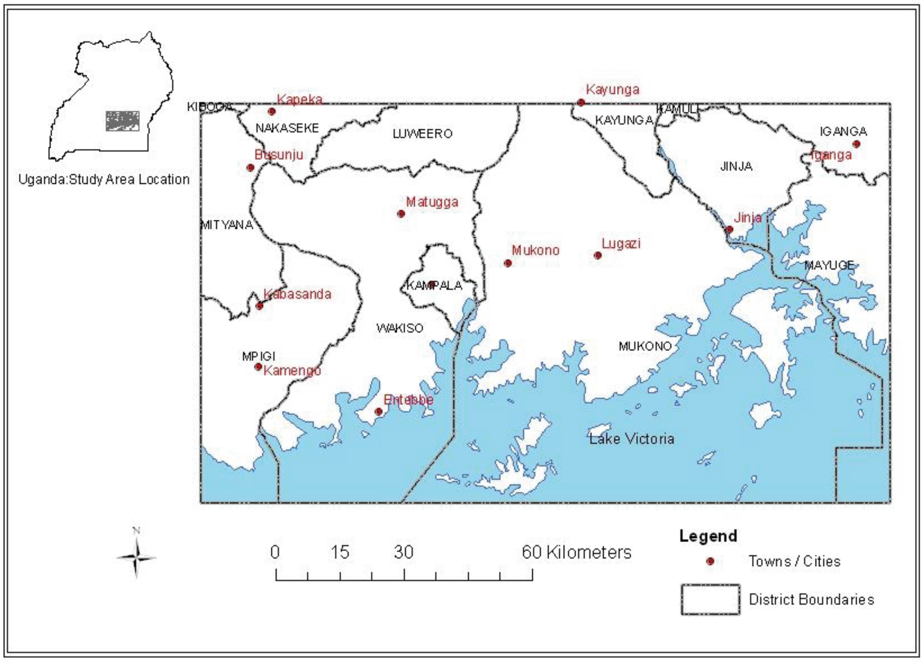

Figure 3.1 Study Area

Of Uganda's forests and woodlands covering 4.9 million ha (NEMA, 2006/07), a substantial portion of them, including both natural forests (Namaalwa, 2008; UNEP, 2008) and plantation forests of different sizes, lie within the Lake Victoria crescent (NEMA, 2004/05). Since most forests on private land have been heavily degraded and about 1.9 million ha of natural forest are protected areas, only Central and Local Forest Reserves remain available for various uses (NEMA, 2006/07).

The human population in this densely populated area is heavily dependent on forest resources for human livelihood needs (Mwavu and Witkowski, 2008; Oryem-Origa *et al*., 2001). The area's economy is majorly dependent on agriculture, both small and large scale. However, other economic activities associated with urbanization do exist.

This area was therefore selected for this study because of the presence of many types of forests of different sizes and management profiles in a densely populated area with the human population known to depend on forest resources for its livelihood. Additionally, this area possessed Landsat imagery with less cloud cover for at least two points in time since 1989 that could facilitate time series analysis.

3.3.2 Methods

3.3.2.1 Datasets

The dataset consisted of temporal land-cover categorical maps with open water, forest and non-forest classes for 1989 (Fig. 3.2), 1995 (Fig. 3.3), 2002 (Fig. 3.4) and 2009 (Fig. 3.5) obtained through unsupervised classification of Landsat Thematic Mapper and Enhanced Thematic Mapper Plus imagery. All datasets exhibited the same spatial extent of about 1,509,328 ha. This dataset was obtained from this broader study's first objective which focused on assessing forest cover dynamics in the Lake Victoria crescent since 1980s. The dataset was characterized by very high classification accuracy making it appropriate for subsequent analysis.

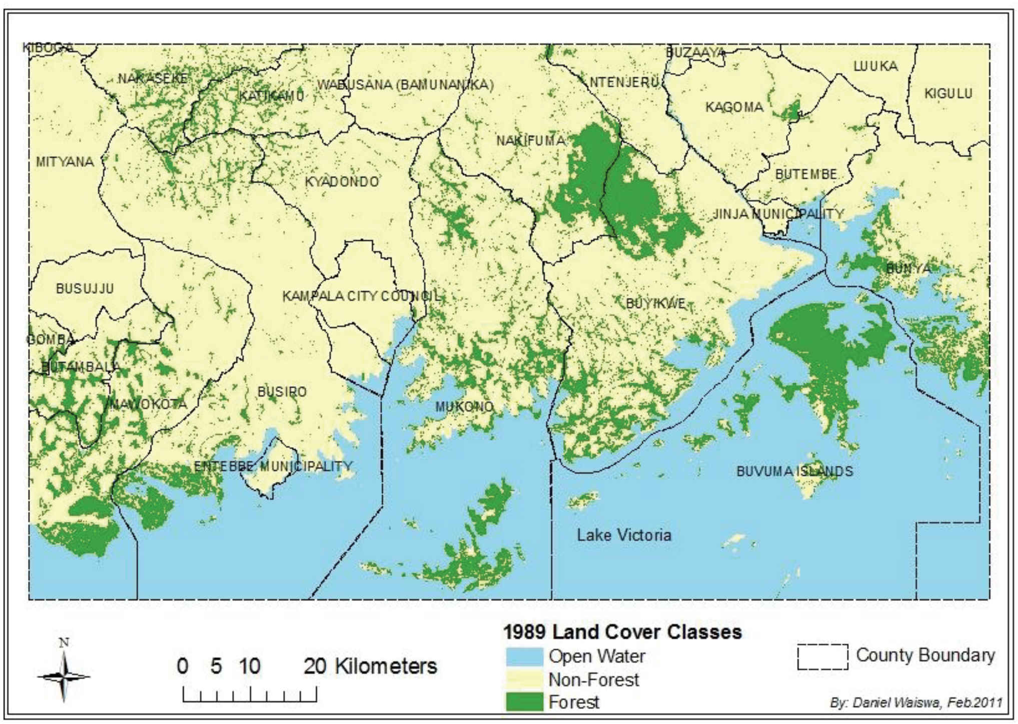

Figure 3.2 Land-cover categorical map of the Lake Victoria crescent, Uganda in 1989

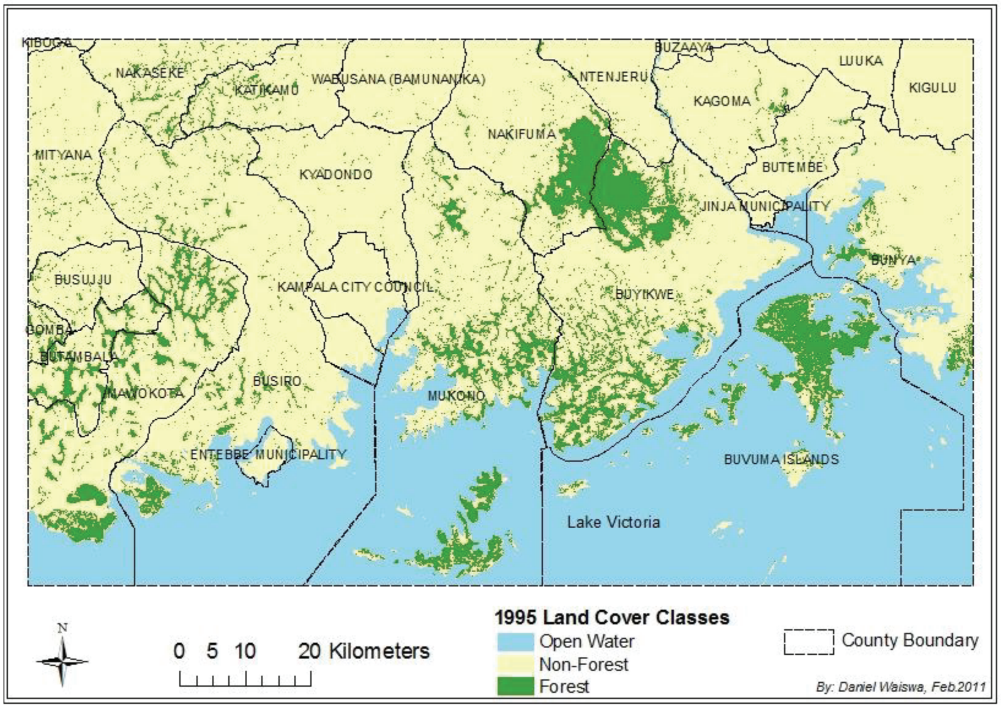

Figure 3.3 Land-cover categorical map of the Lake Victoria crescent, Uganda in 1995

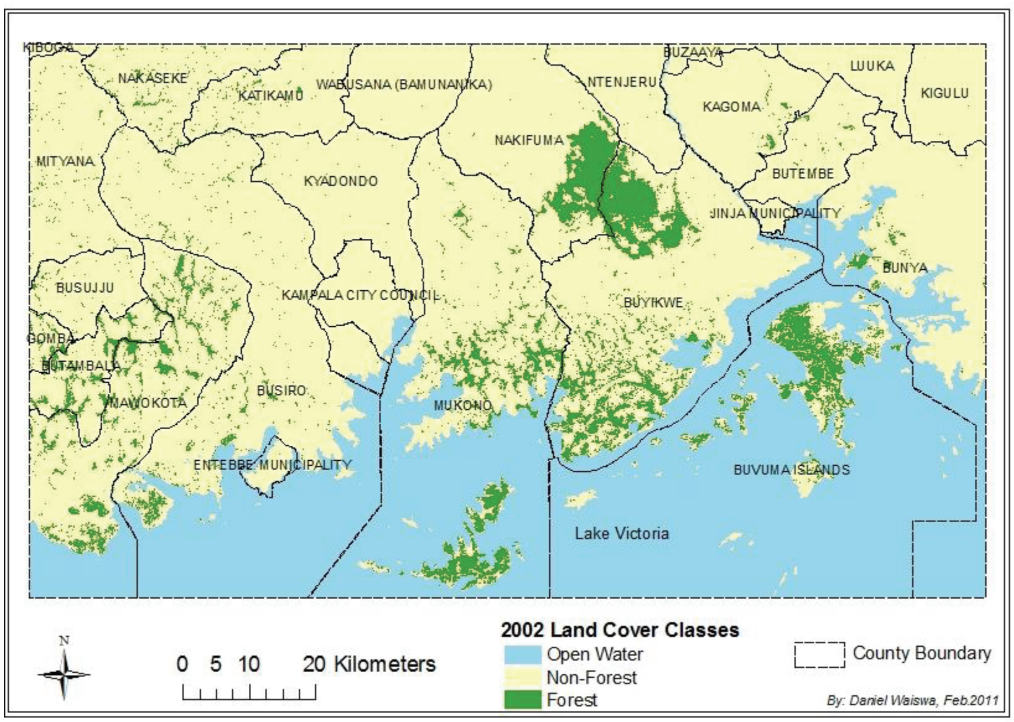

Figure 3.4 Land-cover categorical map of the Lake Victoria crescent, Uganda in 2002

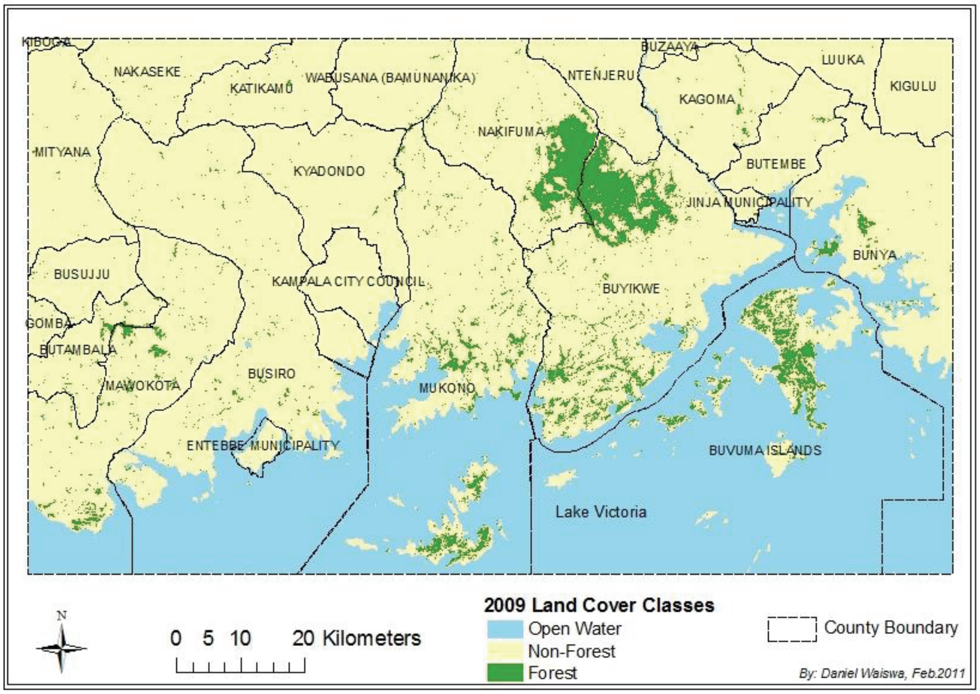

Figure 3.5 Land-cover categorical map of the Lake Victoria crescent, Uganda in 2009

3.3.2.2 Data Analysis

Landscape metrics were used in the characterization of forest landscape patterns. This was because of the known ability of landscape metrics in quantifying landscape patterns such as forest fragmentation using statistics in terms of the landscape unit itself like patch size, shape, abundance and spacing as well as the spatial relationship of the patches and matrix comprising the landscape like nearest-neighbor distance and amount of contiguous matrix (Ripple *et al*., 1991). Many studies including Reed *et al*. (1996), Lele *et al*. (2008), Butler *et al*. (2004), Midha and Mathur (2010), and Echeverria *et al*. (2006) used landscape metrics in measuring forest fragmentation. However, since several landscape metrics exist, and many of them are reported to measure the same thing thus introducing redundancies, only a few metrics were selected for use in this study based on the scale of analysis and questions to be answered (Butler *et al*., 2004). These included: (i) Number of patches, (ii) Total area of patches, (iii) Largest Patch Index (LPI), (iv) Shape Index, (v) Aggregation Index (AI) and (vi) Contagion Index. Many indices were selected because of the absence of a single universal measure of forest fragmentation; thus, making its determination to be based on an aggregation of evidence from multiple landscape metrics. Table 3.1 describes the selected metrics (McGarigal and Marks, 1995).

Table 3.1 Description of selected landscape metrics with their hypothesized behavior under forest fragmentation for the forest class

Landscape Metric	**Landscape metric description and its hypothesized behavior under forest fragmentation**
Number of Patches	This refers to the number of forest patches. It is a simple measure of the extent of subdivision or fragmentation of the forest patch type. Its minimum value is 1 when the landscape contains only one forest patch and its does not have a maximum value. *Under forest fragmentation, keeping other factors constant, number of patches of forest was hypothesized to increase with time.*
Total Area	This defines the total extent of the forest class in the landscape. Its value has to be greater than zero. *Under forest fragmentation, total area of forest was hypothesized to decrease with time due to loss of forest cover.*
Largest Patch Index	Largest Patch Index (LPI) refers to the percentage of the total landscape comprised by the largest patch of a given cover class, in this case the forest class. As such, it is considered a simple measure of dominance. Its value is defined by the function: $0 < LPI \leq 100$. *Under forest fragmentation, LPI was hypothesized to decrease with time, especially if the biggest forest patch was affected.*
Shape Index	Shape index is a proportion of patch perimeter to the minimum perimeter possible for a maximally compact patch of the corresponding patch area. It is a measure of the complexity of a patch shape in comparison with a standard shape. Values of shape index are greater than or equal to 1 with no maximum limit. Shape index is maximally compact when shape index is 1. The shape then becomes irregular and more complex as the shape index increases from 1. *Under forest fragmentation, shape index associated with forest patches was hypothesized to increase with time as forest patches, especially the large ones, become geometrically more complex and irregular or linear.*
Aggregation Index	The Aggregation Index (AI) measures the aggregation of patch types. Its value is defined by the function: $0 \leq AI \leq 100$. An aggregation index of 0 means that patch types are maximally disaggregated with class pixels sharing no edges and it increases as the landscape increasingly gets aggregated, with class pixels sharing more edges. Aggregation index is 100 when the landscape consists of a single patch. *Under forest fragmentation, it was hypothesized that a single forest patch would split into smaller but closer patches creating a higher aggregation of forest patches, thus resulting into aggregation indices tending towards 100 and would increase with time with increasing forest fragmentation.*

Contagion Index	This is a measure of both patch type interspersion and patch dispersion. Interspersion refers to the intermixing of units of different patch types while dispersion refers to the spatial distribution of a patch type. Contagion index is an indicator of the extent to which patch types are aggregated or clumped. Its value is defined by the function: $0 < \text{CONTAGION} \leq 100$. A lower contagion index characterizes a landscape with many small and well dispersed patches while a higher contagion index is associated with landscapes that have few large contiguous patches. *Under forest fragmentation, it was hypothesized that the contagion index would tend towards 0 and would increase with time with increasing forest fragmentation as there would be more small forest patches that are well dispersed or disconnected.*

The selected landscape metrics had the potential of determining forest fragmentation by not only employing statistics based on forest patches themselves but also the spatial relationship of the forest patches and matrix comprising the landscape (Ripple *et al.*, 1991). These landscape metrics were computed at both patch and class levels for the forest class in each of the temporal land-cover categorical map using Fragstats spatial analysis software package version 3.3 (McGarigal and Marks, 1995) to foster an understanding of observed patterns at different landscape levels. This was because simultaneous use of patch and class level landscape pattern indices enable assessment of spatial configurations of forest cover and its relation to other land-cover types (Echeverria *et al*., 2006). In conformance with FAO (2000), 0.5 ha was set as the minimum area of a forest patch in this study.

Using a similar approach as Lele *et al*. (2008), the forest patches were further segregated into seven (7) classes based on forest patch total area. The forest patch size classes included 0.5-25 ha, 25-50 ha, 50-75 ha, 75-100 ha, 100-1000 ha, 1000-5000 ha and Over 5000 ha. This categorization was based on observed variability amongst forest patch sizes. Within each class and with respect to each temporal land-cover categorical map, number of forest patches, total area and mean shape index with its associated standard deviation were computed. This would further help in understanding among other issues which patch size(s) were under acute threat of fragmentation, as this has important management implications.

3.4 RESULTS AND DISCUSSION

3.4.1 Class Level Forest Landscape Metrics

There was a continuous decline in total area of forest patches constituting the forest class in the landscape from 170,593 ha in 1989 to 59,092 ha in 2009 (Table 3.2). This was an indicator that forest cover declined from 1989 to 2009 through deforestation. Additionally, the decline in forest cover could be attributed to forest fragmentation. This is because a progressive reduction in size of forest habitats (forest patches) is a key component of ecosystem fragmentation (Echeverria *et al*., 2006). From 1989 to 1995, the number of forest patches increased by 377 patches with a corresponding decrease in mean patch size of 6.8 ha (Table 3.2). This could be an indicator that bigger forest patches split into small patches with a simultaneous decrease in size. This is in agreement with Echeverria *et al*. (2006) assertion that increasing numbers of small patches are a basic symptom of forest fragmentation. However, from 1995 to 2002, the number of forest patches drastically reduced by over 2,000 patches and remained generally unchanged up to 2009.

Table 3. 2 Temporal variation in class level forest landscape metrics

Forest Landscape Metrics		Categorical Map Date			
		1989	**1995**	**2002**	**2009**
Total Area (ha.)		170593	135129	100587	59092
Number of Patches		7757	8133	5985	5986
Patch Size (ha.)	Mean	22.0	16.8	16.8	9.9
	Standard Deviation	432.6	338.5	329.8	296.8
	CV (%)	1966.9	2037.2	1962.1	3006.4
Largest Patch Index (LPI)		1.73	1.64	1.51	1.49
Aggregation Index (AI)		91.93	90.84	90.69	88.13
Contagion Index		0.44	0.43	0.43	0.40

Correspondingly, mean patch size remained unchanged at 16.8 ha between 1995 and 2002 when it decreased to 9.9 ha in 2009 (Table 3.2). The reduction in number of forest patches from 1995 to 2002 signaled loss of forests due to deforestation. The assertion of deforestation is also supported by the unchanged mean patch size between 1995 and 2002 as forest fragmentation is generally associated with decreasing mean forest patch size (Midha and Mathur, 2010). Between 2002 and 2009, it is probable that equilibrium was reached between number of forest patches that were being lost through deforestation and number of forest patches arising from fragmentation of large forest patches thus accounting for the observed constancy in number of forest patches from 2002 to 2009. And the decrease in mean patch size from 2002 to 2009 further signified both fragmentation of forest patches and subtle erosion of large forest patches, especially at the edges, thus converting them into smaller patches in addition to the complete elimination of entire forest patches through deforestation. Mazgajski *et al*. (2010) also noted that the process of forest fragmentation consists of both habitat loss and fragmentation itself. In a study aimed at measuring forest landscape patterns in the Cascade Range of Oregon, USA, Ripple *et al*. (1991) concluded that forest fragmentation increased as revealed by reducing forest patch area and increasing perimeter to area ratio (shape index) over time. Hence, the observed progressive decrease in mean patch size could be taken as indicator of forest fragmentation in the Lake Victoria crescent. The generally declining LPI from 1989 to 2009 was an indicator of the dwindling dominance of forest cover in the landscape (Table 3.2). Decreasing forest dominance was also manifested by declining total area of all forest patches. Other land-cover types were thus replacing forest cover signifying increasing forest fragmentation.

The spatial distribution of forest patches in the landscape was determined using dispersion as its indicator. Dispersion refers to the tendency for patches to be regularly or contagiously distributed (i.e., clumped) with respect to each other. Indices used to measure dispersion included the aggregation index (AI) and contagion index. The aggregation index, which measured aggregation of patch types, ranged from 88.1% in 2009 to 91.9% in 1989 (Table 3.2). This indicated that the landscape consisted of many small but closer patches, thus exhibiting a high degree of aggregation. This could have been a result of single forest patches splitting into smaller but closer forest patches, signifying the occurrence of forest fragmentation from 1989 to 2009. However, the gradual decrease in aggregation index from 1989 to 2009 was a probable indicator that the rate of forest fragmentation decreased with time. Similarly, the low contagion indices tending towards 0 indicated the presence of many small forest patches which are associated with forest fragmentation. The contagion index, which measured both patch type interspersion and patch dispersion, was very low with values tending towards 0 throughout the study period. The low contagion indices were an indicator that the landscape consisted of many and disconnected forest patches, which indicated that forest fragmentation had occurred. However, just like the aggregation index, the contagion index exhibited a gradual decline from 1989 to 2009 which signified a probable decrease in the rate of forest fragmentation with time (Table 3.2). The assertion that forest fragmentation occurred as evidenced by the presence of many small forest fragments is in agreement with Echeverria *et al*. (2006) that increasing forest fragmentation decreases the connectivity of forest patches by dissecting the forest patches into more compact and smaller fragments.

3.4.2 Patch Level Forest Landscape Metrics

Patch level forest landscape metrics which included number of patches (Table 3.3), total area (Fig. 3.6) and mean shape index (Fig.3.7) for different forest patch size classes at different temporal scales (1989, 1995, 2002 and 2009) in the Lake Victoria crescent revealed a number of trends vital to understanding forest fragmentation.

The number of patches within each class generally decreased with time from 1989 to 2009. Additionally, the number of patches varied so much and this variation was more evident among the small-size classes (<100 ha) as compared to the large-size classes (>100 ha). The decrease in number of forest patches across all size-classes could be attributed to their loss through either degradation or deforestation. However, the 0.5-25 ha class exhibited a lot of variation as exhibited by big increases and decreases in number of forest patches from one time to the other (Table 3.3). The increase in number of forest patches could have been as a result of fragmentation of forest patches in the bigger size classes during those times resulting in many smaller forest patches thus the observed increases. On the other hand, the decrease in number of forest patches could have been as a result of entire loss of forest patches through deforestation. Mazgajski *et al*. (2010) found habitat loss and forest fragmentation to occur together in their study of forest habitat loss and fragmentation in Central Poland. Hence, the direction of the variation (increase or decrease in number of forest patches) could have been a net effect of both processes (fragmentation of bigger forest patches and deforestation) as they are likely to have occurred simultaneously.

Table 3. 3 Temporal variation in number of forest patches in the Lake Victoria crescent, Uganda: 1989, 1995, 2002 and 2009

Patch Size (ha)	**Number of Patches**			
	1989	**1995**	**2002**	**2009**
0.5-25	7332	7758	5686	5822
25-50	192	165	126	74
50-75	55	67	45	36
75-100	36	31	32	13
100-1000	122	94	84	37
1000-5000	16	16	10	3
Over 5000	4	2	2	1

Total area of patch size classes greater than 100 ha continually declined with time from 1989 to 2009. This trend was also generally exhibited by smaller forest patch size classes (less than 100 ha) with exception of a few deviations where increases in total area were observed. For instance, total area of forest patches within the 50-75 ha class increased by 791 ha from 1989 to 1995 while that of the 75-100 ha class increased by 44 ha from 1995 to 2002 (Fig. 3.6). The continued decrease in total area of forest patches greater than 100 ha in size was an indicator that such large forest patches experienced continuous fragmentation and erosion especially at the edges making them smaller in size. As a result, the smaller patches formed due to fragmentation and or erosion of larger patches got relegated to the classes of forest patches less than 100 ha in size thus probably accounting for some of the observed variations. However, the continued decline in total area of forest patches less than 100 ha in size could be attributed to loss of entire forest patches through deforestation.

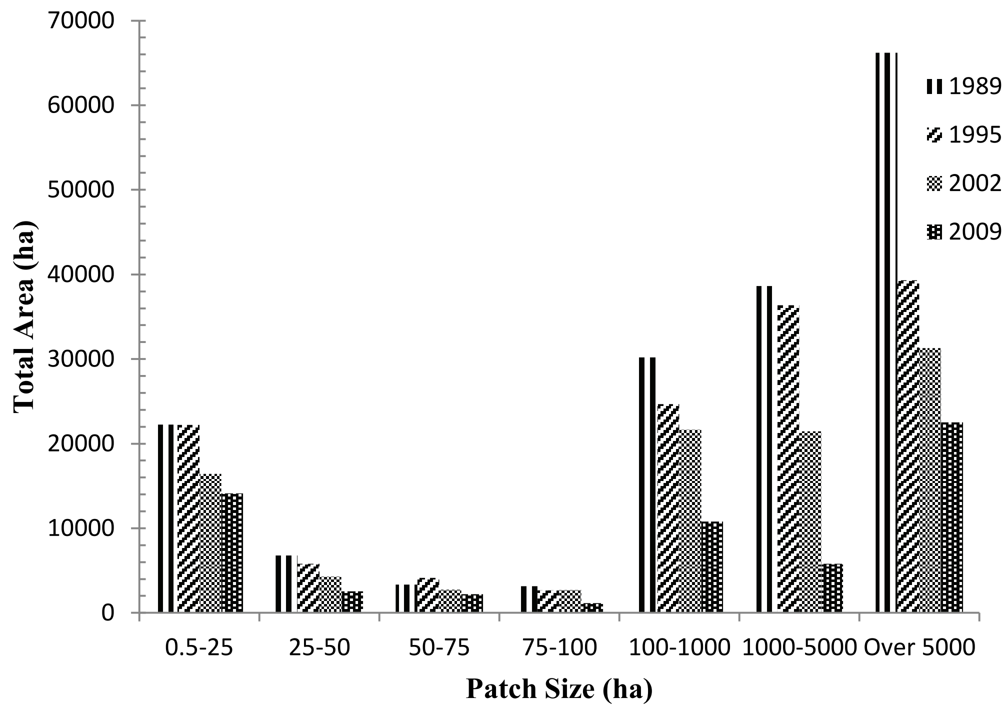

Figure 3.6 Temporal variation in forest total area with forest patch size in the Lake Victoria crescent, Uganda: 1989, 1995, 2002 and 2009

The mean shape index (Fig. 3.7) for each of the size classes from 1989 to 2009 was greater than 1 implying that all forest patches were irregular in shape. Additionally, the mean shape index for the small size classes was generally small in addition to exhibiting smaller variability as compared to the large size classes. Within the 0.5-25 ha class, the declining or constant mean shape index from 1989 to 2009 indicated increasing stability of forest patches in that class. The increasing patch stability implied that forest fragmentation did not occur in that class. Therefore, the observed increase in number of patches in this size class could be attributed to fragmentation of forest patches in the larger size classes making them fit into this class. On the other hand, the decrease in number of forest patches could be attributed to entire loss of forest patches through deforestation.

Within the 25-50 ha class, the generally increasing mean shape index from 1989 to 2009 indicated increasing instability of forest patches, thus signifying increasing forest fragmentation. Forest patches within the 50-75 ha class increasingly became less complex and more stable as revealed by the continuous decrease in shape index from 1989 to 2002. However, their complexity increased and hence became unstable between 2002 and 2009 as revealed by the increase in shape index. This indicated that forest patches in the 50-75 ha class became more fragmented from 2002 to 2009.

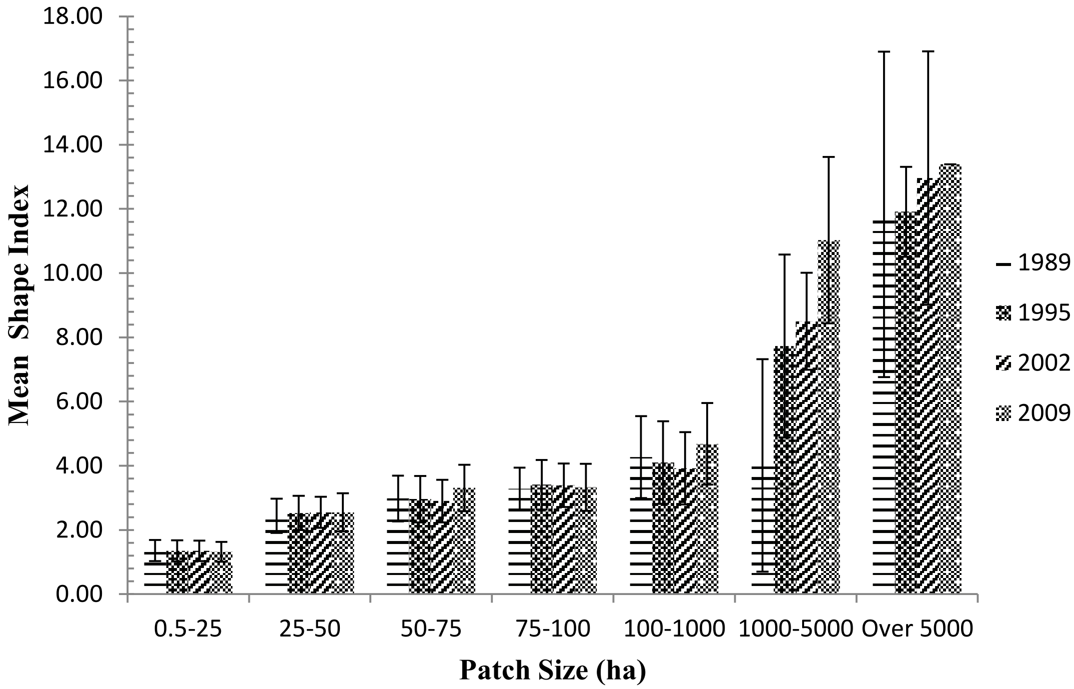

Figure 3. 7 Temporal variation in mean shape index with associated standard deviation against forest patch size class in the Lake Victoria crescent, Uganda: 1989, 1995, 2002 and 2009

Forest patches within the 75-100 ha class generally got defragmented from 1989 to 2009 as indicated by the increasing shape index indicating more shape complexity and instability. Forest patches in the 100-1000 ha class increasingly became less complex and more stable as revealed by the continuous decrease in shape index from 1989 to 2002. However, their complexity increased and hence became unstable from 2002 to 2009 as revealed by the increasing shape index. This indicated that forest patches in the 100-1000 ha class increasingly became fragmented from 2002 to 2009.

All forest patches within classes over 1,000 ha increasingly got fragmented with time. This was revealed by the generally sustained increase in shape indices from 1989 to 2009. The increase in shape indices indicated increased shape complexity and subsequently increasing instability of forest patches as their edges interacted more with adjacent land-cover classes as well as threats to forests, including human-induced disturbances (Lele *et al*., 2008) like forest fragmentation. Therefore, forest patches greater than 1,000 ha were undergoing continuous fragmentation from 1989 to 2009.

It can be asserted that forest patches of larger size (greater than 100 ha) were fragmented more than forest patches less than 100 ha in size. This assertion is further justified by the fact that total area of forest patches in size classes greater than 100 ha dropped by 95,930 ha (71%) from 1989 to 2009 in comparison with total area of forest patches in size classes less than 100 ha which declined by 15,571 ha (44%) during the same period. Using the same classification, it was revealed that the total number of forest patches greater than 100 hectares declined by 101 (71%) from 1989 to 2009 in comparison with 1670 (22%) decline within forest patches less than 100 ha in the same period. This dynamic with regard to number of forest patches further justifies the assertion that larger size forest patches experienced more fragmentation as compared to smaller size forest patches. Although forest patches greater than 100 ha experienced more forest fragmentation, they still constituted about twice the amount of forest cover in the Lake Victoria crescent as of 2009 in comparison with forests that were less than 100 ha. There is therefore a need to focus more on especially protecting and or sustainably managing the remaining forests that are greater than 100 ha in size as they are under intense pressure of fragmentation and subsequent loss. Continued fragmentation of these large forests could also make them less functional ecologically**.** Additionally, the rates of forest loss will likely increase as small forests are easily wiped out by agriculture encroachment and other human-induced activities (Lele *et al*., 2008).

Although class level forest fragmentation analysis was able to reveal the occurrence of forest fragmentation in the Lake Victoria crescent, forest fragmentation was more pronounced within the size-class based forest patch dataset which revealed generally increasing forest fragmentation from 1989 to 2009. This could have arisen as a result of the fragmentation of large forests being overshadowed by the dynamics of especially the large number of small size forests. This therefore helps highlight the need for consideration of forest size in assessing forest fragmentation.

3.4.3 Summary Discussion and Implications of the Study

There was a general modification of the various landscape metrics computed in this study including number of patches, total area, patch size, shape index, largest patch index, aggregation index and contagion index on a temporal scale. The modifications helped confirm the hypotheses about forest fragmentation. Echeverria *et al*. (2006) found changes in landscape patterns as reflected by significant modifications in size, edge, density, isolation, connectivity and core area of forest patches in the Chilean temperate forests. Similarly, Hartter and Southworth (2009) also found modifications in a number of landscape metrics including total class area, number of patches, mean patch size, and per cent landscape comprised by largest patch in forest patches around Kibale National Park, Uganda. Both Hartter and Southworth (2009) and Echeverria *et al*. (2006) concluded that forest fragmentation occurred. Based on the similar trends in landscape metrics, it was concluded that forest fragmentation occurred in the Lake Victoria crescent from 1989 to 2009. However, forest fragmentation seemed to have been more prevalent from 1989 to 1995. This was manifested by the increase in number of forest patches during that period. The increase in number of patches could have been due to fragmentation of especially the large forest patches (forest patches greater than 100 ha in size). In contrast, the number of forest patches reduced or remained constant after 1995 which also corresponded with some relative stability in number of forest patches of the large size classes, an indicator that they were not being relegated to small size classes due to fragmentation. The decrease in number of forest patches in the entire landscape from 1995 to 2009 could be attributed to deforestation which was resulting into their complete disappearance. Hence the observed dynamics between 1989 and 2009 could be attributed to both forest fragmentation and deforestation, which sometimes occur simultaneously (Mazgajski *et al*., 2010).

Although this study revealed the occurrence of forest fragmentation in the Lake Victoria crescent, it was beyond its scope to assess the impacts of forest fragmentation. However, several studies outside the Lake Victoria crescent point to some impacts of forest fragmentation. In addition to forest habitat loss, Midha and Mathur (2010) noted that forest fragmentation has far-reaching consequences for native plants, vertebrates and invertebrates, especially survival of threatened species. Forest fragmentation thus has a direct influence on flora and fauna (Ripple *et al.*, 1991). In line with this argument, Behera (2010) found high fragmented forests to have fewer plant species and newer community types than medium and low fragment forests in the Himalayan tropical forest. The reported presence of new and invasive plant species communities of paper mulberry (*Broussonetia papyrifera*) in the Lake Victoria crescent could be a result of forest fragmentation (Junior, 2008; Miti, 2009). Species dominance was also found to be directly proportional to forest fragmentation. Nyeko (2009) found abundance, species richness and diversity of dung beetles in Budongo, Uganda to be generally higher in larger forest fragments (100-150 ha) as compared to small forest patches (10-50 ha). In trying to understand the differences in species diversity, dominance and abundance, the conclusion by Vetter *et al*., (2011) that herbivores and other species able to use open habitats were significantly less negatively affected by forest fragmentation could be helpful.

Recognizing the potential impacts of forest fragmentation, it is recommended that studies be conducted to determine the impacts of forest fragmentation in the Lake Victoria crescent. This will play a vital role not only in planning for the sustainable management of forests in the Lake Victoria crescent but also in other areas with similar habitats. This will particularly be relevant in understanding the role of forests, especially forests greater than 100 ha that are very susceptible to forest fragmentation and yet still constitute the biggest proportion of forest area in the Lake Victoria crescent.

3.5 CONCLUSION

This study focused on characterization of forest fragmentation in the Lake Victoria crescent, Uganda. Several landscape metrics including number of patches, size of patches, total area, shape index, largest patch index, aggregation index, and contagion index were examined using Fragstats spatial analysis software package version 3.3 for temporal categorical land-cover maps of Uganda's Lake Victoria crescent. The results revealed modifications in the landscape metrics with time and also confirmed the hypotheses about forest fragmentation. Forest fragmentation occurred in the Lake Victoria crescent from 1989 to 2009, although more prevalent from 1989 to 1995. Forests whose area was greater than 100 ha experienced greater fragmentation than smaller forests thus pointing to the great risk forests greater than 100 ha face with regard to fragmentation. Forest fragmentation also occurred simultaneously with deforestation from 1989 to 2009.

The understanding of forest fragmentation is vital for future forest management in the Lake Victoria crescent. More focus should be put on sustainably managing forests that are greater than 100 ha as they are very susceptible to forest fragmentation; yet their fragmentation into smaller forests has the potential of exacerbating deforestation as small forests are easily lost through deforestation. This could be achieved through developing interventions that combat deforestation and/ or promote afforestation. Research aimed at understanding the impacts of forest fragmentation on the functioning of forests in the Lake Victoria crescent should be conducted. This will play a vital role in planning for sustainable management of forests not only in the Lake Victoria crescent but also in other areas with similar habitats.

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CHAPTER FOUR

DRIVERS OF DEFORESTATION IN THE LAKE VICTORIA CRESCENT, UGANDA

4.1 ABSTRACT

Deforestation, especially in the tropics, continues to occur at alarming rates. This continued loss of forest cover poses a major threat to continued availability of goods and services that support livelihoods of a huge proportion of the human population, especially in developing countries. Despite numerous interventions by governmental and non-governmental entities to combat deforestation, forest cover has continued to decline. In Uganda's Lake Victoria crescent, forest cover declined from about 10.6% in 1989 to about 4.3% in 2009. The lack of effectiveness of interventions suggests that presumptions regarding the primary drivers of deforestation may be inaccurate or incomplete. The objective of the study was to identify key drivers of deforestation in the Lake Victoria crescent, Uganda from 1989 to 2009. A case study approach with a multiple-case design was adopted. Data was obtained from archival sources, interviews and direct observation while data analysis majorly involved within and cross-case analyses. A model of drivers of deforestation based on empirical research was developed. Deforestation appears to have been a consequence of proximate causes which were triggered by a number of underlying drivers acting singly or in combination. The proximate causes included agricultural expansion into forests, extraction of wood forest products, and clearing of forests for non-agricultural uses while the underlying drivers included policy and institutional factors, economic factors, population growth, technological changes, changes in culture, and alienation of local people from forest resources. Deforestation in the Lake Victoria crescent is expected to continue unless addressed through interventions that target its underlying drivers, especially alienation of local people from forest resources. One potential intervention could involve empowerment of local communities to manage forest resources.

Key words: Proximate Causes, Underlying Drivers, Alienation, Local Communities' Empowerment, Sustainable Forest Management

4.2 INTRODUCTION

Forest resources are a mainstay in the three pillars of sustainable development, namely economy, society and environment (Kayanja and Byarugaba, 2001). Many world economies, including Uganda, are wholly or partly dependent on forest resources (FAO, 1997). Despite the presence of some forested areas that have exhibited stability or enhancement (Lung and Schaab, 2010; Vogt *et al*., 2006) through reforestation, a general trend of deforestation can be witnessed in the tropics (Nagendra, 2007). Forest cover loss poses a great threat to the continued availability of goods and services provided by forests. In recognition of the fast disappearance of forests in the tropics, many interventions aimed at either conserving or sustainably managing forest resources, ranging from government-owned protected areas to private conservation through parks and community reserves, have been implemented over time (Nagendra, 2007). Outcomes of these interventions have been mixed. Most interventions are based on dominant paradigms or theories about drivers of forest change (deforestation or reforestation) such as population growth leading to deforestation (Nagendra, 2007; Vogt *et al*., 2006). Most of these paradigms or theories are a result of studies conducted at regional, national, continental or global scales (e.g. Geist and Lambin, 2002; Nagendra, 2007). Other interventions are based on knowledge about drivers of forest change obtained from local scale studies which usually focus on a single site (e.g. Mwavu and Witkowski, 2008).

Uganda covers an area of about 24 million hectares (UNEP, 2008), of which approximately 4.9 million hectares (20%) are under forest cover (MWLE, 2003a). Uganda's forest resources contribute 6% of the national gross domestic product, employ millions of people (MWLE, 2001; Kayanja and Byarugaba, 2001), and provide raw materials for various industries. Most of Uganda's population (85.1%) is in rural areas (UBOS, 2008) and generally poor. Most Ugandans are thus heavily dependent on natural resources like forests for meeting basic needs (Mwavu and Witkowski, 2008). These include medicine, crafts and furniture, food and flavoring, firewood and charcoal, building materials and timber (Oryem-Origa *et al.*, 2001; UNEP, 2008; MWLE, 2001; Kayanja and Byarugaba, 2001). Forests also act as a catchment for water bodies including Lake Victoria, the second largest fresh water lake in the world. Other environmental services provided by forests include maintenance of high biodiversity (Kayanja and Byarugaba, 2001; UNEP, 2008) and protection of globally important carbon sinks that sequester carbon dioxide from the atmosphere, which is critical to future climate stabilization (Stephens *et al.,* 2007).

The Lake Victoria crescent, one of the most forested areas in Uganda (NEMA, 2004/05), has experienced considerable deforestation between 1989 and 2009. Estimates from time-series analysis of Landsat imagery showed that forest cover declined from 9.0% in 1989 to 4.4% in 2009 (*Waiswa et al.: manuscript in preparation*). Mugumya (2010) also reported a deforestation deficit of about 1.4 million hectares in Uganda between 1990 and 2005. Clearly, interventions aimed at curbing deforestation have not been effective, suggesting that presumptions regarding primary drivers of deforestation upon which interventions are based may be inaccurate or incomplete. Most of these assumptions are derived from singular small-scale studies that can potentially hinder the ability for comparison and generalization. In conformance with Nagendra (2007), this research aimed at developing a more complete theoretical understanding of the drivers of land-cover change to better inform useful interventions to combat deforestation in the Lake Victoria crescent, Uganda. The objective of the study was to determine key drivers of deforestation in the Lake Victoria crescent, Uganda from 1989 to 2009. With enhanced understanding of the drivers of deforestation, alternative interventions for promotion of sustainable forest management in the region could be developed.

4.3 LITERATURE REVIEW

Deforestation continues to affect the humid tropical forests of Latin America, Africa and Asia (Tangley, 1986; Bawa and Dayanandan, 1997; Nagendra, 2007). Some of the consequences of deforestation include soil erosion, drought, flooding, water quality degradation, declining agricultural productivity and ultimately greater poverty for rural inhabitants of tropical nations in addition to species extinction (Tangley, 1986). Deforestation will also lead to loss of globally important carbon sinks that currently sequester carbon dioxide from the atmosphere thus impacting climate stability (Stephens *et al.,* 2007). Addressing deforestation is especially important as it impacts the lives and livelihoods of millions of forest-dependent inhabitants around the world (Tangley, 1986; Nagendra, 2007).

Reforestation serves as the antithesis to deforestation. The secondary forests that result from reforestation provide important environmental services that assist efforts toward sustainable development, increase carbon sequestration, assist in soil conservation and stabilization of hydrological cycles, and increase overall biodiversity levels (Nagendra, 2007). This research paper is aimed at investigating the drivers of forest cover change in the Lake Victoria crescent, Uganda. The purpose of this literature review is to provide an overview and evaluation of existing knowledge about drivers of forest cover change (deforestation or reforestation) with the ultimate goal of acquiring a broader understanding of potential drivers of deforestation.

Several studies have examined deforestation and its causes. Bawa and Dayanandan (1997) examined the correlations between tropical deforestation and socioeconomic variables across sites in Latin America, Africa and Asia. They found deforestation to be positively correlated with population density, per capita external debt, cattle density, cropland area/total land area, land in other use/total land area, forest products (fuelwood, charcoal, round wood and panel products) extracted per unit forest area, and per capita energy consumption. In Latin America, proportion of crop-land had the greatest effect followed by per capita external debt and then population density. This was in comparison with population density, per capita external debt and proportion of crop-land in Africa and proportion of crop-land, per capita external debt and population density in Asia. Population density, per capita external debt, proportion of crop-land area, fuel-wood and charcoal production, and per capita traditional fuel consumption accounted for 42 % (all tropical countries), 33 % (Africa), 96 % (Asia) and 48 % (Latin America) of the variance in rate of deforestation. These results, in addition to revealing some causes of deforestation, also highlight the variability of causes of deforestation with geographical location.

Place and Otsuka (2000) determined factors driving tree cover change around Lake Kyoga in Uganda in which they found the important factors to be population pressure, market access and land tenure. Utilizing International Forestry Resources and Institutions (IFRI) protocols (Nagendra, 2007), Uganda Forestry Resources and Institutions Center (UFRIC) at Makerere University has created a dataset about forests and their users. Namaalwa (2008) analyzed the UFRIC dataset and concluded that establishing appropriate forms of tenure to delineate boundaries and limit exploitation is an important step toward achieving forest sustainability. Vogt and others (2006) also found land tenure to have significant influence on land-cover changes in Uganda.

Geist and Lambin (2002) explored proximate causes and underlying driving forces of tropical deforestation from local-scale case studies. Proximate causes of deforestation included agricultural expansion, wood extraction and infrastructure extension. These were driven by a number of underlying factors which included: (i) economic factors (e.g., commercialization and development of timber markets; market failures; product price increases, especially of cash crops; low domestic costs for land, labor, fuel and timber; the requirement to generate foreign exchange earnings at the national level; and frontier colonization in the form of either poverty- or capital-driven deforestation), (ii) institutional factors (e.g., formal pro-deforestation measures such as policies on land-use and economic development related to colonization, transportation or subsidies for land-based activities; land tenure arrangements and policy failures such as corruption and mismanagement of the forestry sector; insecure ownership, quasi-open access conditions, maladjusted customary rights and legalization of land titles), (iii) technological factors (e.g., agro-technological change and poor technological applications in the wood sector), (iv) cultural and sociopolitical causes (e.g., attitudes of public unconcerned about forest environments), and (v) demographic factors (e.g., in-migration of colonizing settlers into sparsely populated forest areas resulting into higher population densities). In agreement with Bawa and Dayanandan (1997), they also found the causes of deforestation to vary with geographic location. They thus recommended that detailed understanding of the complex set of proximate causes and underlying driving forces affecting forest cover change in a given location be acquired prior to any policy intervention. The findings were based on only 9 case studies from Africa out of the total 152 case studies. This small number of cases reinforces the assertion that processes of deforestation have not been generally well studied in Africa compared to other parts of the world (Lung and Schaab, 2010; Nagendra, 2007).

Another study about drivers of deforestation is reported in Nagendra (2007). This study was aimed at evaluating hypothesized drivers of forest cover change and identifying significant variables that appeared to impact forest clearing or regeneration in Nepal. Results showed tenure regimes, monitoring and user group size per unit of forest area were significantly associated with forest cover change while leadership was not. National forests were associated with deforestation while community and leasehold forests were associated with reforestation. Lack of monitoring was associated with deforestation while different levels of monitoring resulted into differing levels of reforestation. User group size per unit of forest area exhibited a curvilinear relation with 5 to 15 individuals per hectare of forest area providing maximum positive impact. Other factors that influenced forest change included management of social conflict, adoption of new technologies to reduce pressure on the forest, and involvement of users in forest maintenance activities. Recognizing that no single governance system could protect all forests, in all parts of the world, all of the time, it was recommended that studies be extended to other regions to identify factors that could help explain additional aspects of forest change in these locations.

Mwavu and Witkowski (2008) analyzed land-use and cover changes within and around Budongo Forest Reserve in Uganda from multi-temporal images and field based studies (field observation, household interviews and key informant interviews) aimed at understanding the dynamics of land-use and cover changes, especially deforestation and associated agricultural developments from 1988 to 2004. Deforestation was found to be driven by a number of socioeconomic factors including agricultural expansion, increasing human population, unclear land tenure, conflicts of interest and political interference in addition to local people's perception that the forest was an obstacle to agriculture. Mwavu and Witkowski (2008) noted that sugar cane growing, which is known to have serious environmental impacts, is not subject to Environmental Impact Assessment (EIA), a legal requirement for any large development project in Uganda. In addition to demonstrating the haphazardness in environment management (Mwavu and Witkowski, 2008), it could also be a case of an institutional pro-deforestation measure (Geist and Lambin, 2002). Mwavu and Witkowski (2008) also agreed with Geist and Lambin (2002) that deforestation was associated with population increases as a result of in-migration.

Odada and others (2009) examined ecosystem-level cases to determine causes of land-use and land-cover changes in the Lake Victoria Basin stretching across six countries. Core at the underlying level included climatic factors, economic factors, institutional factors, national and regional policies, population growth and other remote influences. The underlying factors drove cropland expansion, overgrazing, infrastructure extension and rates of land degradation at the proximate level. Drivers at local scales within the basin were not examined. Odada and others (2009) noted a need for fine-tuning to locale-specific dynamic patterns associated with inherent ecosystem changes. In yet another study within the Lake Victoria Basin, Lung and Schaab (2010) assessed land-cover dynamics and its drivers around three protected areas, Kakamega-Nandi forests in Kenya, Mabira and Budongo forests in Uganda. Results showed both Mabira and Kakamega-Nandi forests to have generally experienced continuous forest loss while Budongo showed a much more stable forest extent between early 1970s and 2003. There was also a clear relationship between forest loss and high population density suggesting population pressure as a major driver of deforestation.

The drivers of deforestation acted in various combinations in differing geographic locations (Bawa and Dayanandan, 1997; Geist and Lambin, 2002; Nagendra, 2007) which rendered deforestation a location-specific problem (NRC, 1999). This explains why there is no hope of a single governance system or intervention protecting all forests worldwide all of the time (Nagendra, 2007). So, despite the existence of knowledge about drivers of deforestation, the question “What causes deforestation in geographic location X?” still remains unanswered. Addressing this question begs the acquisition of location-specific information for fine-tuning existing knowledge (Odada *et al*., 2009) necessary for developing useful policy interventions to reverse location-specific deforestation (Nagendra, 2007). In this study, the location is the Lake Victoria crescent, Uganda. Adopting Geist and Lambin's (2002) classification, it was hypothesized that deforestation in Uganda would be driven by a combination of several proximate (direct) and underlying (indirect) factors that acted at local, regional or global scales. The prominent proximate factors found in the literature included agricultural expansion, wood extraction and infrastructure extension while the underlying factors include economic factors, demographic factors, institutions, national policies, socio-cultural factors and remote influences. All drivers of deforestation identified in the reviewed studies (Tangley, 1986; Bawa and Dayanandan, 1997; Place and Otsuka, 2002; Mwavu and Witkowski, 2008; Odada *et al*., 2009; Lung and Schaab, 2010) fit into the classification of proximate and underlying factors.

4.4 MATERIALS AND METHODS

4.4.1 Study Area

The study area is located between 0˚8´S and 0˚42´N and between 32˚5´and 33˚32´E. It encompasses all or parts of Mayuge, Iganga, Jinja and Kamuli districts in eastern Uganda and Kayunga, Mukono, Luwero, Kampala, Wakiso, Mpigi, Mityana, Nakaseke and Kiboga districts in central Uganda. The study area measures about 162 by 94 km, an equivalent of 1,509,328 hectares (Fig 4.1). We refer to this area as the Lake Victoria crescent. This area was selected for this study because of the presence of many types of forests of different sizes and management profiles in a densely populated area with the human population known to depend on forest resources for its livelihood. Additionally, this area possessed Landsat imagery with less cloud cover for at least two points in time since 1989 that could facilitate time series analysis (*Waiswa et al.: manuscript in preparation*).

Uganda lies astride the equator and thus has a climate typical of equatorial regions. However, the climate in the southern part of Uganda including the Lake Victoria crescent is modified by maritime conditions due to closeness to Lake Victoria in addition to altitudinal effects, as this area is over 1000 m asl. The temperatures range between 15 ºC to 30 ºC. The rainfall has a bimodal distribution with two fairly well marked seasons which are March-June and October/November-December/January. The rainfall averages 1200 to 1500 mm and is well distributed (NEMA 2006/07; NEMA 2008).

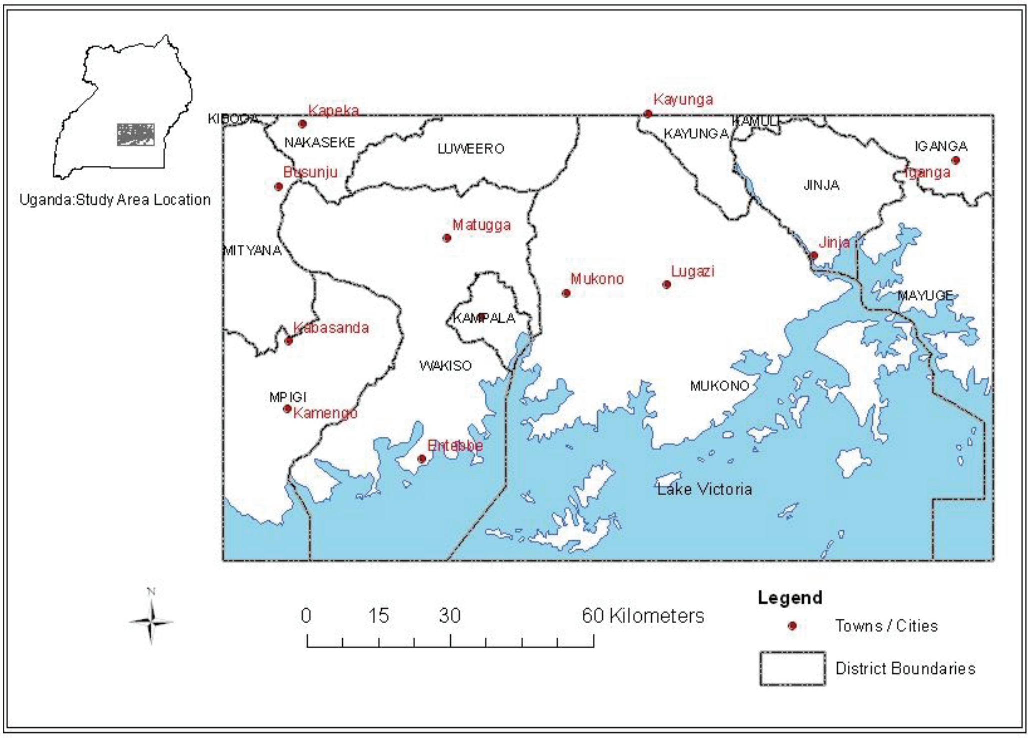


Figure 4.1 Study Area

Of Uganda's forests and woodlands covering 4.9 million hectares (NEMA, 2006/07), a substantial portion of them, including both natural forests (Namaalwa, 2008; UNEP, 2008) and plantation forests of different sizes, lie within the Lake Victoria crescent. Because most forests on private land have been heavily degraded and about 1.9 million hectares of natural forest are protected areas, only Central and Local Forest Reserves remain available for various uses (NEMA, 2006/07). The human population in this densely populated area is heavily dependent on forest resources for human livelihood needs (Mwavu and Witkowski, 2008; Oryem-Origa *et al*., 2001). The area's economy is majorly dependent on agriculture, both small and large scale.

4.4.2 Methods

4.4.2.1 Overview

The study aimed at developing a theoretical understanding of the drivers of deforestation in Uganda's Lake Victoria crescent through addressing the question "What were the key drivers of deforestation in the Lake Victoria crescent, Uganda between 1989 and 2009?" A case study approach with a multiple-case design (Yin, 2009; Eisenhardt, 1989) was employed. This approach enables both testing and generation of theory (Eisenhardt, 1989).

4.4.2.2 Selecting Cases

Theoretical sampling, which involves selecting cases for theoretical rather than statistical reasons (Eisenhardt, 1989), was employed in selecting cases. Cases in this study were defined as locations that included a natural forest in the immediate vicinity of a local community where forest cover loss had occurred between 1989 and 2009. This selection was facilitated by a reconnaissance survey coupled with Landsat imagery classification maps and personal knowledge of the study area. Thirteen (13) cases were randomly selected out of 36 cases that fit the criteria. The use of multiple cases was aimed at enhancing generalizability of the findings to the region of interest.

4.4.2.3 Data Collection

Data sources included archival sources, interviews and direct observation. Archival sources included mass media articles and publications related to forestry in Uganda, the UFRIC database based on IFRI protocol (Nagendra, 2007), and past study reports on long-term community-level forestry monitoring studies under the IFRI program at Makerere University that were relevant to selected cases.

Nineteen semi-structured interviews, containing both closed and open-ended questions, with individual key informants or groups of key informants were conducted. The purpose of the interviews was to gather local understanding and accounts of the drivers of forest cover loss in the selected cases from 1989 to 2009. These interviews were aided by

Landsat imagery-based land-use and land-cover dynamics maps of the study area printed on poster size paper. Each map had a base layer showing the 1989 land-cover classification of the study area showing open water, non-forest and forest cover classes. The base layer was overlaid with inter-conversions from forest to non-forest and vice-versa for each of the four phases under consideration: 1989 to 1995, 1995 to 2002, 2002 to 2006 and 2006 to 2009. During each interview, immediately after introducing the study and gaining consent from the key informants, a poster containing the four maps was displayed and the local area depicted on the maps was explained. The maps were then discussed chronologically i.e. 1989 to 1995, 1995 to 2002, 2002 to 2006 and 2006 to 2009. For each map, the key informants were asked to identify whether change (afforestation or deforestation) or no change took place. Based on the identified change, a discussion was held with the leading question being: "What prevailing factors accounted for the observed change or no change in forest cover status?" This question was followed by probing questions to ensure that there was clarity in responses and to explore multiple potential explanations. The probing questions focused on forest activities, forest management, policy and institutions, population dynamics, culture and technology as they related to forest cover status. While notes were taken during all interviews, only a few were digitally recorded as some of the key informants did not consent to being recorded. Each interview averaged about 50 minutes. All recorded interviews were transcribed.

Purposive and snowball sampling were used in the selection of key informants believed to be most knowledgeable about forest cover change in the area (Babbie, 2007). The key informants included: (i) Local opinion leaders, (ii) Community elders, (iii) Local community members, (iv) Managers at different levels in the government forestry sector (National Forestry Authority and District Forestry Service), and (v) Private forest owners. In gaining access to local communities, Local Council leaders were contacted through visits or telephone and introduced to the study as a way of building rapport. The Local Council leaders were useful in identification and introduction of some of the key informants.

Direct observation of phenomena of interest during field visits also informed discussions during interviews and helped to verify previously collected data. For example, issues such as agricultural encroachment in forest reserves are easily observed.

4.4.2.4 Data Analysis

Data analysis was executed in five steps which included within-case analysis, cross-case synthesis, shaping hypotheses, enfolding literature and reaching closure (Eisenhardt, 1989; Gersick, 1988). Within-case analysis involved developing detailed case-study reports consisting of narrative descriptions of data for each of the 13 case studies. This was done to reduce the volume of field data and also to facilitate familiarization with each case, a vital requirement for cross-case comparison (Eisenhardt, 1989). During within-case analysis, the focus was on building explanations of the drivers of forest cover loss between 1989 and 2009 so as to establish causal links (Yin, 2009). Within-case analysis also focused on identification of unique patterns of each case before attempting to generalize across cases (Eisenhardt, 1989). Within-case analysis involved reading written notes and transcripts associated with each interview repeatedly while taking notes specifically about drivers of deforestation which constituted the narrative description.

Cross-case synthesis (Yin, 2009) followed within-case analysis. Its purpose was to search for cross-case patterns (Eisenhardt, 1989). This involved making comparisons of narrative descriptions to determine similarities and differences amongst selected pairs or groups of cases. General patterns based on observed similarities and differences formed hypotheses about drivers of deforestation. Cross-case synthesis was deemed necessary because of its potential for generating an accurate and reliable theory as it closely fits with the data while also enhancing the probability of capturing novel findings (Eisenhardt, 1989). Analyzing cross-case patterns would also help in identifying any drivers that occurred across cases (Yin, 2009). This facilitated the shaping of hypotheses and use of replication logic across cases to refine them. Cross-case synthesis was implemented through an iterative and constant comparison of hypotheses with evidence (data) for each case to determine fit. This provided opportunities to refine theories about the drivers of deforestation and to consider the conditions under which they may or may not hold true (Eisenhardt, 1989). Emergent hypotheses were compared with existing literature, seeking both confirmatory and contradictory cases and exploring the reasons underlying the observed patterns. This provided an opportunity for deeper insight and sharper definition of the emerging constructs and theories within the study and for better understanding the potential generalizability of the findings (Eisenhardt, 1989). Closure was reached at a point when no new phenomena were observed in the analysis of cases and also when minimal improvements in theory were gained through additional comparisons between the data, theory, and the literature.

4.5 RESULTS

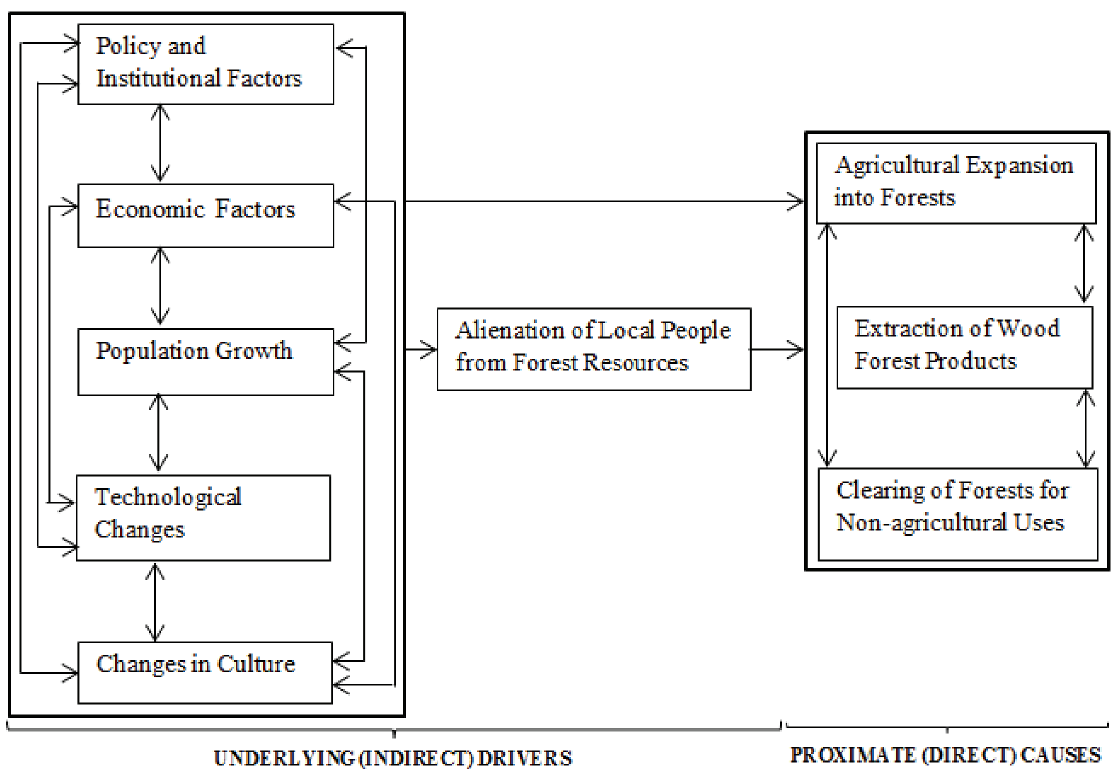
4.5.1 Model of Drivers of Deforestation in the Lake Victoria Crescent

Figure 4.2 presents a basic theoretical model of the drivers of deforestation in the Lake Victoria crescent, Uganda from 1989 to 2009 Deforestation was a consequence of proximate (direct) causes which were triggered by a number of underlying (indirect) drivers. The proximate causes included agricultural expansion into forests, extraction of wood forest products, and clearing of forests for non-agricultural uses. The underlying drivers included policy and institutional factors, economic factors, population growth, technological changes, and changes in culture. These underlying drivers influenced another underlying driver, alienation of local people from forest resources. Each of the proximate causes and underlying drivers acted singly or in combination in causing deforestation. Each of these causes and drivers is explained in greater detail below.

4.5.2 Description of model elements with illustrative examples

4.5.2.1 Proximate (Direct) Causes

Proximate (direct) causes are the human uses of forests including forest land at the local level that directly impact forest cover (Geist and Lambin, 2002). The uses may either be legal or illegal while the purpose of use may be subsistence, commercial or both. In the Lake Victoria crescent, agricultural expansion occurred through legal allocation of forest land by government or its agencies to private investors to establish large-scale crop plantations. However, there was also illegal establishment of small-scale crop gardens of especially seasonal crops such as maize, beans and green vegetables in the forest reserves. The small-scale crop farming was mainly carried out by people living in the immediate vicinity of forests. Extraction of wood forest products included commercial harvesting of timber, firewood, wood billets and charcoal, while clearance of forests for non-agricultural uses included settlement, sand mining and brick-making. The extraction of wood products for commercial purposes and the clearing of forests for non-agricultural uses were generally illegal activities, as most of the forests in the study area are government-owned forests.



Key: Arrows (single or double-sided) indicate interactions between model components

Figure 4.2 Model of drivers of deforestation in Uganda's Lake Victoria crescent from 1989 to 2009

4.5.2.2 Underlying (Indirect) Drivers

Underlying (indirect) drivers of forest cover loss refer to social and institutional processes that trigger proximate causes impacting forest cover at a local, national or global scale (Geist and Lambin, 2002). The underlying drivers are as described below.

Policy and Institutional Factors

Policy and institutional factors generally encompass the relationships between and actions of formal government institutions with influence over the forestry sector. From 1989 to 2009, deforestation in the Lake Victoria crescent was associated with a number of policy and institutional issues. One government policy initiative attempted to address escalating unemployment in Uganda by allocating forest land to foreign investors to enhance industrialization. These investors ultimately cleared some forests for private ventures. Government leases of forest land to both local and foreign investors for tree plantation establishment also led to clearing of natural forests. In some cases, the intended plantation establishment was not fully implemented.

Existing policies and laws such as the Uganda Forestry Policy (MWLE, 2001) and the National Forestry and Tree Planting Act (Republic of Uganda, 2003) aimed at promoting sustainable forest management seemed not to be achieving their goal. Many people seemed not be aware of them, indicating that they were not efficiently disseminated. In talking about policies and laws, it was not uncommon to hear responses such as “Was there a change in forestry laws?” Some people perceived the policies and laws as not being pro-people, explaining that they reduced access to forest products. Such a perception made implementation very difficult. Enforcement of forest rules and regulations was hampered by the inadequacy of resources, especially human and financial, amongst forestry management agencies. Interview excerpts such as “We are two staff here in charge of 21 central forest reserves”, “Three supervision motor cycles broke down; only one running” and “We manage 70% of the forests but have no budget allocation from central government” help illustrate the gravity of the inadequacy of resources. There were also alleged loopholes attributed to lack of clarity in the existing forestry policy and law with regard to clearing of forest products for transportation. This enabled forest products illegally harvested from central forest reserves under the jurisdiction of National Forestry Authority (NFA) to be cleared by District Forestry Services (DFS) for transportation and subsequent marketing as DFS argued that it was not legally required to verify the origin of forest products it clears. This resulted in a conflict between DFS and NFA which was reported to have distracted NFA from its role of sustainably managing central forest reserves, as illegal forest users also took advantage of the loophole to inflict damage to central forest reserves, mainly in the form of deforestation. Political interference in the management of forestry resources also contributed to deforestation. Interview excerpts such as “Politics in this area is mainly about the forest because people mainly depend on it” and “If he wins, people will cultivate in forests since forest belong to government” manifest the magnitude of the interference. Many politicians were reported to have sacrificed forests for votes. They supported illegal forest activities and some even ordered the return of tools confiscated by forestry officials to forest encroachers. Corruption and mismanagement within the forestry sector, and lack of political will to protect forests further contributed to deforestation in the region.

Economic Factors

Poverty, which refers to the people’s inability to afford the basic human needs such as food, clean water, clothing, shelter, health care and education, was one of the major economic issues driving deforestation in the Lake Victoria crescent. Poverty, especially within local communities, increased the vulnerability of forests to anthropogenic change. Increasing levels of poverty in the Crescent were commonly attributed to crop failures due to pest and disease infestations and droughts. Coffee, the long-time main cash crop was attacked by the coffee wilt disease which nearly wiped out coffee plants. Agro-processing industries relying on coffee and other impacted crops also collapsed during the study period. Declining crop production was also attributed to declining soil fertility due to continuous cultivation and increasing scarcity of land for agricultural production, both consequences of population increase, caused by both natural births and immigration.

As ecological factors decimated incomes from agricultural enterprises, residents also were experiencing reduced returns from alternative economic activities, such as fishing. Over fishing associated with antiquated fishing methods was reported to be responsible for the decline in fishing returns. Government initiatives had also failed to adequately catalyze alternative livelihoods for residents, often due to inadequate coordination amongst government sectors. For example, while one government agency encouraged farmers to grow crops such as *Vanilla planifolia* and *Moringa oleifera* or raise silk worms, there weren't sufficient mechanisms in place to market such products. As a coping strategy, local people resorted to multiple forms of forest resource extraction.

The increasing demand and associated markets for forest products in Uganda's Lake Victoria crescent from 1989 to 2009 was another major economic driver of deforestation. Respondents commonly attributed this to increasing economic development, political stability and population growth. Urbanization also led to higher demand for energy and wood for the construction industry among other uses. There were also economic activities such as fish smoking, brick baking and local gin distillation which were heavily dependent on firewood. The increasing demand for products such as charcoal, firewood, agricultural crops (especially food) and timber from forests resulted in higher and quicker financial returns as compared to traditional non-forest income generating activities such as agriculture and fishing. These greater returns worked to increase both legal and illegal forms of deforestation.

Population Growth

The Lake Victoria crescent covering eastern and central Uganda witnessed quickly increasing population density due to natural births and immigration from 1989 to 2009. One 20 year old respondent stated that "We are now many. We used to be in our father's house but now I have my own house with a wife and 5 children". Population data covering the study area (eastern and central Uganda) from Uganda Bureau of Statistics (http://www.geohive.com/cntry/uganda.aspx) further supported the findings. Population density for eastern Uganda increased from 105 persons per square km in 1991 through 157 persons per square km in 2002 to 210 persons per square km in 2010. On the other hand, the population density for central Uganda increased from 79 persons per square km in 1991 through 107 persons per square km in 2002 to 134 persons per square km in 2010. Population growth not only led to increasing scarcity of agricultural land but also to continuous cultivation of existing land. The ultimate result was declining crop productivity which led to increased poverty and food insecurity. Due to unavailability of other alternative means of survival, people resorted to forests. This was through increased extraction of commercial forest products such as timber and firewood and through clearing additional forest land, which they believed to be more fertile, for crop cultivation. The increase in population also meant increased consumption of resources, including forest resources, which led to more demand for a shrinking supply, further exacerbating deforestation rates.

Technological Changes

Enhanced transportation and transition from hand tools to power tools, such as chainsaws, accelerated deforestation in the region between 1989 and 2009. These changes were driven primarily by immigration of individuals with enhanced technologies. It was common during interviews to hear statements such as "Bakiga started the practice" and "Bakiga could fell the trees with power saws and then use hand saws." Bakiga are an immigrant tribe. Other drivers of technological change included leasing of forest lands to external enterprises, and increased demand which catalyzed more production and transportation. Furthermore, with increasing alienation from forest resources, local people readily adopted such new technologies as they moved away from their more traditional role as forest stewards.

Changes in Culture

Relevant cultural factors include beliefs, myths and perceptions that people have towards forests (Machlis *et al*., 1997). Traditional beliefs described by respondents included discussions of the sacred values of forests and the role of local people as forest stewards. Examples of such sacred beliefs and practices that helped conserve forests included designation of certain forests as worship sites, limitations on quantities of forest products that could be taken out of the forest and beliefs that certain tree species could not be harvested from some forests. Multiple factors interacted to erode these perceptions. With increasing economic desperation, a perceived expropriation of the resource, new ideas and competition introduced through immigration, increased demand for products, and new means to produce them, the region witnessed a cultural shift toward more utilitarian values associated with local forests, further contributing to its deforestation.

Alienation of local people from forest resources

Alienation describes a scenario where an individual or a group of people feel disenfranchised of their rights to utilize or access resources, including forestry resources. Local feelings of alienation diminished local interest in sustainable management of forest resources. Alienation was found to be influenced directly or indirectly by the other identified underlying drivers of deforestation. Alienation was deeply rooted in perceived historical injustices regarding tenure disputes over government forest reserves as well as more contemporary causes. For example, there were reports of a group called "*Itaaka Lyange*" translated as "*My Land*" which continues to claim ownership of a gazetted forest reserve stating that its members were not compensated as original land owners when the government took over the forest. Another group consisted of army veterans claiming portions of a forest reserve alleging it was allocated to them in the 1970s. Such claims of ownership have fomented a number of conflicts that have undermined sustainable forest management thus leading to deforestation. Leasing or selling concessions within government forest reserves to people from outside local communities for private business ventures such as the establishment of tree plantations or timber harvesting has drawn local ire and been seen as a dispossession of sorts. One respondent claimed "Our forests are being given to non-natives." Even when the local people needed to engage in legal forestry activities, the required permits were deemed too expensive. Local feelings of alienation from forest resources were worsened by poor communication and inadequate collaboration between forestry sector management and forest-dependent local communities. Some local people asserted that forest managers were rather utilizing personnel with guns in guarding the forests. As a coping strategy, local people intensified their illegal utilization of forest resources despite forest management agencies' attempts to restrict utilization through more restrictive policies and increased enforcement of rules and regulations. These government efforts were short-lived due high costs of enforcement. Local people became hostile, and forest managers were chased, beaten, and even killed in some cases. Perceptions of rampant corruption and political interference in the affairs of forestry sector further exacerbated the situation. As local people perceived a loss of ownership over forest resources, their interest in maintaining them diminished.

4.6 DISCUSSION

Deforestation in Uganda's Lake Victoria crescent from 1989 to 2009 was driven by a number of broad factors. There were proximate (direct) causes which included agricultural expansion into forests, extraction of wood forest products and clearing of forests for non-agricultural uses. The proximate causes were triggered by underlying drivers which included policy and institutional factors, economic factors, population growth, technological changes, changes in culture and alienation of local people from forest resources. Each of the proximate causes and underlying drivers of deforestation could act singly or in combination with others to cause deforestation.

These findings about drivers of deforestation generally agree with empirical findings from prior studies. Studies showed that deforestation was due to unplanned spread of agriculture or increasing crop-land area (Mwavu and Witkowski, 2008; Geist and Lambin, 2002); firewood and timber harvesting (Geist and Lambin, 2002); increasing population density (Bawa and Dayanandan,1997; Place and Otsuka, 2000; Mwavu and Witkowski, 2008; Struhsaker, 1987); Lung and Schaab,2010); market access (Place and Otsuka, 2000); unclear land tenure and or property rights (Place and Otsuka, 2000; Namaalwa, 2008; Vogt *et al*.,2006; Nagendra, 2007; Mwavu and Witkowski, 2008); lack of forest monitoring and non-involvement of users in forest maintenance (Nagendra, 2007); and conflicts of interest, political interference, negative perception about forests and unfavorable or pro-deforestation policies (Mwavu and Witkowski, 2008).

On the other hand, the model of drivers of deforestation is also reflected to some extent in multiple models of human impacts on the landscape. The human ecosystem model highlights the interaction between socioeconomic resources, cultural resources, social institutions, social cycles and social order with natural resources (Machlis *et al*., 1997). The model of drivers of deforestation makes explicit the key results of the interactions of the human ecosystems model, which have resulted in the alienation of local people from resources as a major driver of human impacts on the landscape. Other models of environmental or landscape change related to the model of drivers of deforestation included the IPAT model (Ehrlich and Holdren, 1972) and the POET model (Vaillancourt, 1995). The IPAT model conceptualizes environmental impact as a product of population, affluence and technology while the POET model portrays environmental change as being influenced by an interaction between population, organization and technology. Both the IPAT and POET models consist of multidirectional relations between their model elements. The model of drivers of deforestation encompasses the factors in both the IPAT and POET models.

One of the key lessons from these results is that deforestation will probably continue to occur in the Lake Victoria crescent as demonstrated by not only the many drivers of deforestation, but also the interactions between them, rendering deforestation a complex process. Addressing deforestation is a prerequisite for ensuring that forests continue to provide goods and services today and for generations to come**.**

Although both proximate and underlying causes of deforestation were identified, the underlying ones seemed more responsible for causing deforestation. This assertion is in agreement with Brosius and Russell (2003) who stated that underlying factors are the more fundamental and ultimate reasons for observed deforestation as compared to proximate factors. It is therefore important that attempts at addressing deforestation focus on interventions that combat the underlying drivers of deforestation.

In consideration of the elements of the model of drivers of deforestation, reasonable points of intervention could involve both government and non-government organizations and their relationships with local communities. However, local communities may be the key to sustainable management of forests. Despite government's efforts to reform the Uganda forest sector for the better through implementing changes like adoption of The

Uganda Forestry Policy (MWLE, 2001) and enactment of The National Forestry and Tree Planting Act (Republic of Uganda, 2003), deforestation still continues. This was, among other reasons, attributed to government's failure to fully implement some of its policies and laws. Results from this study point to the government's inefficiency in disseminating the forestry policy and law. These policies and laws are also vague, leading to conflicts between forestry management agencies. This further hinders them from performing their roles of managing forests efficiently, resulting in increased deforestation. The forest sector also lacks adequate resources, especially human resources, as it is usually underfunded by government because of being a non-priority sector in Uganda's economy (Kamugisha-Ruhombe, 2010). A similar scenario of inadequate resources and/or political will for successfully enforcing regulations also occurs in protected area management, including parks (Dourojeanni, 2002; Salafsky and Margoluis, 2002). According to Svensson (2005), Uganda is ranked amongst the most corrupt countries in the world based on the International Crime Victim Surveys (ICVS). Corruption continues to be a major hindrance to improved service delivery. This and prior studies (e.g., Otieno and Buyinza, 2010) found instances of forestry officials themselves or by proxy engaging in illegal forestry activities. On the other hand, local communities have been shown to be excellent stewards if given the proper incentives and protections from external exploitation (Ostrom, 1990; Stevens, 1997; Tangley, 1986). Local communities also have the potential of positively impacting biological diversity through both their traditional land-use practices (Alcorn, 1993; Fairhead and Leach, 1996) and application of local ecological knowledge (McNeely, 1989; Alcorn, 1993; Chambers, 1994; Kellert, 1996). Local communities also have tendencies to defend their territories against outside encroachment (Schwartzmann, Nepstad and Moreira, 2000; Fearnside, 2003).

For local communities to take center stage in efforts to curb deforestation, the focus in the model of drivers of deforestation has to be on addressing their feelings of alienation from forest resources. Alienation has created a sense of lack of ownership and responsibility denial towards forest resources amongst local communities. Viewing especially forest reserves as government resources was associated with opposition to forestry rules and regulations, and mistrust of forestry officials. This agrees with the findings of Obua *et al.*

(1998) that restricted access to forest resources amongst local communities around Budongo Forest Reserve in Uganda resulted in mistrust, antagonism and conflicts with the Forest Department. Because of alienation, local people utilized forests for economic gains without any sense of care. As people felt the forest expropriated, they could no longer see the benefit of conservation.

A multi-faceted approach is required if alienation is to be addressed. This will involve among other approaches rebuilding a sense of ownership and responsibility for forestry resources amongst local communities in addition to building trust amongst various forestry stakeholders including forestry officials, non-government organizations and local communities. It has been argued that local communities lack the capacity to manage forests (e.g. Agea *etal*., 2009). Non-governmental organization involvement could be key in enhancing this capacity, as evidenced by other examples around the world (Normile, 2010; Borges-Mendez, 2008; Baral and Stern, 2011**)**. There are concerns, however, that with increasing poverty, ceding management of forests to local communities will only lead to further degradation and deforestation through over-exploitation without some additional intervention (Brandon and Wells, 1992). While poverty is a multi-faceted issue that would require a holistic approach to resolve, evidence suggests that enhanced relationships between local people and natural resource governance institutions can help to offset the economic pressures on forests, even in areas of high poverty (Stern 2008). While numerous forms of integrated conservation and development projects (ICDPs) may be possible, they are unlikely to succeed without improved relationships (Stern, 2010). Stern (2008; 2008a; 2010) has found trust in natural resource management officials to be fair and honest to be the single most predictive factor associated with compliance with protected areas regulations in widely varying contexts. Recent research has also suggested that projects aimed at producing alternative livelihoods for natural resource dependent people rely heavily upon the empowerment of local people in natural resource governance and upon trust between local entities and governing institutions (McShane and Wells, 2004; Stern, 2008; Baral and Stern, 2011). Key factors fomenting trust in such situations that have been found in empirical research include meaningful and respectful communication between officials and local residents, officials' receptiveness to local input, consistent and honest performance, benefits to local people associated with protected area presence, and equitable treatment of different groups (Stern, 2008a).

The empowerment of local communities may serve to effectively combat the negative impacts associated with alienation. This would involve the development of protections from external entities harvesting in local forests, rather than its encouragement, opening new lines of communication, and developing local capacity to govern local forest use. Non-governmental organizations may serve as an effective bridge between government organizations and local communities to start along this path. However, the policy environment must also shift to allow for new forms of resource governance. If local people no longer feel alienated from their resources, they are more likely to be interested in working together to sustain its benefits into the future.

4.7 CONCLUSION

This study was aimed at creating a theoretical understanding of the drivers of deforestation in Uganda's Lake Victoria crescent between 1989 and 2009. The model of drivers of deforestation reveals that deforestation was a consequence of proximate causes which were triggered by a number of underlying drivers. The proximate causes included agricultural expansion into forests, extraction of wood forest products, and clearing of forests for non-agricultural uses while the underlying drivers included policy and institutional factors, economic factors, population growth, technological changes, changes in culture and alienation of local people from forest resources. Each of the proximate causes and underlying drivers acted singly or in combination in causing deforestation. Deforestation in the Lake Victoria crescent was predicted to continue unless addressed through interventions that target its underlying drivers, especially alienation of local people from forest resources. One potential intervention could involve empowerment of local communities.

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CHAPTER FIVE

SUMMARY

The overarching objective of this study was to provide information on the dynamics of forest cover and their drivers vital for enhancing sustainable forest management in the Lake Victoria crescent, Uganda. The study methodology integrated remote sensing and Geographic Information Systems techniques, analysis of landscape patterns and various social science techniques. Results showed that the Lake Victoria crescent, Uganda covering an area of about 1,509,228 ha, experienced a decline in forest cover from 9.0% in 1989 to 4.4% in 2009. This was in comparison with non-forest cover which increased from 58.7% in 1989 to 63.5% in 2009 while open water coverage generally remained unchanged averaging 32.3% from 1989 to 2009. Mean annual deforestation decreased with a weighted mean of 2.56% from 1989 to 2009. Both deforestation and afforestation declined between 1989 and 2009 although deforestation still exceeded afforestation. Deforestation was spatially clustered around major forests while afforestation exhibited a random spatial distribution with exception of a few places where it large afforestation or reforestation patches were observed. It was found that forests in the Lake Victoria crescent, Uganda experienced fragmentation from 1989 to 2009 with forest fragmentation being more pronounced from 1989 to 1995. Forests greater than 100 ha in size were the most affected by fragmentation but they also constituted a bigger proportion of forest cover in the Lake Victoria crescent as compared to forests less than 100 ha in size. Forest fragmentation also occurred simultaneously with deforestation. Deforestation , the main observed form of forest cover dynamics, was as portrayed in the developed model of drivers of deforestation in the Lake victoria crescent, a consequence of proximate causes which were triggered by a number of underlying drivers acting singly or in combination. The proximate causes included agricultural expansion into forests, extraction of wood forest products, and clearing of forests for non-agricultural uses while the underlying drivers included policy and institutional factors, economic factors, population growth, technological changes, changes in culture and alienation of local people from forest resources. Underlying drivers were found to be the main causes of deforestation.

The continued forest cover loss through both deforestation and forest fragmentation re-affirms that sustainable forest management still remains a challenge in the Lake Victoria crescent that needs to be addressed. The mean rate of deforestation in the Lake Victoria crescent of 2.56% from 1989 to 2009 was higher than some of the reported national estimates of deforestation rates such as 1.76% from 1990 to 2000 and 2.13% from 2000 to 2005 (FAO, 2005). NEMA (2006/07) also noted the variations in rates of deforestation in different parts of Uganda. Knowledge of the sub-national rates of deforestation might be helpful in targeting interventions. However, this requires regular assessments of forest cover dynamics including deforestation at the sub-national level so as to obtain detailed forest resource information.

Forests greater than 100 ha in size should be the focus of protection and or sustainable forest management as they are very vulnerable to forest fragmentation. This is necessary because forest fragmentation will ultimately lead to smaller forest fragments that could easily be lost through deforestation thus exacerbating deforestation. The protection of forests greater than 100 ha in size is also vital because they still constituted a big proportion of forest cover in the Lake Victoria crescent, Uganda in 2009. Since a number of studies in other locations have shown that forest fragmentation sometimes negatively influences the functioning of forests **(**Midha and Mathur, 2010; Ripple *et al.*, 1991; Behera, 2010; Nyeko, 2009)**,** protection of forests in the Lake Victoria crescent from fragmentation and deforestation could help in maintaining their functional integrity. However, research aimed at understanding the impacts of forest fragmentation on the functioning of forests in the Lake Victoria crescent is still required as it is will play a vital role in planning for sustainable management of forests not only in the Lake Victoria crescent but also in other areas with similar habitats. Alienation of local people from forest resources should be addressed through empowerment of local communities if deforestation is to be curbed.

Obua *et al.* (2010) noted the continued need for accurate and reliable information about forest cover dynamics to inform debates, discussions and decision making on forest management and conservation in Uganda. This study has thus contributed towards meeting that information need in addition to meeting its stated goal. The information acquired in this study has revealed the continued occurrence of deforestation and forest fragmentation in the Lake Victoria crescent, Uganda in addition to identifying the causes of forest cover loss. It is upon this baseline that research aimed at furthering the understanding of forest cover dynamics and the pursuance of suggested interventions to curb underlying drivers of deforestation, especially alleviating alienation of local people from forest resources, are being recommended for enhancement of sustainable forest management.

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APPENDICES

Appendix A: Error Matrices with Map Marginals

1989

Map	*Reference*				
	Open water	Non-Forest	Forest	**Row Total**	**Map Marginals**
Open Water	222	2	0	224	0.3205
Non-Forest	0	395	12	407	0.5823
Forest	0	6	62	68	0.0973
Column Total	222	403	74	699	

1995

Map	*Reference*				
	Open water	Non-Forest	Forest	**Row Total**	**Map Marginals**
Open Water	221	3	0	224	0.3205
Non-Forest	0	411	8	419	0.5994
Forest	0	5	51	56	0.0801
Column Total	221	419	59	699	

2002

Map	*Reference*				
	Open water	Non-Forest	Forest	**Row Total**	**Map Marginals**
Open Water	222	2	0	224	0.3205
Non-Forest	0	421	8	429	0.6137
Forest	0	3	43	46	0.0658
Column Total	222	426	51	699	

2009

Map	*Reference*				
	Open water	Non-Forest	Forest	**Row Total**	**Map Marginals**
Open Water	223	1	0	224	0.3205
Non-Forest	1	438	5	444	0.6352
Forest	0	6	25	31	0.0443
Column Total	224	445	30	699	

Appendix B: True Marginal proportions with their associated variances and standard deviations for each land cover class in the classified images for 1989and 1995

	1989			1995		
	Forest	Non-Forest	Open Water	Forest	Non-Forest	Open Water
True Marginal Proportion	0.1059	0.5765	0.3176	0.0844	0.5994	0.3162
Variance	3.5×10^{-5}	4.21×10^{-6}	9.97×10^{-9}	1.13×10^{-7}	6.17×10^{-6}	1.45×10^{-8}
$2^*(\text{Variance})^{0.5}$	0.0118	0.0041	0.0002	0.0007	0.0050	0.0002

Appendix C: True Marginal proportions with their associated variances and standard deviations for each land cover class in the classified images for 2002 and 2009

	2002			2009		
	Forest	Non-Forest	Open Water	Forest	Non-Forest	Open Water
True Marginal Proportion	0.0730	0.6094	0.3162	0.0429	0.6366	0.3205
Variance	9.74×10^{-8}	4.15×10^{-6}	9.46×10^{-9}	8.94×10^{-8}	2.14×10^{-6}	2.05×10^{-6}
$2^*(\text{Variance})^{0.5}$	0.0006	0.0041	0.0002	0.0006	0.0029	0.0029