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Analysis of Land Use/Land Cover Change Impacts Upon Ecosystem Services in Montane Tropical Forest of Rwanda: Forest Carbon Assessment and REDD+ Preparedness

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DISSERTATION COMMITTEE PAGE

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ANALYSIS OF LAND USE/LAND COVER CHANGE IMPACTS UPON ECOSYSTEM SERVICES IN MONTANE TROPICAL FOREST OF RWANDA:

FOREST CARBON ASSESSMENT AND REDD+ PREPAREDNESS

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ANALYSIS OF LAND USE/LAND COVER CHANGE IMPACTS UPON ECOSYSTEM SERVICES IN MONTANE TROPICAL FOREST OF RWANDA:

FOREST CARBON ASSESSMENT AND REDD+ PREPAREDNESS

by

McArd Joseph Mlotha

MA GISDE. Clark University, Worcester, MA, 2004

A dissertation submitted in partial fulfillment of the requirements for the degree of

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DEDICATION

This dissertation is dedicated to my beloved late parents, my late father, Laston Bywell Songiso Mlotha, and my late mother Cecilia Laston Mlotha (Nyamvula), whom I cherish as my role models, full of love and care. I am grateful for the great love and support, you taught me to work hard and persevere right from my childhood to this day, and I will miss you forever. I wish you were available to witness the fruits of your great work as parents.

RIP Mum and Dad

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ABSTRACT

Changes in forest cover, especially changes within tropical forests, affect global climate change, together with ecosystems and forest carbon. Forests play a key role in both carbon emission and carbon sequestration. Efforts to reduce emissions through reduced deforestation and degradation of forests have become a common discussion among scientists and politicians under the auspices of the United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation (UN-REDD Programme). This dissertation research assessed the impacts of land use land cover change upon ecosystem services from a protected area focusing on forest carbon distribution and vegetation mapping using remote sensing and geographical information systems (GIS). I also assessed Rwanda's preparedness in the United Nations global program, *Reducing Emissions from Deforestation and forest Degradation, Measuring, Monitoring, Reporting, and Verifying* (REDD+MMRV). I carried out research in Nyungwe National Park (NNP), one of four National Parks of Rwanda. NNP is a montane tropical forest located in the Albertine Rift, one of the most biodiverse places in central and east Africa. I used remote sensing and field data collection from December 2011 and July 2012 in the western part of the Park to assess distribution and quantities of aboveground (ABG) forest carbon using generalized allometric functions. Using Landsat data together with 2009 high resolution color orthophotos and groundtruthing, I analyzed land cover changes between 1986 and 2011 for NNP. The landuse land cover change analysis showed that between 1986 and 1995 there was a minor increase in forest cover from 53% to 58% while from 1995-2003 a substantial decrease in forest cover occurred. Between 2003 and 2011 was a period of recovery with forest cover increasing by 59%. Vegetation analysis based on a 2009 Park biodiversity survey yielded 13 vegetation communities based on dominant and co-dominant species. *Macaranga kilimandscharica* was found to be dominant in three communities, representing 42% of the Park, and co-dominant in one community, representing 7% of the Park. While ~50% of the Park is secondary forest, the change in protection status has had a positive impact upon forest cover change within the Park. . Assessment of REDD+-MMRV readiness revealed that Rwanda has higher capacity and readiness in remote sensing and GIS than in forest inventory and carbon pools inventory. Lack of data to support development of emission models is a major problem at the national level which needs to be addressed.

Key words: Carbon, emission, land cover change, land use, orthophotos, protected areas, Reducing Emissions from Deforestation and forest Degradation, Measuring, Monitoring, Reporting, and Verifying (REDD+MMRV), tropical forest, vegetation communities.

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Chapter 1: Introduction

While global efforts to reduce carbon emission by reducing deforestation and forest degradation are a major focus of the UN-REDD member countries, loss of forest cover continues at an alarming rate (Baccini et al., 2012; M. C. Hansen et al., 2013; Laurance, Sloan, Weng, & Sayer, 2015; Sloan & Sayer, 2015). Critiques of REDD+ show that increased tree cover loss has continued despite REDD+ implementation in some countries such as Brazil and Indonesia and some forest dependent communities are experiencing oppression from REDD+ implementation (Filewod, 2017; Fletcher, Dressler, Büscher, & Anderson, 2016; Howell & Bastianses, 2015; Sunderlin & Atmadja, 2009). In the 1990's the global annual deforestation rate was estimated to be around 0.18%; between 2000 and 2015, however, the rate dropped to 0.08% (Keenan et al., 2015; MacDicken, Reams, & de Freitas, 2015).

Tropical forests play a key role in the global carbon cycle as both carbon sources and sinks (Achard et al., 2002; Lu, 2005;Bombelli et al., 2009; Bright et al., 2012). They are home to many endangered, endemic and rare plant and animal species (Gardner et al., 2009; Lewis et al., 2009; Schelhas & Greenberg, 1996). Houghton (2005) and Lewis et al. (2009) argued that tropical forests store up to 50% of the global carbon; consequently, any loss or negative changes in tropical forests will influence climate variations. Changes in forest cover, which are synonymous to changes in land use, and changes in land cover are two of the largest sources of carbon emission into the atmosphere by human activities (Köthke, Schröppel, & Elsasser, 2014; MacDicken et al., 2015; Strassburg et al., 2014; Verburg, Schot, Dijst, & Veldkamp, 2004). The global carbon cycle directly affects global climate patterns through the amounts of carbon emissions into the atmosphere and how much is absorbed by the oceans and forests (Le Quéré et al., 2014)

. Most tropical forests are located within areas of high poverty and within least developed countries with high human population densities, in part driving the conversion of tropical forest cover to other land uses or degradation by selective harvesting of woody products (Achard et al., 2002; Geist & Lambin, 2002; Hansen et al., 2013). Many communities in least developed countries rely on forests for most of the resources for their livelihoods, including food, medicines, raw materials for construction, sources of income, water, energy, firewood, charcoal, and wild plants (Belcher, Ruíz-Pérez, & Achdiawan, 2005; Heubach, Wittig, Nuppenau, & Hahn, 2011; Ndoye & Tieguhong, 2004; Shackleton & Shackleton, 2004). As populations that depend on forests for livelihood increase, so do deforestation rates. The causes and drivers of deforestation and forest degradation are many and vary from region to region. In Africa, subsistence and intensive agriculture is considered a major source of deforestation (Geist & Lambin, 2001; Gibbs & Herold, 2007). Increased demand for food, and economic development as human populations increase, has caused some forests to be cleared. Although some of the drivers and causes of deforestation and forest degradation are considered genuinely important for human survival, for example areas cleared for food production, national development infrastructure or urban centers, or timber extraction, the impact of the degraded or clear cut forest affects biodiversity and carbon emissions at all levels (Gibbs & Herold, 2007). Lewis et al., (2015) argued that over 50% of the original tropical forests globally have been cleared. Hansen et al. (2013) argued that the global cover percentage of tropical forests has decreased over time from an estimated 12% of global terrestrial land to about less than 5%, which in a real sense impacts the carbon emission dynamics and other environmental aspects.

Dissertation overview

This dissertation research was designed to assess impacts of land use land cover change upon the ecosystem services provisions from a protected area focusing on forest carbon distribution and vegetation mapping using remote sensing and geographical information systems (GIS). Secondly, the dissertation assessed Rwanda's preparedness in *Reducing Emissions from Deforestation and forest Degradation, Measuring, Monitoring, Reporting, and Verifying* (REDD+MMRV) (UN-REDD, 2011).

I carried out research in Nyungwe National Park (NNP), one of the four national parks of Rwanda. Nyungwe National Park (NNP) is a montane tropical forest located in the Albertine Rift, one of the most biodiverse places in Africa (Carr et al., 2013; Plumptre et al., 2007). The vegetation of Nyungwe National Park is a mixture of trees, shrubs, herbs, ferns, and lianas. Distribution of vegetation in Nyungwe has been described based on physiognomic characteristics using characteristics such as height, canopy cover, stem density, and environmental conditions to classify vegetation (Ewango, 2001; Fischer, 1993; Fischer & Killmann, 2008; A. Plumptre et al., 2007). Fischer (1993) described Nyungwe vegetation distribution based on elevation. For example, within the elevation of 1800 to 2100m, the forest is characterized by 2-3 distinguishable tree layers with a canopy layer reaching over 35m. In this forest type, the primary forest is characterized by *Parinari excelsa, Entandrophragma excelsum, Carapa grandiflora, Symphonia globulifera* and *Chrysophyllum gorungosanum* trees with an understory canopy layer of either *Psychotria mahonii* or *Alchornea hirtella*. However, a biodiversity study conducted in Nyungwe (WCS 2009) showed that this kind of community can be found at a wider elevation range, between 1700 to 2400m.

Ewango (2001) classified the vegetation by elevation and habitat type. He used three habitats, namely primary forest, secondary forest and bamboo/savannah forest. His findings show that *Syzygium guineense* was found in all habitats and within the elevation range of 1590 -2685m, while other species were found only in primary forest, such as *Cleistanthus polystachyus, Chrysophyllum gorungosanum, Garcinia volkensii, Parinari excelsa, Strombosia scheffleri,* and *Symphonia globulifera.* Changes in land use and land cover in protected areas are mostly associated with human activities that put pressure on available resources. The forests in Nyungwe are surrounded by high human population density and intensive agriculture, leaving the forest as the main source of natural resources and wildlife for the surrounding community. There are signs of poaching in the Park, as well as mining activities, traces of honey hunters and collection of other forest products; these activities are considered threats to biodiversity, and by 2011 reports indicate that there was a drop in occurrences (Mulindahabi et al., 2011) while from 2011, poaching increased from 2759 occurrences a year to 9473 a year in 2015 (Moore et al., 2018). These anthropogenic activities within the Park, together with natural events like landslides and wind throws, affect the changes in land cover.

In chapter two I present an assessment of the vegetation communities of the park, including distribution of the liana *Sericostachys scandens* using various tools. I mapped and analyzed vegetation communities within the protected area by hierarchical analysis using TWINSPAN (Two-way Indicator Species Analysis). The outcome of TWINSPAN analysis was further analyzed using GIS and remote sensing techniques, generating clusters and vegetation communities. Maximum entropy (MaxEnt) modeling of species geographic distributions was employed to simulate and estimate distribution of *Sericostachys scandens*. According to Elith et al., (2011), MaxEnt is a program for modelling species distributions from presence-only species data. Understanding vegetation associations and extent of distribution of the liana *Sericostachys scandens* is one of an important ecological knowledge to appreciate some of the ecological processes and systems within Nyungwe National Park. One of the concerns is that some believe that *Sericostachys scandens* is spreading in the Park, and may be one of the causes of tree mortality. However, this situation needs further research to determine changes and current extent of this liana.

In chapter two I present an assessment of the vegetation communities of the park, including distribution of the liana *Sericostachys scandens*. I mapped and analyzed vegetation communities within the protected area by hierarchical analysis using TWINSPAN (Two-way Indicator Species Analysis). The outcome of TWINSPAN analysis was further analyzed using GIS and remote sensing techniques, generating clusters and vegetation communities. Additionally, I identified vegetation associations and extent of distribution of the liana *Sericostachys scandens*, which some believe is spreading in the Park, possibly causing increased tree mortality. However, this situation needs further research to determine changes and current extent of this liana.

In chapter three, I focused on land use and land cover change within Nyungwe National Park and buffer zone. I examined land cover changes between 1986 and 2011 for Nyungwe National Park. The study covers a period of 25 years and Landsat Thematic Mapper satellite images were used in order to determine impacts of land cover change and extent of change on forest cover. The chapter highlights the use of remote sensing and GIS techniques to analyze the past land cover and also demonstrate the linkages between socio-political history, population growth and changes in land cover. Tassel

Cap Transformation (TCT) and Normalized Difference Vegetation Index (NDVI) were used as tools to assess qualitative and quantitative changes in vegetation cover, together with analysis of the history of conservation management and socio-economic policies, and activities that led to land cover change. Considering that land use and land cover changes are part of environmental history, I highlight some of the major historical events which might be drivers or causes of land use land cover change affecting Nyungwe National Park.

In chapter four, I assess distribution and quantities of aboveground (ABG) forest carbon within Nyungwe National Park, using generalized allometric functions and vegetation indices including Normalized Difference Vegetation Index (NDVI) based on 2011 Landsat TM images. The chapter reviews literature on vegetation indices mostly focusing on NDVI and biomass estimation. I calculated ABG for each sample plot and overlaid an NDVI layer to extract corresponding NDVI values for each of the sample plots. I used regression analysis to determine correlation between field-measured and computed ABG values versus NDVI values of each sample plot. By linking the computed ABG to NDVI, I attempted to convert NDVI values to ABG values for the study area. When using models to estimate ABG, adequate data are required to assess accuracy of the models. Although some models can be generated that do not require ground-based measurement to estimate AGB, for these models to provide useful information, more ecological studies as well as remote sensing technological studies are needed to feed data into the models. Additionally, this study highlights some of the lessons in planning for routine monitoring and verification of forest carbon as part of preparation REDD+.

Chapter five explores REDD+ MMRV (Reducing Emissions from Deforestation and Forest Degradation+ Measurement, Monitoring, Reporting and Verification) preparedness in Rwanda. I review the literature related to climate change, green economy, GHG emissions, REDD+ and trainings related to monitoring climate change and carbon research within Rwanda. In order to highlight REDD+ MMRV preparedness in Rwanda, this chapter explores the literature considering what has been done in terms of policies and initiatives, various studies and research related to REDD+. To assess preparedness, I considered three capacities, namely (a) Remote sensing and GIS capacity, (b) Carbon pool inventorying capacity and (c) Baseline, intervention and monitoring capacity. I discuss how these three capacities relate to MMRV and recommend further research as a possible solution to the identified deficiencies in capacity regarding MMRV preparedness.

The final chapter, chapter six, provides a brief synthesis of findings, implications of the research, and discusses directions for future research.

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Chapter 2: Land use and land cover change within Nyungwe National Park and buffer zone, Rwanda. Analysis of drivers of change and historical perspectives

Abstract

Protected areas are important for biodiversity conservation and considered to have lower rates of land conversions and clearings in comparison to their surroundings. Changes in land cover affect wildlife habitats, biomass and ecosystems. In this study, I examined land cover changes between 1986 and 2011 within Nyungwe National Park, south western Rwanda. The study covers a period of 25 years and Landsat Thematic Mapper satellite images were utilized in order to determine impacts of land cover change and extent of change on forest cover. Tassel Cap Transformation (TCT) and Normalized Difference Vegetation Index (NDVI) were used as tools to assess qualitative and quantitative changes in vegetation cover together with analysis of the history of conservation management and socio-economic policies, and activities that led to land cover change. The NDVI analysis showed that between 1986 and 1995, there was a minor increase in forest cover while the period between 1995 and 2003 experienced the most decrease in forest cover. The period 2003 to 2011 experienced the most increase in forest cover. Change detection showed that closed forest covered approximately 53% of the Park and this category increased to 58% in 1995. However, in 2003, the closed forest category reduced from 58% to 32% while in 2011; there was an increase from 32% to 59%. Other land cover classes also changed within the period 1986 to 2011. These changes in forest cover suggest that changes in protection status of the forest and changes in conservation management policies, introduction of ranger based monitoring and community conservation might have contributed positively to the changes for the period 2003 to 2011.

Key words:
Land use/cover change, Landsat Thematic Mapper, Normalized Difference Vegetation Index (NDVI), Protected area, Tassel Cap Transformation (TCT)

INTRODUCTION

Protected areas are a cornerstone of biodiversity conservation (National Research Council, 1996; Brosius and Russell, 2003; Gaston et al., 2008). These areas provide ecosystem services that are important for human and wildlife wellbeing such as food, shelter, raw materials, clean water supply, medicines, climate change mitigation and mitigation of natural disasters (Forslund et al., 2009; Kofinas and Chapin III 2009; Vo et al., 2012). Over the past decades, there has been an increase in the number of protected areas worldwide (Chape et al., 2003, 2005; Mulongoy and Chape, 2004; Locke and Dearden, 2005); however, in recent years protected areas are threatened by increasing demand for land and other natural resources (Geist and Lambin, 2002; Ervin, 2003; Green et al., 2013; Sambou et al., 2015). In some cases, protected areas are affected by changes in conservation policies, where some are either degazetted in order to change the designated land use, or degraded as socio-economic development activities are initiated, while illegal encroachment due to governance problems affects other protected areas (Mascia et al., 2014). With the increase in human population, there are not many areas on earth that are undisturbed by human activities. Human activities, both direct as well as indirect, have affected 83% of the earth's land surface (Sanderson et al., 2002). Land use/land cover (LULC) changes within protected areas are inevitable due to this pressure, as well as to the spatial and temporal dynamic nature of ecological systems and functions.

Changes in land use land cover within protected areas are usually categorized based on the causes and drivers of land use and land cover change. Lambin and Geist (2008) grouped causes of land use change into six major categories: (1) natural variability, (2) economic and technological factors, (3) demographic factors, (4) institutional factors, (5) cultural factors, and (6) globalization. The terms “land use” and “land cover” are sometimes used synonymously in the literature; however, Gaston et al. (2008) distinguished the two by defining “land use” as the purposes for which humans exploit land cover, while “land cover” is defined by the attributes of the earth’s land surface and immediate sub-surface (including biota, soil, topography, etc). In other words, “land use” refers to the series of anthropogenic activities undertaken to produce one or more goods or services, such as cultivation, animal grazing, or settlements, while land cover is the substance covering the surface, including natural or planted vegetation, infrastructure, soil, water, ice, bare rock, or sand (Reyers et al., 2009). For example, an agricultural fallow land is considered both “agriculture” under a land use description and “forest” (depending on level of forest regeneration) under land cover (Geist and Lambin, 2001a; Rudel et al., 2005; Ramankutty et al., 2006; Lambin and Meyfroidt, 2010).

Lack of clear distinctions add to the challenges of understanding the long list of impacts of changes in land use and land cover change (LULC) on a wide range of issues including climate change, wildlife populations, and the environment (Jansen and Di Gregorio, 2002; Reyers et al., 2009). One of the indicators of such change is derived from vegetation status over time. While some changes are detrimental to biodiversity, other natural causes of change may support the maintenance of biodiversity or have natural processes of recovery. The anthropogenic influences on land use/cover change are a major concern to management of ecosystems and wildlife (Dale et al., 2000; Lambin et al., 2003; Allan, 2004). Analyzing causes and drivers of historical land use/cover changes (LULC) highlights the consequences of some of the conservation policies, socio-economic demands and human influences on global environmental change. It is very important that these changes are identified, quantified, mapped and regularly monitored as part of studying patterns and trends of global environmental change (Geist and Lambin, 2001; Nemani et al., 1996; Lambin and Meyfroidt, 2010; Rogan et al., 2003, 2008).

One of the primary indicators of LULC change is variation in vegetation cover over time. Forest loss is commonly termed "deforestation" and is one of the major threats to forest conservation world-wide although the drivers of deforestation are not fully understood (Hobbs, 2000; Desanker and Justice, 2001; Geist and Lambin, 2002; Lambin et al., 2003; Hansen et al., 2008). The transition of forest loss can be either from closed forest cover to a selectively thinned forest then to clear-cut, or from closed forest cover to clear-cut depending on the type of disturbance (Huang and Asner 2010). Similarly, forest gain can be achieved from natural regeneration or mass planting of trees (Duncan and Chapman, 2003; Brockerhoff et al., 2008; Gibbons et al., 2010; Lambin and Meyfroidt, 2010; van Kuijk et al., 2014). Some of the known possible causes of deforestation are also known to cause changes in LULC. For example, human population growth means more demand for food and natural resources which leads to increased clearing of forest resources and in turn negative land cover change. Consequently, the increase in global human population has been cited as one of the major drivers of global environmental change, including deforestation and changes in LULC due to increased demand of natural resources, food, shelter, and economic development (Meyer and Turner, 1992; Geist and Lambin, 2001b; Radeloff et al., 2001; Ramankutty et al., 2006). Diouf and Lambin (2001), Chowdhury (2006), and Geist et al., (2006) argue that environmental and social factors influence most of the land use decisions at a wide range of spatial scales from the individual household to the district and national level. At the household level, forested areas can be cleared for agricultural food production either in search of fertility soil or expansion of food production, while at the national level the governmental development programs consider forested areas or undeveloped areas to be economically and socially convenient for new infrastructure projects. Understanding policies and practices of land use provide key information to identify the causes and drivers of LULC change (Lambin et al., 2001).

In this study I focused on specific drivers and causes of land use land cover change, and assessed the probable impacts of these changes on the current status of land cover within Nyungwe National Park, Rwanda, one of the largest single blocks of montane forest and an important biodiversity hotspot in the Albertine Rift (Plumptre et al., 2007). I examined land cover over a 25-year period from 1986 to 2011 using Landsat Thematic Mapper satellite images in order to determine land cover and extent of change. Additionally, I reviewed available literature to understand socio-economic policies and events related to land cover change.

METHODS

Study site

This study was conducted in Nyungwe National Park, a tropical montane forest located in southwestern Rwanda. This park is one of four national parks in Rwanda. Nyungwe National Park lies between 2◦15 and 2◦55 south of the equator and between 29◦00 and 29◦30’ east of prime meridian. It is estimated to cover about 1013 km^2 of land area. The Park has a partial buffer zone of exotic tree species including Eucalyptus spp and pines and some sections are under tea plantation or cultivation (Gapusi, 2007) (Figure 2.1). The forest extends southwards crossing the international boundary into Burundi, where it is known as Kibira National Park. The combination of Nyungwe and Kibira National Parks forms one of the largest contiguous blocks of lower montane forests in Africa (Vedder, 1992; Weber and Vedder, 2001). The area receives an average rainfall of between 1800-2500 mm per year. The temperature ranges from 0^0 C to 30^0 C (Sun et al. 1996; Kaplin, 2001).

Figure 2.1. Map showing location of Nyungwe National Park, Rwanda.

The elevation of Nyungwe National Park ranges between 1600m and 2950m (Figure 2.2). The 30m digital elevation model (DEM) by ASTERGDEM shows that the lowest elevation in Nyungwe National Park is 1437m and the highest peak is 2924m (Tachikawa et al., 2011). The elevation range is a fundamental basis to describe natural vegetation and ecosystems that occurs at distinct altitudes due to varying environmental conditions (Frahm, 1994; Kessler, 2000; Hemp, 2011). Consequently, the vegetation types found at a specific location characterize the land cover of the area.

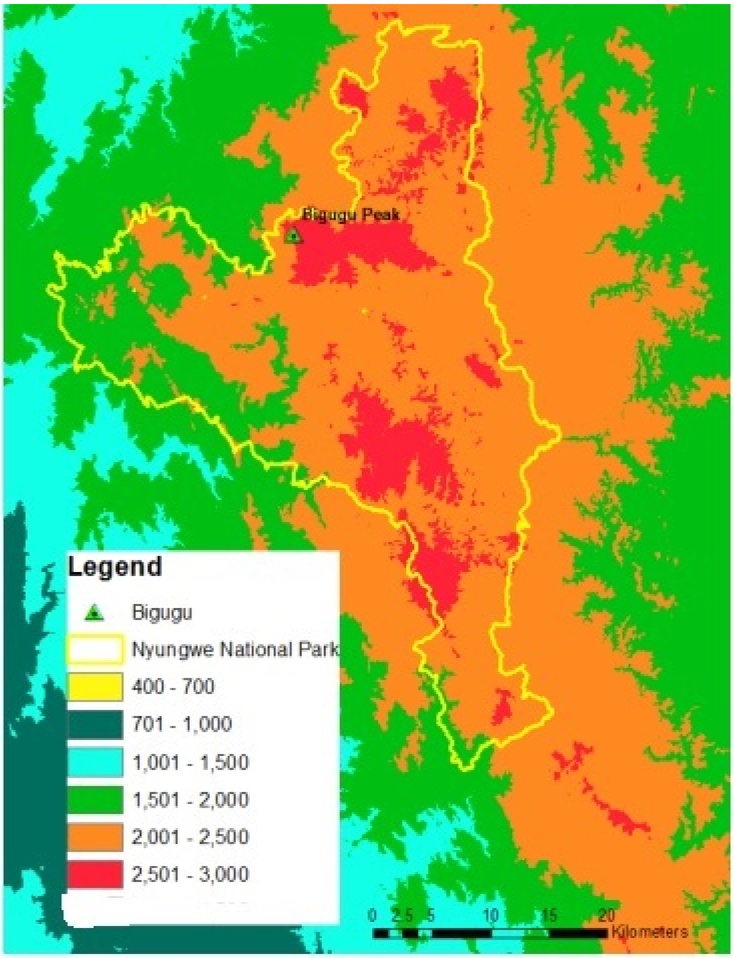


Figure 2.2. Map showing the elevation of Nyungwe National Park, Rwanda.

The forests of Nyungwe are classified as montane tropical forests, which are found around the equator at an altitude of over 1500m elevation (Malhi and Grace, 2000; Grace et al., 2014). Plant species in montane forests are often distinct from the surrounding lowland regions. Tree species of high altitude such as *Hagenia abyssinica*, *Prunus africana*, *Ficalhoa laurifolia*, *Podocarpus* spp. and *Olea* spp. are characteristic of these forests (White 1983). Nyungwe forest is characterized by 2-3 distinguishable tree layers with canopy layer reaching over 35m within the elevation of 1700 to 2700m (Ewango, 2001; Plumptre et al., 2002). The primary forest is characterized by *Parinari excelsa, Entandrophragma excelsum, Carapa grandiflora, Symphonia globulifera* and *Chrysophyllum gorungosanum* with a lower canopy layer of either *Psychotria mahonii,* or *Alchornea hirtella* while the higher elevation is characterized by Ericaceous species and *Hagenia abyssinica* (Ewango, 2001; Plumptre et al., 2007, 2002). The wetlands of Kamiranzovu, Tangaro and Uwansenkoko are characterized by a mixture of short grasses, herbs like *Cyperus* species and ferns together with Ericaceous species and *Hagenia abyssinica* (Ewango, 2001). There is a section of bamboo forest (*Sinarundinaria alpina*) in NNP with pockets of primary and secondary forest characterized by *Chrysophyllum gorungosanum, Macaranga kilimandscharica,Rapanea melanophloeos, Nuxia floribunda,* and *Polyscias fulva* tree species (Plumptre et al., 2007; Crawford, 2012).

The park has high biodiversity and ecological importance. It hosts more than 260 species of trees and shrubs, almost 300 bird species, about 100 orchids, and about 75 species of mammals including 13 species of primates (Kaplin, 2001; Plumptre et al., 2002; USAID, 2010). The drainage system includes Nile-Congo watersheds and it is a source of about 70 percent of Rwanda's water supply. As a tropical forest it is an important storage of carbon stocks (USAID, 2010). Soils are humiferous, acidic, and as a result the area is classified as of moderate agricultural value. According to Ghehi et al. (2012), Nyungwe National Park soils developed mainly from schists, micaschists, quartzitic schists and granites. Storz (1983) described the geology of Nyungwe forest as composed of old Precambrian rocks mainly of granite, quartzite and dolerite.

Brief History of Nyungwe National Park

Prior to European arrival, Rwanda was ruled by the *Mwami,* or king. The main activities that shaped the landscape included pastoralism and cultivation of crops. The three ethnic groups of Rwanda, *Batwa, Bahutu*, and *Batutsi*, seem to have arrived in the area at different times.The *Batwa* group is believed to be the first inhabitants of Rwanda, and they currently compose the minority of the population in Rwanda (Olson, 1995). The Germans were the first European colonialists to arrive in Rwanda, sometime around 1890. One of the prominent Germans in Rwanda, Richard Kandt (1867-1918) wrote in his publication (*Caput Nili 1905)* where he described his discovery of the source of the Nile River (in August 1898) within what is now called Nyungwe National Park (Scholz 2015). After the First World War in 1918 the Belgians took over rule of the country. In 1962, Rwanda was declared independent from colonial rule and the first republic government was Hutu dominated. A significant action by this government was to reverse most of the land use policies established by previous colonial powers (Olson, 1995; Prunier, 1995).

Land use polices established by the colonial powers started in 1903, when the German colonial government declared the then “Rugege forest”, now known as Nyungwe forest, as a protected area. However, there were not many restrictions on activities in the forest, and forest clearing and burning for green pastures, artisan mining, poaching, honey collection and cultivation continued after declaration as a protected area (Lusch and Du, 1995; Olson, 1995; Weber and Vedder, 2001). After Belgium took over the colonial rule of Rwanda, they declared the forest a protected area again in 1933, and as under the previous colonial power the management level was not well enforced. After Rwanda attained independence, the level of protection did not improve until the 1980s when *Projet Conservation de la Foret de Nyungwe (PCFN)* was created by the Wildlife Conservation Society, an international NGO (Weber and Vedder, 2001; Masozera, 2002). Although the launch of the conservation project brought improvements in conservation management policies and approach, the threats and illegal activities (mining, poaching, timber sawing, and cultivation) mentioned above continued. For example, there were gold mining villages located at Pindura and Karamba, within the protected area. In the 1980's there was planting of exotic tree species in buffer zones around Nyungwe forest for timber and other raw materials including poles and fuel-wood supply (Weber and Vedder, 2001; Gapusi, 2007).

In 1994, the country suffered a genocide that brought disturbances and constraints in management of the protected areas including Nyungwe. The senior management of the park fled the country, leaving only junior staff to protect the forest during the difficult times (Plumptre 2003). As part of improving management and conservation of the park, ranger-based monitoring and community conservation were introduced in 2003 (Mulindahabi et al., 2011). In 2005, Nyungwe was elevated to National Park status that bans any collection of natural resources from the park (GOR, 2005). Looking at this brief description of events, it is evident that four main historical periods might be considered to have impacted land use cover change in Nyungwe National Park. These time periods are (a) before initiation of PCFN in 1980s (b) between initiation of PCFN and genocide in 1994 (c) between 1994 and 2003 when the RBM was introduced thus patrolling the park (d) between 2003 to current. This period include the elevation of Nyungwe Forest to Nyungwe National Park in 2005.

Data acquisition and processing

I examined land cover for the years 1986, 1995, 2003 and 2011 representing land cover change for a period of 25 years using Landsat satellite images. Using optical images like Landsat TM data over montane forests which are sometimes classified as cloud forests, is always a challenge due to the problems associated with the cloud cover percentage which in most cases exceeds acceptable limits of 10%. Nyungwe National Park has few Landsat images that are classified as cloud free or within the acceptable 10% cloud cover. This study utilized free access Landsat images downloaded from USGS EarthExplorer website. The images downloaded were within acceptable cloud cover limits. Table 2.1 outlines the dates and type of sensor of the Landsat images used in this study.

I also used Normalized Difference Vegetation Index (NDVI) and Tassel Cap Transformation (TCT) for 1986, 1995, 2003 and 2011 in order to understand the variation in vegetation greenness and cover change over time. The advantages of using remotely sensed data in vegetation analysis include the fact that the vegetation indices can be derived from satellite reflectance data. With the repeat cycle of imaging or temporal resolution of the satellites, there is a great opportunity to analyze land and vegetation cover change over time (Lambin et al 2006, Lambin and Geist 2008, Li et al., 2013).

Table 2.1. Satellite image data acquired from USGS website for Nyungwe National Park, Rwanda.

Land sat	**Sensor**	**Path/ Row**	**Date**	**Scene ID#**
5	Thematic Mapper (TM)	173/062	19 July1986	LT51730621986200XXX12
5	Thematic Mapper (TM)	173/062	17 January 1995	LT51730621995017XXX02
7	Enhanced Thematic Mapper (ETM)	173/062	15 January 2003	LE71730622003015SGS00
5	Thematic Mapper (TM)	173/062	8 July 2011	LT51730622011189MLK01

Image classification for forest cover change within the tropics displays variations in reflectance due to phenology(Cherrington et al., 2016; Liu, Heiskanen, Aynekulu, & Pellikka, 2015a; Tottrup, 2004). The aim of this research was to utilize images captured within the same season in order to determine land use and land cover change. However, the temporal resolution of Landsat TM data is 16 days (Landsat, 7), thus an image is captured every 16 days which in many cases coincide with cloud cover over Nyungwe National Park. As a result, it is not possible to find the required images for the required dates of this study. Therefore, I utilized Landsat Thematic Mapper images for two different seasons to analyze forest cover changes, thus July images for 1986 and 2011 and January images for 1995 and 2003. The months of January and July falls within the dry season (June – September and January – February) however, as a tropical montane there are some precipitation days recorded within the dry season (Dong et al., 2003; Haggag, Kalisa, & Abdeldayem, 2016; Liu, Heiskanen, Aynekulu, & Pellikka, 2015b; Ndayisaba et al., 2017; Zhu, Woodcock, & Olofsson, 2012).

The images were georeferenced and resampled to 30m spatial resolution using Erdas Imagine 9.2. Resampling RMS (Root Mean Square) was 0.0005 for the 1986 image, 0.0004 for 1995, 0.0008 for 2003 and 0.0003 for the 2011 image. I used the Universal Transverse Mercator (UTM) projection with 27^0 East as a central meridian for zone 35 south based on World Geodetic System 1984 (WGS84), a terrestrial reference datum. This projection is convenient for data sharing and integration because most other existing maps and data are based on this projection. However, there are some other projections which are being used within the region including the local Rwanda 1992 Transverse Mercator projection using 30 degrees east as a central meridian. Although longitude 27 degrees East is in Democratic Republic of Congo, it is the best fit for the Nyungwe National Park projection.

Land cover and land cover change were analyzed using tassel cap transformation (TCT), Normalized Difference Vegetation Index (NDVI) and cluster analysis using unsupervised maximum likelihood classification. Tasseled cap transformation (TCT) compresses spectral data into a few bands associated with physical scene characteristics (Kauth and Thomas 1976; Crist 1984; Shi et al. 2011; Baig et al. 2014). It was developed for Landsat Multispectral scanner (MSS) by Kauth and Thomas (1976) for agricultural crops and soil applications. The coefficients for each sensor and each band are computed by transforming the data into a new rotated coordinate system with a new set of orthogonal axes. Currently, six bands are used to run the TCT and three of the six tasseled cap transform bands explain more information while the other three explain little information. The first three bands are termed “Brightness” which measures soil, “Greenness” which measures vegetation, and “Wetness or moist” which measures moisture content of soil and vegetation, respectively (Kauth and Thomas 1976; Crist 1984; Baig et al. 2014). In Landsat TM and ETM, bands 1, 2, 3, 4, 5, and 7 are used while in Landsat 8 Operational Land Imager (OLI) bands 2, 3, 4, 5, 6, and 7 are used (Crist 1984; Shi et al. 2011Baig et al. 2014). Tassel cap transformation was analyzed for 1986, 1995, 2003 and 2011 generating three main index maps for each year, Brightness, Greenness and Moist/Wetness (Figure 2.6).

NDVI, a band ratio vegetation index created from red and infrared bands (Tucker 1979), is the ratio of the difference between red and infra-red bands divided by the sum of red band and infra-red (NDVI= R-IR/R+IR). Several authors (Tucker 1979, Jiang et al. 2006, Huang et al. 2013, Pettorelli 2013, and Benliay and Altuntaş 2014) argued that NDVI is a useful tool to monitor changes in land cover, plant biomass and natural ecosystems. The origins of NDVI include the fact that chlorophyll, the pigment in plant leaves, tends to absorb visible light within the spectral wavelength ranging from 0.4 to 0.7 µm mostly as a source of energy for photosynthesis (Tucker, 1979; DeFries and Townshend, 1994; Anyamba and Tucker, 2005; Indeje et al., 2006). On the other hand, the near infrared (NIR) spectral wavelengths ranging from 0.7 to 0.9µm are reflected by the cell structures of the leaves. According to USGS (1985) and NASA (1999), Landsat TM spectral bands that correspond with the spectral wavelengths that absorb visible light and those spectral wavelengths that reflect near infrared (NIR) in Landsat 5 Thematic mapper are Band 3-Red with spectral wavelengths ranging from 0.63 to 0.69µm and Band 4-Near Infrared with spectral wavelengths ranging from 0.77 to 0.90µm respectively. I compared NDVI using median NDVI values that were generated by dividing the sum of minimum and maximum NDVI of each year by 2, thus 1986, 1995, 2003 and 2011.

Image classification was done using a combination of prior knowledge and unsupervised classification in Idrisi Taiga environment employing maximum likelihood cluster analysis, a classification tool based on statistical decision criteria to group similar pixels into categories using likelihood probabilities (Myung 2003; Bartels and Wei 2006; Liu and Yetik 2010). The first classification process yielded numerous classes. I used histogram analysis to determine the cut-off points to identify the number of classes to be considered. After running the classification process again, final land cover classes were identified. Color Orthophotos from 2008/2009 with approximately 0.25m resolution together with 2009 SPOT multispectral image with approximately 2.5m resolution were used as feature interpretation aids. However, the SPOT image had lots of cloud cover over the eastern part of the Park.

Post classification and change detection

Post classification is a process that compares two bi-temporal classified images to generate a change matrix (Rogan 2004; Bouziani et al., 2010). Change detection can be done by cross-tabulation or image differencing. These procedures work well when the bi-temporal images have identical classes in order to allow pixel by pixel analysis (Lunetta, 1999; Eastman 2006). However, errors from individual image classification can be propagated in the final change map, which in turn affects the accuracy of the final map (Dai and Khorram, 1999; Chan et al., 2001; Lillesand et al., 2008). In this study there were three change images derived from the four analyzed years: 1986 and 1995; 1995 and 2003; and 2003 and 2011. A threshold of 10% change in a pixel was set for both positive and negative change, meaning that if a pixel changed in a time period by less than 10%, it was considered as "unchanged" and if the change was 10% or greater it was considered as changed. This included decreasing change or increasing change, thus vegetation loss and vegetation gain (Pouncey and Swanson 1999). In the period 1995 to 2003, all the pixels within the study area decreased by more than 10%, and the period 2003 to 2011 all the pixels increased by more than 10%. Consequently, I increased the threshold from 10% to 20% for these two time periods so that I could detect areas that changed during those two time periods

In order to understand patterns and trends of land use/cover change, it is important that the historical occupations and land uses are analyzed together with the probable impacts that lead to current land use/cover. Although the focus is from 1986 to 2011, I reviewed literature covering environmental history, land use change and economic development for the period before Europeans arrived through the colonization period to the country's independence, then during 1994 genocide, and the post-genocide era to provide a context for the potential drivers and causes of land use land cover change in the study area.

Results

The study yielded four land cover maps for Nyungwe National Park, one for each year 1986, 1995, 2003 and 2011, achieved through image analysis and land cover classification using Landsat TM data. The Park has a partial buffer zone which is used as a production forest, including cultivation of Tea and other crops and plantations of exotic tree species including Eucalyptus species, Pinus species and Cupressus species. The 1986 image shows that most of the buffer zone was bare soil or cleared forest as compared to other years. Closed forest (excluding the buffer acreage) covered approximately 53% of the Park and this category increased to 58% in 1995. However, in 2003, the closed forest category was reduced from 58% to 32% while in 2011; there was an increase from 32% to 59%. Other land cover classes also changed within the period 1986 to 2011. Figures 2.3 a,b,c,& d shows the land cover maps for 1986, 1995, 2003 and 2011 respectively.

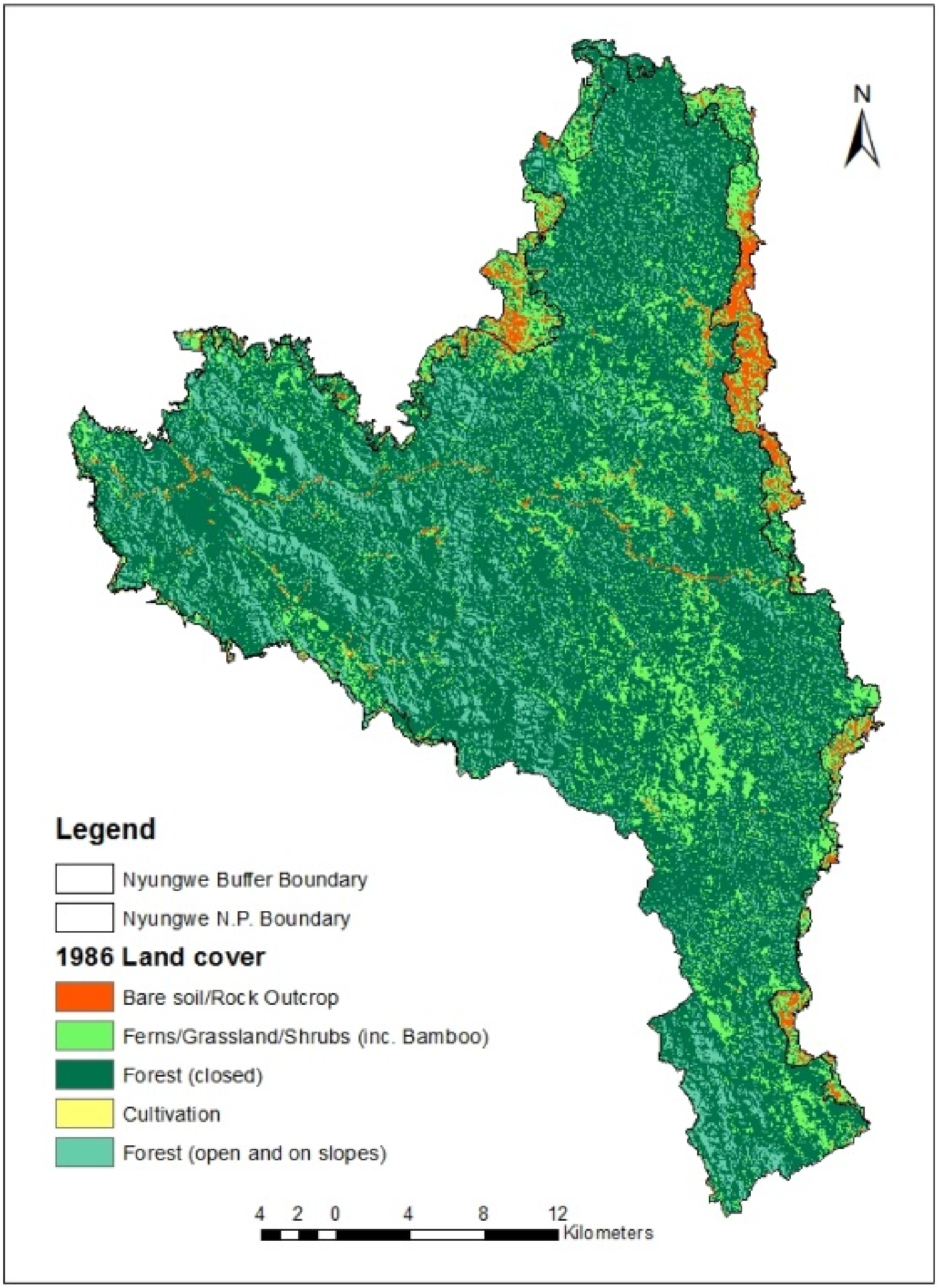


Figure 2.3a. 1986 Land cover map for Nyungwe National Park, Rwanda.

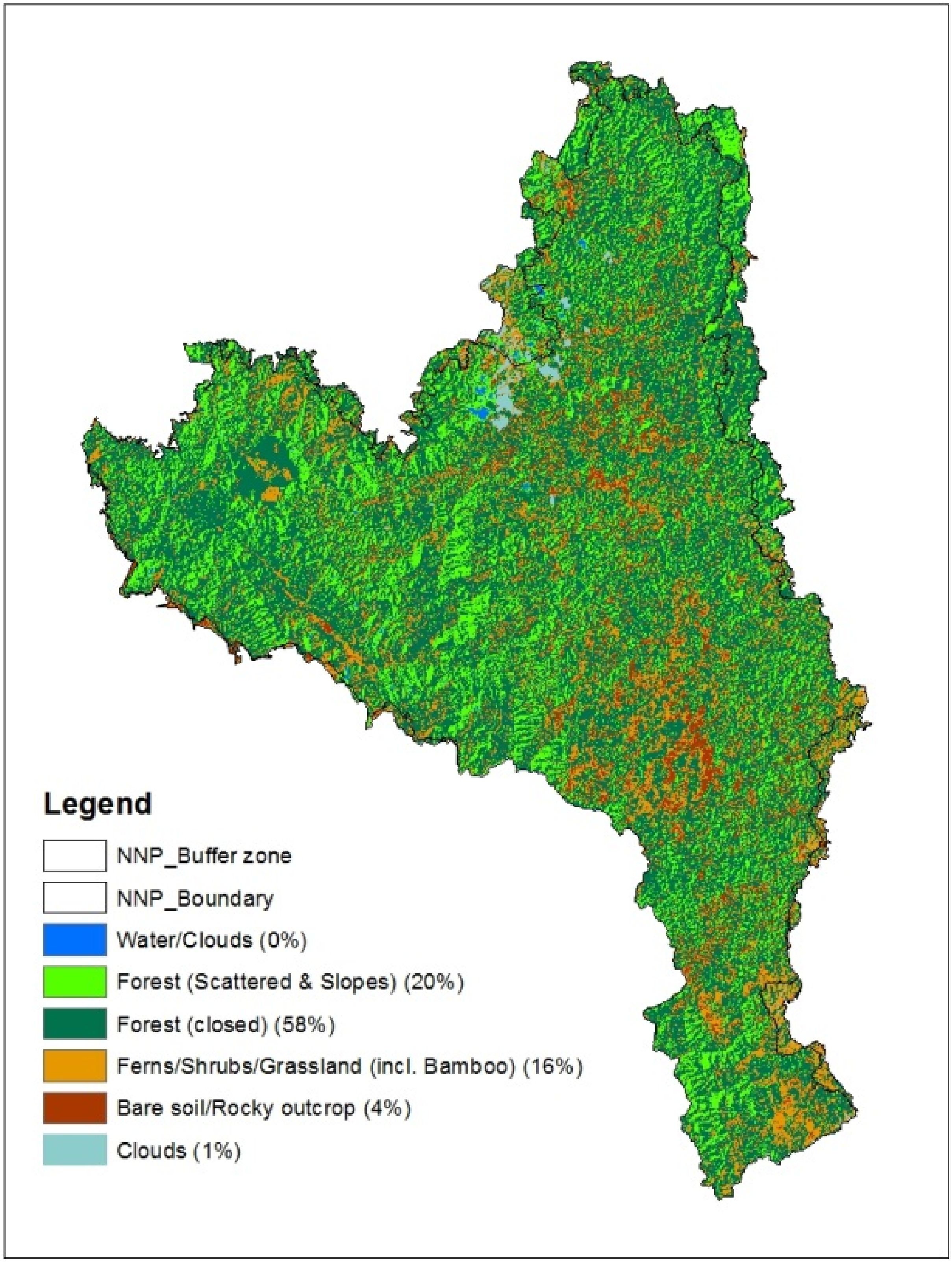


Figure 2.3b. Land cover map for Nyungwe National Park, Rwanda.

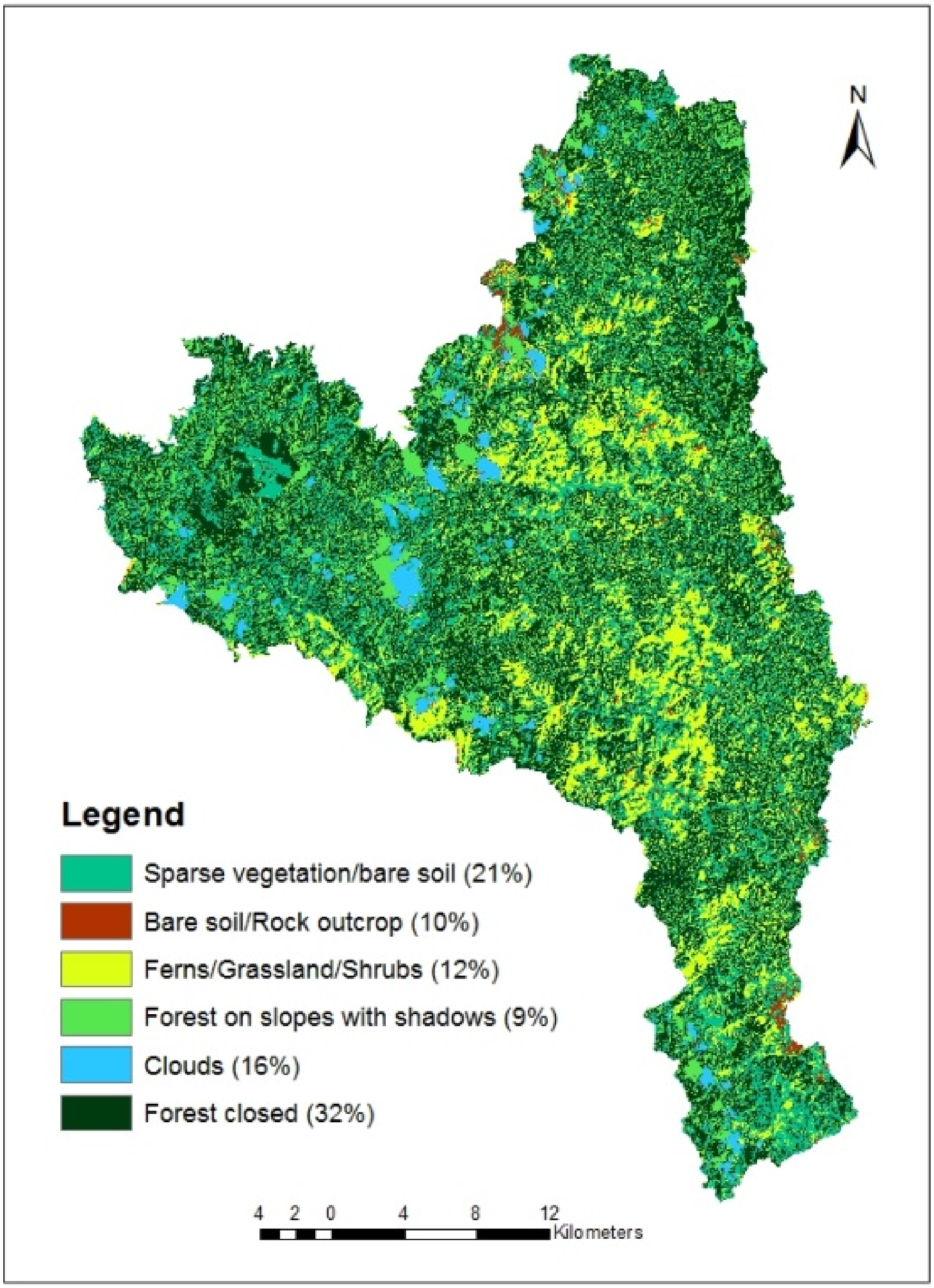


Figure 2.3c. Land cover map for Nyungwe National Park, Rwanda.

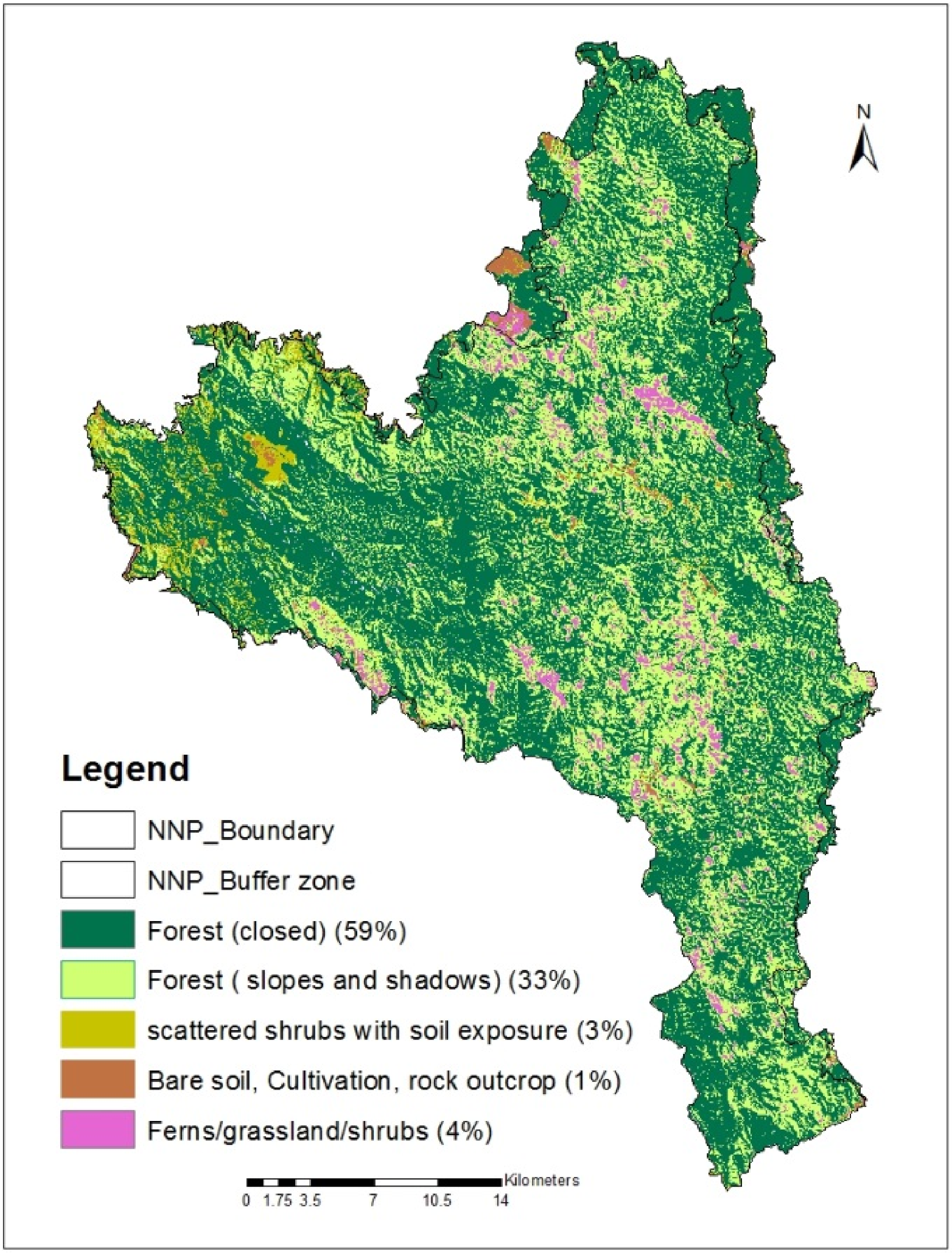


Figure 2.3d. Land cover map for Nyungwe National Park, Rwanda.

Negative land cover change was highest between 1995 and 2003 while positive change was highest between 2003 and 2011. When average NDVI values for each of the years, 1986, 1995, 2003, and 2011 were compared, 2011 showed the highest average NDVI data value of 0.8 representing vigorous vegetation cover, and the lowest average NDVI value was in 2003 with a value of 0.15 (Figure 2.4). This finding indicates that forest greenness or forest health was lowest in 2003 and highest in 2011 which agrees with the outcome of forest cover change analysis.

Change detection results using tassel cap transformation image differencing for 1986-1995, 1995-2003 and 2003-2011, created three change maps covering each of the three time periods spanning 25 years of analysis (Figures 2.5 (a), (b), and (c)). Between 1986 and 1995, about a quarter of the Nyungwe National Park forest cover remained unchanged, and nearly 60% experienced increases (Table 2.2). Between 1995 and 2003, Nyungwe National Park forest cover decreased, and then between 2003 and 2011, forest cover experienced a complete increase in all pixels representing 100% based on 10% threshold (Table 2.2).

Within the buffer zone, in the period between 1986 and 1995, the majority of the buffer zone experienced decreases in forest cover (Table 2.3). The same trend was detected between 1995 and 2003, where the buffer zone forest cover experienced 52% experienced complete decrease and 48% experienced partial decrease based on 10% threshold. In the period between 2003 and 2011, 38% of buffer zone forest cover remained unchanged, 10% of buffer zone forest cover experienced an increase (Table 2.3).

Table 2.2. Percent change in forest cover in Nyungwe National Park, Rwanda.

Description/Period	**1986-1995**	**1995-2003**	**2003-2011**
Decreased	7	49	0
Some decrease	7	51	0
No change	24	0	0
Some increase	31	0	34
Increase	31	0	66
TOTAL %	**100**	**100**	**100**

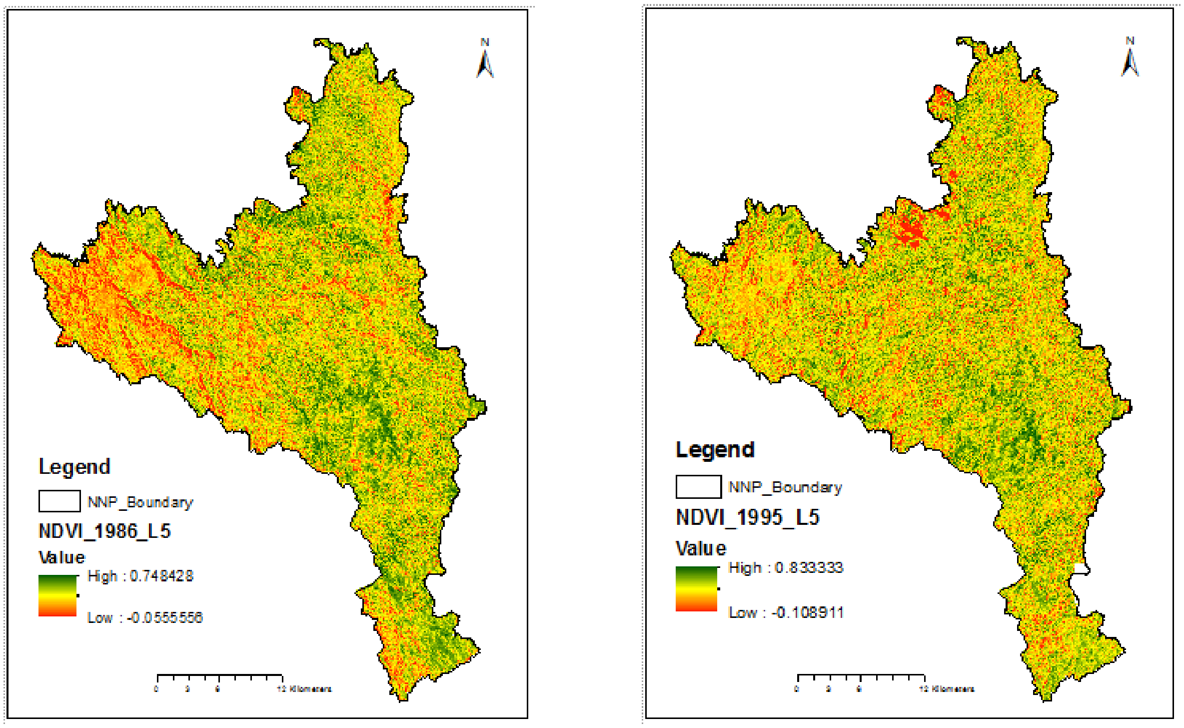
Table 2.3. Percent change in forest cover of buffer zones around Nyungwe National Park, Rwanda.

Description/Period	**1986-1995**	**1995-2003**	**2003-2011**
Decreased	17	52	17
Some decrease	56	48	28
No change	0	0	38
Some increase	26	0	7
Increase	1	0	10
TOTAL %	**100**	**100**	**100**

Negative land cover change was highest between 1995 and 2003 while positive change was highest between 2003 and 2011. When average NDVI values for each of the years, 1986, 1995, 2003, and 2011 were compared, 2011 showed the highest average NDVI data value of 0.8 and the lowest average NDVI value was in 2003 with a value of 0.15. This finding indicates that forest greenness or forest health was lowest in 2003 and highest in 2011 which agrees with the outcome of forest cover change analysis. Figure 2.4 shows the average NDVI of the four images analyzed in this study (1986, 1995, 2003 and 2011); 2003 had the lowest values depicting less greenness and poor vegetation health while 2011 had the highest values representing vigorous vegetation cover.

1986 NDVI

1995 NDVI



2003 NDVI

2011 NDVI

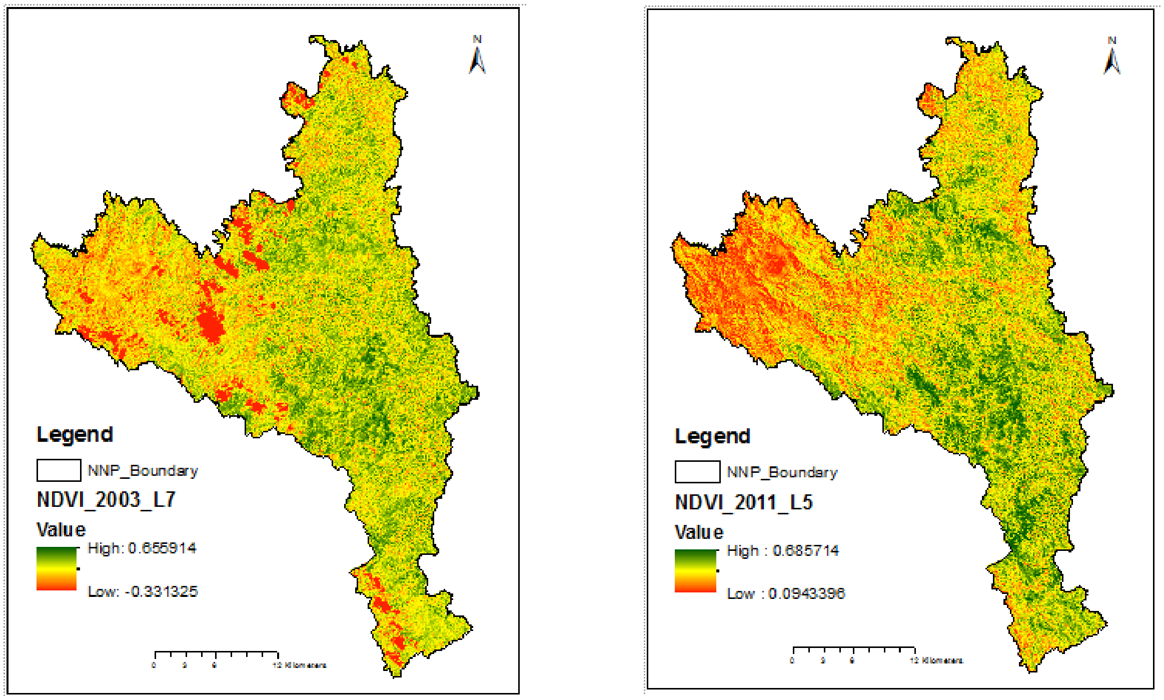


Figure 2.4. NDVI Maps for Nyungwe National Park, 1986, 1995, 2003 and 2011

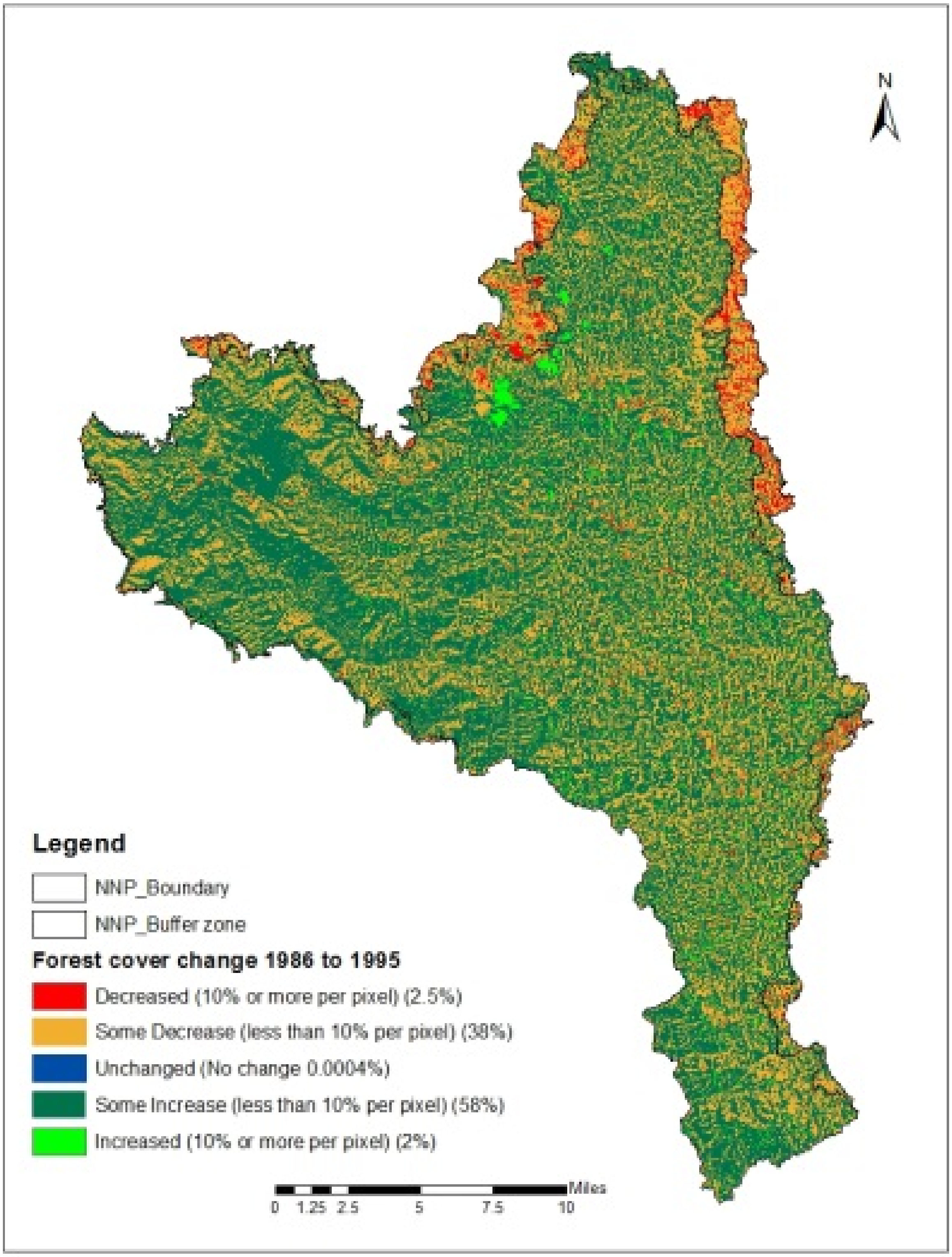


Figure 2.5a. Change detection 1986-1995, Nyungwe National Park, Rwanda. Dark green areas indicate areas of forest cover increase change and red indicates areas of decrease in forest cover.

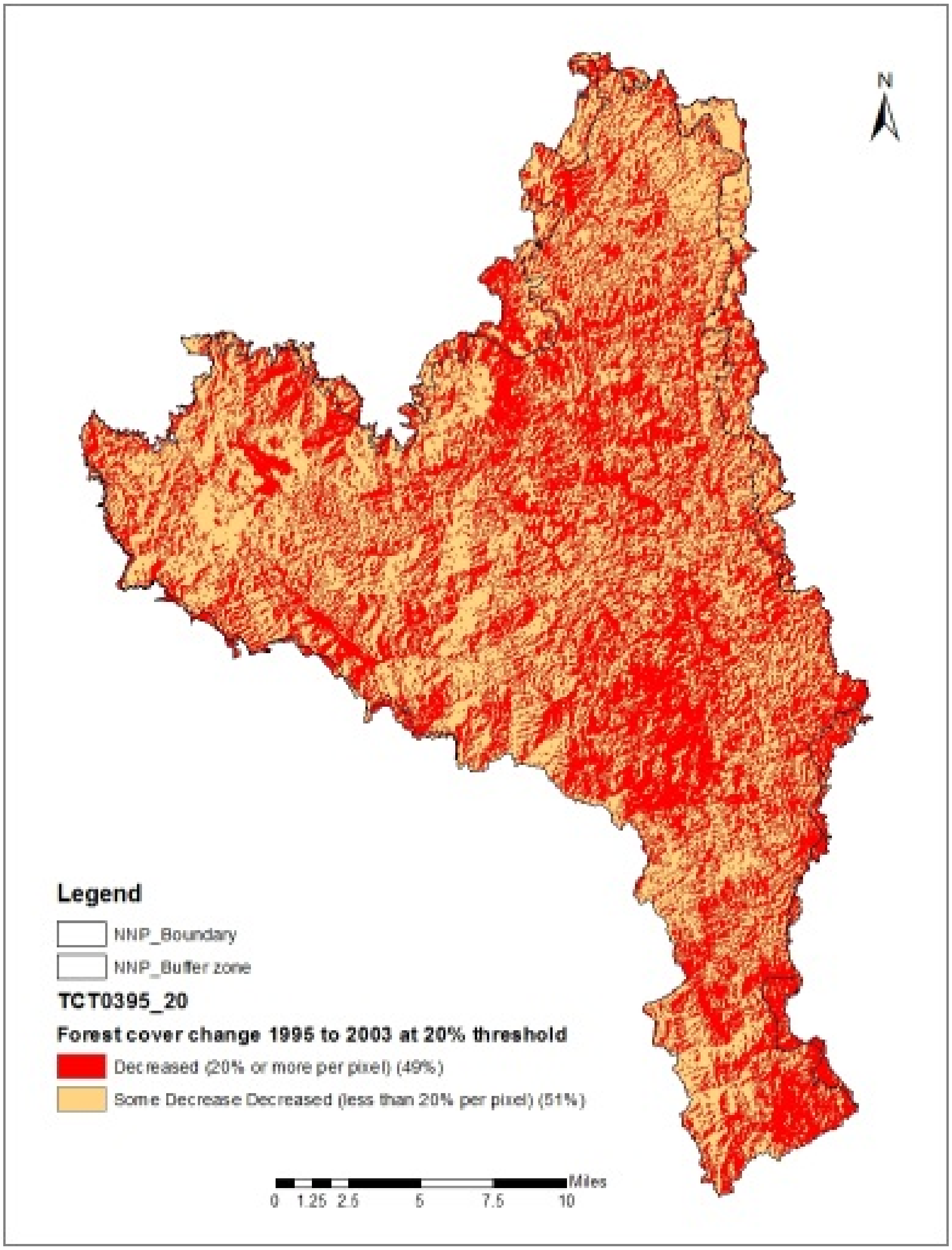


Figure 2.5b. Change detection 1995-2003; the whole park experienced a decrease in forest cover at 10% of pixel threshold. Red areas represent areas that decreased in forest cover at 20% of a pixel or more while the brown areas represent areas that decreased in forest cover below the threshold of 20% of a pixel.

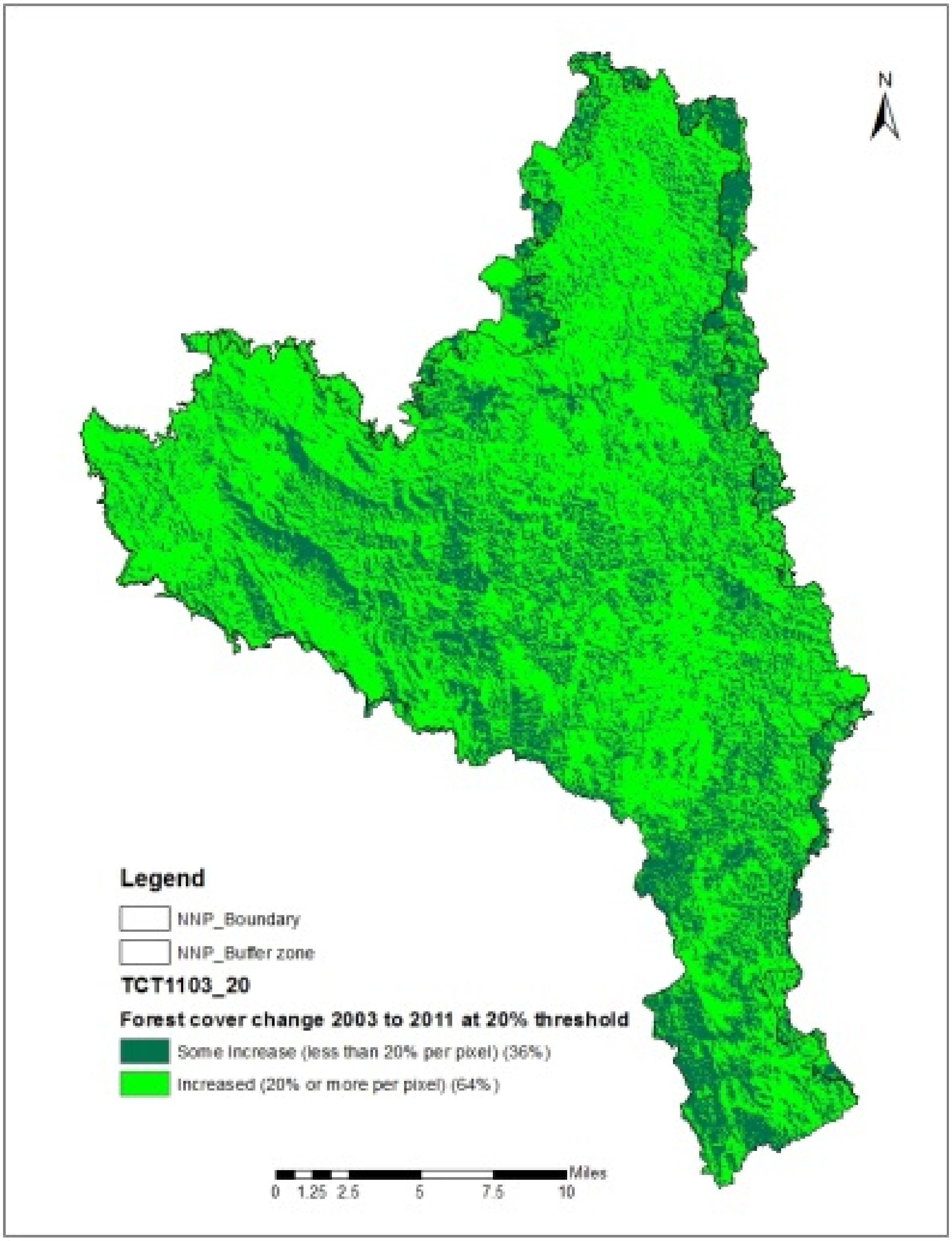


Figure 2.5c. Change detection 2003-2011; the whole park experienced an increase in forest cover at 10% of pixel threshold. Dark green areas represent areas that increased in forest cover at 20% of a pixel or more while the light green areas represent areas that increased in forest cover below the threshold of 20% of a pixel.

NDVI yielded a map for each year (Figure 2.4) while the tassel cap transformation (TCT) yielded three useful maps for each year analyzed, including brightness, moistness, and greenness. Although the three major output bands of TCT are very important to this study, I was particularly interested in the greenness band. The greenness band is used to detect and compare changes in vegetation which is important component in conservation. The brightness band explains soil characteristics while the moistness band explains the wetness of soil and forest. The resulting TCT maps are presented in Figures 2.6a, b & c. The orange to red areas in TCT maps indicate low values the TCT values in brightness, moistness, and greenness, representing low forest cover values. Dark green areas represent high values; high values in greenness band indicate more forest cover and the low value areas mean less forest cover.

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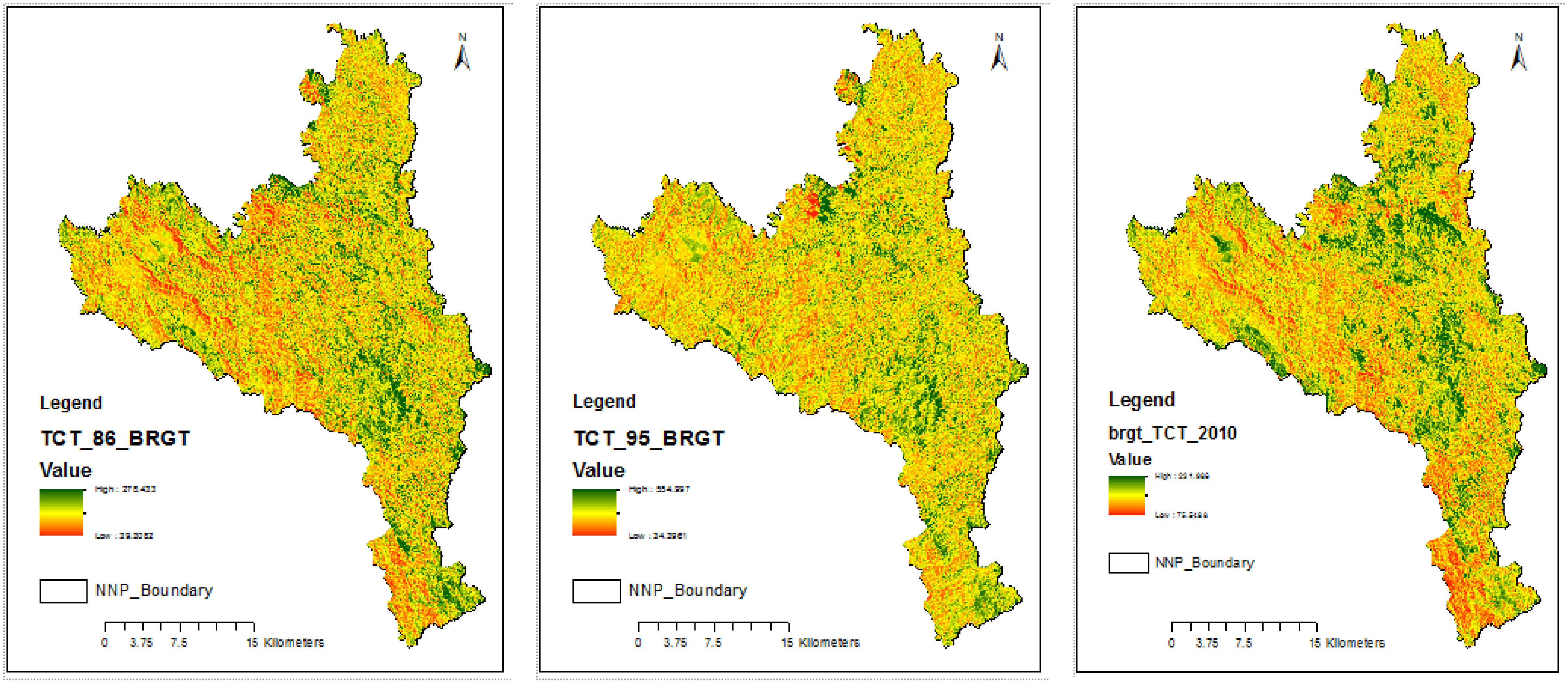

Figure 2.6a. Tassel Cap Transformation Maps 1986, 1995, 2010 (Brightness)

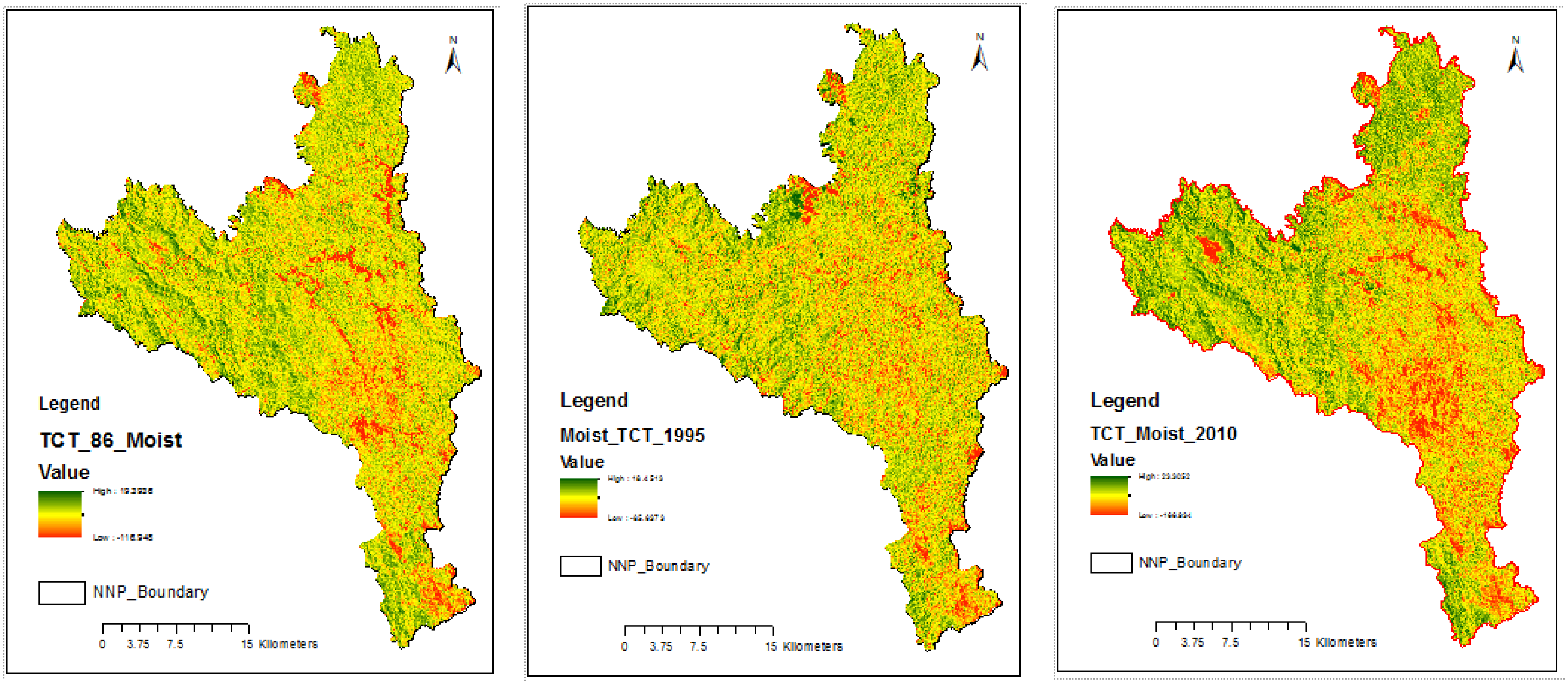

Figure 2.6b. Tassel Cap Transformation Maps 1986, 1995, 2010 (Moistness)

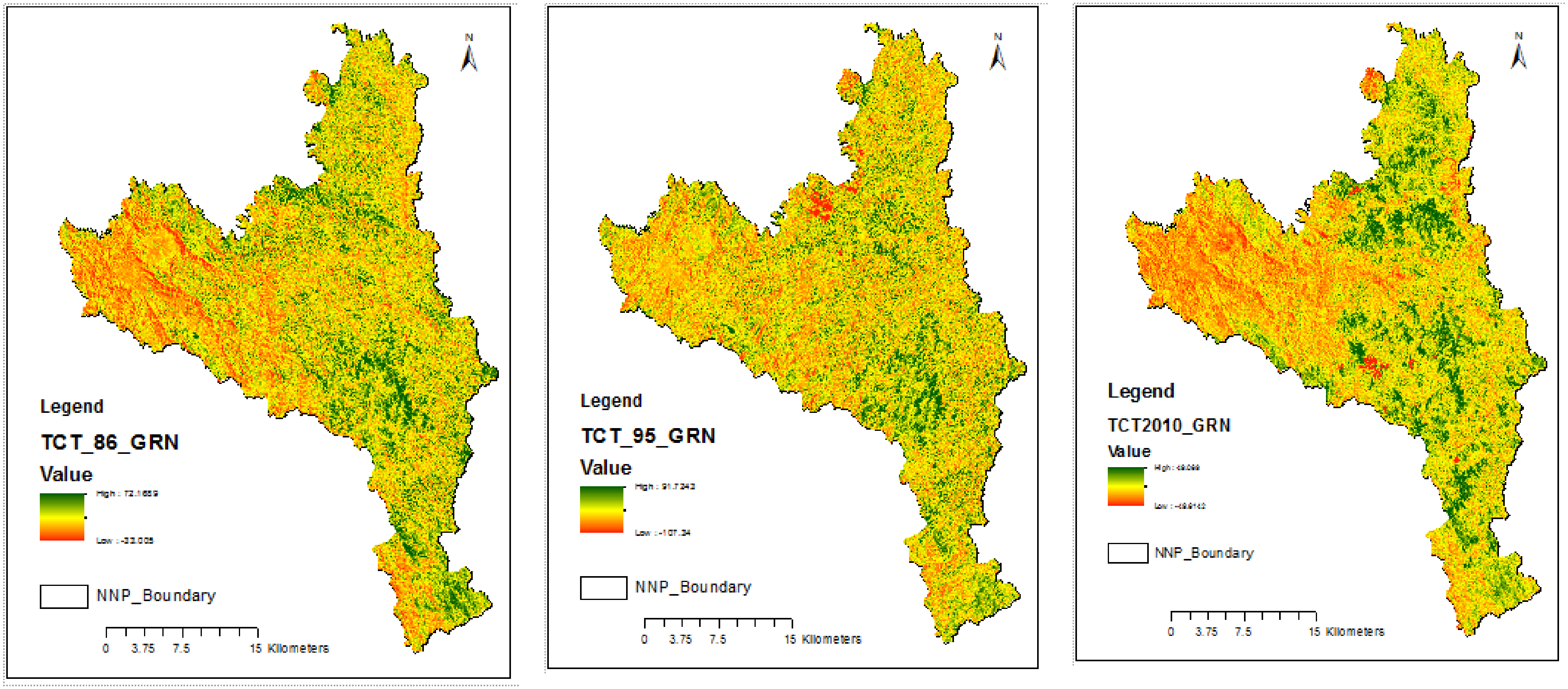

Figure 2.6c. Tassel Cap Transformation Maps 1986, 1995, 2010 (Greenness)

Classification accuracy assessment and Kappa index of agreement

The classification accuracy was assessed using groundtruthing and field verification data together with information extracted from 2009 color orthophoto with an estimated spatial resolution of about 25cm. The information in the classified image was cross-checked with the actual information on the ground using GPS readings in order to locate corresponding land cover classes to the classified image. The collected information was used to create accuracy or error matrix table sometimes known as a confusing matrix (Landis and Koch 1977; Lewis and Brown 2001), in which the rows contain groundtruthed data and the columns contain land cover classification.

I used a total of 197 reference samples to compute classification accuracy. The process yields three different accuracies, including User's accuracy (also known as Reliability accuracy), Producer's accuracy (also known as precision accuracy) and Overall accuracy. User's and producer's accuracies are presented for individual classes based on row and column information. Overall accuracy is the sum of diagonal values divided by the sum of total samples. Forest (on slopes/shadows) class has the lowest user accuracy among all classes (66.67%) and the scattered shrubs class had the lowest producer accuracy among all classes 67.74% (Table 2.4). However, the overall classification accuracy for all classified cover classes was 83.25% with an overall Kappa statistic of 0.768. Although Forest (on slopes/shadows) and scattered shrub classes had lower accuracy values, the kappa statistic suggests that the classification is acceptable and had good agreement between actual land cover classes and the image classification. The user and producer's accuracies show that there were errors of omission and commission in the classification, although the results are within acceptable limits.

Table 2.4. Classification accuracy assessment.

Classification	Ground truth data						
	Forest (closed)	Forest (on slopes)	Scattered shrubs	Bare soil/ cultivation/ rock outcrop	Ferns / grass-land	Row Totals	User's accuracy (%)
Forest (closed)	**73**	1	0	0	0	74	98.65
Forest (on slopes)	15	**42**	6	0	0	63	66.67
Scattered shrubs	0	1	**21**	0	6	28	75.00
Bare soil/cultivation/rock outcrop	0	0	0	**11**	0	11	100.00
Ferns/grassland	0	0	4	0	**17**	21	80.95
Column Totals	88	44	31	11	23	197	
Producer's accuracy (%)	82.95	95.45	67.74	100.00	73.91		
The overall classification accuracy was TD/TR (164/197) = 83.25%, kappa statistic = 0.768							164
Note: *TD sum of major diagonal*							

Discussion

Land and vegetation cover has changed over time within Nyungwe National Park, Rwanda based on results of this study. Change detection images derived from tassel cap transformation analysis indicate that there was a major decrease in forest cover between 1995 and 2003 and a major increase in forest cover between 2003 and 2011. Although the Park has been a protected area since 1933, the decrease in forest cover prior to 2003 is an indicator that there had been a combination of natural as well as anthropogenic impacts on forest and natural resources such as fire, wind-throws and gaps created by falling trees. Active mining sites where topsoil was removed and some trees dug out and were left vulnerable to blowing winds and others felled to create room for mining created a mosaick that contrast with canopy forest cover. Human population density is very high adjacent and around the Park, comprised of communities whose livelihoods are dependent on natural resources (Masozera and Avalapati 2004). Masozera (2002) argued that there are many threats to the biodiversity of Nyungwe National Park and most of them are anthropogenic due to human extraction of natural resources for food both meat and plants, building materials, mineral mining, medicine and raw materials.

The use of Tassel Cap Transformation provided enhanced visibility of areas where forest cover changed such as increase or decrease in forest cover over time. TCT does well in distinguishing vegetation from soil exposed areas and this characteristic makes it an important tool for tropical forest cover analysis. The detection of vegetation greenness and vegetation moisture plays an impotrtatnt role in determining status of forest cover. As mentioned earlier, the tasseled-cap transfornmation process yield all the bands used in the analysis but only first three bands are useful, namely, brightness, greenness and wetness bands. The advantage of using TCT in Nyungwe a tropical forest is that TCT is able to disntinguish different vegetation cover through enhance appearences in wetness band which provides better capability for visual interpretation of forest cover.

Some of the activities that affected cover during the period 1986-1995 included the construction and surfacing of the road that cut through the park from east to west, initiation of PCFN and extensive planting of exotic tree species within the buffer zone. The most decrease in forest cover happened within the buffer zone where indigenous trees were cleared to plant exotic tree species, while in Nyungwe National Park forest cover decreased along the main road that cut across the Park from Kitabi (east side of the Park) to Gisakura (west side of the Park). When buffer zones were created, they were covered by natural forest and the objectives of creating buffer zones included the production of fuelwood and pole supply to the communities; fast growing species like eucalyptus and pines were planted as production forest while in some parts of the buffer there were concessions for tea cultivation and agricultural production by the local community (Gapusi, 2007). In some sections of the buffer zone, natural forests were left undisturbed, while within the park, along the road, digging and clearing of forest for soil haulage as part of the road construction occurred. Although Nyungwe receives an average rainfall between 1800-2500 mm per year that can enhance fast growing vegetation, it seems that most of the areas that were cleared or areas where soil was removed for road construction did not fully recover or vegetation did not cover the area in the period 1986-1995.

Even though the Park has been protected since 1933, the level of protection varied over time depending on protection status and level of tolerance to human activities within the boundaries of the protected area. National park status does not allow the collection of forest resources, animal grazing or bee keeping; however, human activities both legal and illegal continued to negatively affected park (Weber and Vedder 2001). Major improvements in management included initiation of Nyungwe Forest Conservation Project (PCFN) in 1980s, change of park protection status and introduction of community conservation involving the adjacent communities in conservation activities. For example, the ranger based monitoring system was introduced in 2003 to improve protection and monitoring of activities within the National Park (Mulindahabi et al. 2011) and various initiatives to include community education and participation in conservation, small community projects to improve livelihoods and decrease threats to park were also introduced but prior to 2003, adjacent communities were either not involved in conservation activities or the governing policies did not include community conservation. The years after 2003 experienced an increase in forest cover which suggests that illegal resource collection of forest products reduced as ranger patrols were established. However, during the fieldwork I noticed that there are still areas within the Park that experience illegal extraction of natural resources including cutting of trees, we found lots of snares and poaching signs, mining, timber sawing and bamboo cutting. The general pattern observed from ranger based monitoring reports indicate that threats declined with the introduction of ranger based monitoring until 2011 when the occurrences started to increase again, thus there was a drop in occurrences between 2006 and 2011 (Mulindahabi et al. 2011) and then increased after 2011. Moore et al., (2017) found out that poaching has increased from 2759 occurrences per year in 2006 to 9473 per year in 2015. These anthropogenic activities within the Park, together with natural events like landslides and wind throws, affect the changes in land cover.

National events affected changes in land cover especially during the period after the 1994 genocide when the protected forests were some of the locations that provided resettlement resources to internally displaced people and returning refugees (Havugimana 2009). However, Nyungwe did not experience direct excision of land as compared to Akagera National Park, Rwanda where over 250,000 hectares were excised to accommodate returning refugees and internally displaced persons (Chandonait 2013). In the period immediately after 1994, protected areas in Rwanda did not have optimum security and management and as a result there were fires, encroachment, mining and poaching just to mention a few (Weber and Vedder 2001; Rutagarama and Martin 2006).

Variation in climatic conditions over the years might have an effect on vegetation dryness (stress), regeneration and growth (Nakagawa et al., 2000; Asner et al. 2000; Wright and Calderon 2006). Although I did not assess temperature and rainfall during the study period, it is clear that variations in weather can cause changes in vegetation cover. The changes follow a sine graph pattern with a spike in 2011 which coincides with the El Niño Southern Oscillation (commonly called ENSO), associated with changes in sea surface temperatures (Xue et al. 2000; Higginset al. 2001; Rasmusson and Carpenter 1982). Changes in amount of precipitation coupled with warm temperatures can be detected using NDVI which is also a tool to assess crop stress. The maps created in this study indicate that the area around Gisakura (north-west corner of the Park) is predominantly low NDVI over the study period. The tassel cap transformation results and NDVI showed agreement in determining areas where forest cover was lost, such as areas along the edges of the park and areas along the Gasumo-Bweyeye region.

Mining is a major cause of land use/cover change globally (Verburg et al. 2002; Latifovic et al. 2005). In Nyungwe National Park gold mining has left a foot print in some valleys and slopes. Although detailed records of the mining history within Nyungwe National Park are not available, there is clear evidence of sites that were used by peasant miners, especially for gold mining (Plumptre et al., 2002, Kristensen and Kurikunkiko 1992). This demonstrates that the historical land use dynamics of Nyungwe National Park include various human activities which might have influenced some of the trends and patterns of change over time. Kristensen and Kurikunkiko (1992) found that between 1982 and 1991 most forest loss occurred within forest boundaries due to gold mining and not along forest edges. Additionally, some areas remained open without trees after gold miners dug out the area in search of gold (Kristensen and Turikunkiko 1992). The methods used in mining were primitive and destructive. Peasant miners used surface and open cast mining techniques involving diversion or blocking of rivers and streams in order to supply water for processing the soil in search of minerals. Large amounts of soil were dug and washed until metallic sediments show up which in turn were tested and gold extracted. Nearby trees were affected by the process when the surrounding soil was disturbed. Plumptre et al. (1999) argued that gold mining in Nyungwe started around 1930s and the techniques used were influenced by the Belgians. When Nyungwe forest was not protected under the law there were many miners in the park. Apart from mining, miners were also involved in building shelters while living in the forest which involved cutting trees and trapping mammals for meat; cultivation of marijuana and other food crops was also observed in this time frame (Kristensen and Turikunkiko 1992). Miners were removed from the park in 1989 with some of the miners and poachers recruited as park staff to help curb illegal mining and poaching (Weber and Vedder 2002). At Karamba mining village, for example, there were over a thousand people present at one time, until the then President of the Republic of Rwanda ordered the demolition of miners' camp after a surprise visit to Nyungwe forest conservation project office in 1989.

The policies and laws governing conservation work in Rwanda were revised in the early 1990s, and this had implications for Nyungwe forest. The protected status of the forest was elevated in 2004 from a forest reserve which had lesser restrictions and less management resources to a National Park with increased management staff. Conservation management programs were introduced at this time including ranger based monitoring (RBM) and community conservation (GOR 2005). Despite the increased protection and improved management of the Park, however, the monitoring report for the period of 2006 to 2010 indicated the presence of illegal activities such as mining, poaching, and other natural resources extraction (Mulindahabi et al. 2011) However, Mulindahabi et al. (2011) showed that the encounter rate of threats in the Park was higher at the time of inception of the RBM program in 2003 compared to 2006 rates, however, there was an increase of 12% in the period from 2006 to 2010. A large portion of the 12% increase was due to poaching with 62% of all the encounters for that period (Mulindahabi et al. 2011). The recent report indicate that poaching continued to increase from 2759 occurrences a year in 2006 to 9473 a year in 2015 (Moore et al 2017).

Among the threats affecting Nyungwe National Park, wildfire is considered one of the major threats. For a long time now, forest fires are known to be part of the forest ecosystem dynamics; however uncontrolled fires are destructive to forest ecosystems. Nyungwe forest had been experiencing fires for a period of time but major fires occurred in 1997-1998 which created conditions for colonization by *Pteridium aquilinum* (bracken fern) and inhibition of tree regeneration within the fire-affected forest areas (Mlotha 2008; Mulindahabi et al. 2011; Laughlin and Fule 2008). Some of the fire-affected areas have been colonized by ferns, and a study was conducted to test tree regeneration with fern removal, also called assisted regeneration; in this study ferns were cut for a period of three months in a year repeated every year from 2004 (WCS Rwanda 2015). By 2012, results of the study showed that among other improvements, seedling density (9398.37 for areas cut; 588.48 for control areas) and sapling density (2505.85 for cut areas; 96.16 for control areas) increased tremendously within the plots where ferns were cut every year.

The changes in land cover between 2003 and 2011 suggest that alterations in management policies and increase in resources that promote conservation may have had a positive effect, although it is not possible to definitively attribute those management interventions to the land cover changes detected. With the national park status, together with restoration of security and peace, there has been an increase in tourism hence income generation for better park management (Boyer and Stork 2015). Despite the improvement in management, threats remain including mining activities especially around Kamiranzovu, Bweyeye and Gasumo areas bush meat hunting, pit sawing, honey collection, and collection of grasses and wood are still increasing. Park staff and conservation NGOs are working to reduce the threats through improved polices, initiating projects to reduce the needs of encroaching in Park and through community involvement (Mulindahabi et al. 2011). However, the trend from the RBM reports shows that from 2011 to 2016 there was a sharp increase in occurrences of poaching (Moore et al., 2017).

Comparing the findings in this study with those of recent studies, there are agreements with Kayiranga et al., (2017) who analyzed Forest Cover Change and Fragmentation Using Remote Sensing and Landscape Metrics in Nyungwe-Kibira Park for a period from 1986 to 2015. They found out that between 1986 to 1995 there was a decrease in forest cover while between 1995 and 2000 there was a slight increase in forest cover and more increase from 2000 to 2015. However, the results might be affected due to the inclusion of Kibira Park which is in neighboring Burundi and may be managed differently from Nyungwe National Park. Furthermore, the study did not define drivers of change, although they included a statement to acknowledge that most of the land cover changes are caused by anthropogenic factors. The other study is a global assessment by Hansen et al., (2013) which analyzed global forest cover change from 2000 to 2012. This study was carried out rather late in my study period which means that it does not analyze the period from 1986 to 2000; however, the changes from 2000 represent a similar trend of increasing forest cover around the park. Despite some similarity in trends, these studies were carried out with unique objectives and different methods were used in the analysis. One of the objectives of managing a National Park is to conserve the biodiversity and the habitats which forest is a primary source. Additionally, changes in a protected area are mostly detected through changes in forest cover. Therefore, the study brings important information highlighting the trends of forest cover change which in some cases tallies with the policy changes in the management of the park. Introduction of Ranger Based Monitoring (RBM) system has provided the information which revealed the extent of illegal activities such as poaching and illegal collection of forest products. Knowing sites that experienced forest cover change the ability to link forest cover change with the management policies forms an important tool for planning and management of the park. Park managers need to know when and where forest cover changed over time in order to plan better conservation measures.

Conclusion

Elevation of protection status to a national park level did not change the illegal utilization of the park as the adjacent communities' needs did not change nor did their dependency on the park for their livelihood change. Poaching and other anthropogenic threats are still high in the park. With high human population density adjacent to the park, assessing land cover change can help detecting anthropogenic activities that are affecting the protected area of Nyungwe. Human dependence on natural resources is a major driver of land cover change within Nyungwe National Park. Among many anthropogenic activities that are considered illegal in the Park, poaching was singled out to be increasing even with all the efforts that lead to improved management of the Park. Periodic land cover change assessment provides important information about extent and rate of change including both natural as well as anthropogenic causes. The influence of the human population adjacent to Nyungwe National Park cannot be ignored when analyzing the impacts of the changes within the Park.

NDVI and TCT provide tools to assess qualitative and quantitative changes in vegetation cover. Although anthropogenic causes of land cover change are common, in Nyungwe some of the changes might have been caused by natural causes such as falling of large tree which in the process push down other trees and result in land slide. High population density outside the Park clearly exerts pressure on the Park; however I did not directly assess the forces driving land cover change in the park. Gold mining has impacted the area but with the heavy rains and type of soil, vegetation regenerates and grows fast and has covered most of the abandoned areas, for example, Karamba and Kamiranzomvu regions where previously mined areas are now covered by vegetation including various tree species like *Anthocleista grandiflora.* The length of the study period from 1986 to 2011 might be too long to detect immediate changes on ground but it is an ideal period to assess impacts of policies and projects carried out within the protected area. For example, the changes in conservation management policies, introduction of ranger-based monitoring and community conservation and record keeping might have contributed positively to forest cover changes for the period 2003 to 2011. However, there is need to introduce routine periodic land use land cover change assessment at least once a year as part of further monitoring of land cover changes within the Park.

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Chapter 3: Assessment and Mapping of Vegetation Communities within Nyungwe National Park, Rwanda

ABSTRACT

Mapping vegetation communities within a protected area provides vital information for ecological management, research, protection, conservation and utilization of resources. This study was aimed at assessing, classifying, and mapping vegetation community distribution within Nyungwe National Park, Rwanda, a tropical montane forest located in the Albertine Rift, a biodiversity hotspot. Additionally, data analysis was conducted to identify vegetation associations and extent of distribution of the liana *Sericostachys scandens*, which some believe is spreading in the park. Various data sources were used including remote sensing and field surveys. Thirteen vegetation communities were identified from twenty-three vegetation clusters generated in TWINSPAN. *Macaranga kilimandscharica*, an early successional tree species, was the dominant species in the most common vegetation communities identified, representing about 42% of the Park. This suggests that the Park has considerable regions under secondary succession. *Sericostachys scandens* was estimated to be present or cover about 72% of Nyungwe National Park. However, this estimate needs further research to determine changes and current extent of this liana and its impacts on forest ecology.

Key words: Liana, mapping, montane forest, protected area, TWINSPAN, vegetation communities

INTRODUCTION

Tropical montane forests are highly threatened and are experiencing rapid negative changes such as deforestation and degradation (Asner et al. 2005; Bodart et al. 2009; DeFries et al. 2007). These forests host various flora and fauna species with very high diversity and often high levels of endemism (Williams-Linera. 2002; Brummit and Lughadha 2003: Homeier et al. 2010). Conservation and management of tropical forest requires updated qualitative and quantitative information about vegetation cover and distribution of vegetation communities to be available for planning and management assessments. An understanding of plant associations and resulting vegetation types, as well as vegetation structure and composition, are important elements in the management and monitoring of wildlife habitats, water and soil conservation, climate stabilization, amenity, and sources of raw materials.

Mapping vegetation cover within a protected area provides vital information for the protection, conservation, management and utilization of resources. If the mapping is repeated over time, changes in vegetation cover can be detected. Various environmental and biological monitoring programs, such as wildlife assessment, forest carbon, remote sensing applications and conservation programs use the status of vegetation as a principal indicator of change (Eastman 2009; Yagci et al. 2013; Nduati et al. 2013; Holmes et al. 2013). Understanding the distribution of vegetation cover types plays a key role in biodiversity conservation, and is a major indicator of land use/land cover change (Lu et al. 2007). Vegetation assessment is helpful in determining the potential benefits people obtain from ecosystems (Reid 2005). Furthermore, mapping vegetation communities helps to build information for the monitoring and evaluation of changes in vegetation. It is particularly important to note changes in plant species composition, including loss of species or species introductions.

Assessment of vegetation communities can be done either by aerial assessment or ground-based assessment (Strahler et al. 2006; DeFries et al. 2007). In aerial assessments, vegetation cover is interpreted and mapped from aerial photographs or satellite images. Ground-based approaches use physical attributes of the vegetation and land cover is physically mapped through stratified random sampling. Although aerial assessment can be less time consuming than ground based assessment, there are many critical vegetation attributes such as tree size, species composition, and density which can be difficult or impossible to obtain from remote sensing. A combination of these two approaches can fill data gaps data and improve the expected accuracy by reducing errors of commission and omission which are generated through aerial assessment approach alone (Nowak et al. 2007).

Although plant species, and their distributions and densities have been studied by various researchers (Ewango 2001; Fischer and Killmann 2008) in Nyungwe National Park, Rwanda there is no vegetation map for the protected area. *Sericostachys scandens* (Family Amaranthaceae), a monocarpic and heliophilous liana native to the montane tropical forest, is of particular interest due to the belief among some ecologists and conservationists that it is spreading in the park and causing an increase in tree mortality rates (Scholte et al. 2008). In Kahuzi-Biega National Park (Democratic Republic of Congo), Cephas et al., (2012) argued that conservationists and scientists were alerted by the liana replacing former forests and the expansion has been noted as recently as from 1996 when the liana was mentioned among the components of the plant communities of Kahuzi-Biega National Park. Schnitzer and Bongers

(2011) found out that liana abundance has been increasing and the increase has significant effects on composition and functioning of tropical forest.

This liana may be responsible for forest gap creation in Nyungwe National Park (Fimbel 2004; Scholte et al. 2008; Kaplin and Martz 2008). It is a light dependent (shade intolerant) species native to tropical forests in Africa (Kaplin and Martz 2008). Despite on-going research and monitoring activities, the current extent and distribution of *Sericostachys scandens* is not known. Mapping vegetation cover and communities in Nyungwe National Park provides important baseline information; it is however very costly in time and money. For tropical montane forests such as Nyungwe, the rugged terrain and steep slopes, in some cases with lack of road access, add additional challenges. Therefore, utilization of remote sensing and GIS applications are the most economical and viable approach to mapping tropical montane vegetation. A combination of remote sensing and field sampling were used in this study to provide the optimum results in mapping vegetation communities. The major objectives of this study were to (1) assess, classify and map the vegetation distribution within Nyungwe National Park, (2) identify the vegetation associations occurring within the park and establish the extent of the identified vegetation communities, and (3) estimate the extent of distribution of the liana *Sericostachys scandens* in Nyungwe National Park.

Methods

Site description

Nyungwe National Park is located between 2°15'–2 ° 55‘south of the equator, and between 29°00’–29°30’ east, in southwestern Rwanda (Figure 3.1). The area receives an average rainfall between 1800-2500 mm per year and temperature range from 0^0 C to 30^0 C

(Sun et al. 1996). It is one of the largest montane forests remaining within central east Africa (Weber 1986). The area and status of the protected area has changed over time (Fischer and Olson et al. 1995; Masozera 2002; Plumptre et al.2007; Gapusi 2007; Killmann 2008). The approximate area of Nyungwe National Park is not very clear. According to Rwanda Law n° 22/2005 of 21/11/2005, Nyungwe National Park is comprised of three separated land areas, namely Nyungwe Natural Reserve (101,515.59 ha), Cyamudongo Natural Forest (430.38 ha) and Gisakura Natural Forest (11.7 ha) (GoR, 2006), for a grand total of 101,957.67 ha.

Figure 3.1. Map showing location of Nyungwe National Park, Rwanda

Nyungwe has more than 260 species of trees and shrubs identified (Dowsett, 1990; Plumptre et al., 2002) and more than 13 non-human primate species including chimpanzees (*Pan troglodytes*), Angolan black and white colobus (*Colobus angolensis*), and owl-faced guenon (*Cercopithecus hamlyni*) (Plumptre et al., 2002) and almost 300 bird species including turacos (Crawford 2012).

The elevation of Nyungwe National Park ranges between 1600m and 2950m with Bigugu the highest point (Boxnick et al. 2015, Figure 3.2), although the 30m digital elevation model (DEM) by ASTERGDEM shows the lowest elevation in Nyungwe National Park is 1437m and the highest peak is 2924m (Tachikawa et al. 2011). The elevation range is a fundamental basis to describe natural vegetation and ecosystems that occur at distinct elevations due to varying environmental conditions (Allan, 1986; Frahm, 1991; Hemp, 2006). The vegetation of Nyungwe National Park does not appear to follow strict elevation zones, since some species occur in a wider elevational range than others. For example, the 2009 WCS biodiversity survey of Nyungwe National Park recorded *Rytigynia kiwuensis, (*1714 - 2717m)*, Xymalos monospora, (*1714 – 2717m)*,* and *Macaranga kilimandscharica, (*1717 – 2717m) occur in a wider range than other species sampled and *Maytenus acuminata* (2348 – 2717) occurs above 2300m. However, elevation is widely used in characterizing vegetation (Hobohm et al., 2014; Fadrique, B., & Homeier, J. 2016). Although altitudinal based classification of vegetation has been used accurately in other montane forests, in Nyungwe there is an overlap in elevational occurrence of some tree species. For example, some plant species are found both at the highest zone (Bigugu) and also within Uwansenkoko area (2350m), a much lower elevation than Bigugu area, for example *Erica jonstonii* and *Hagenia abyssinica.*

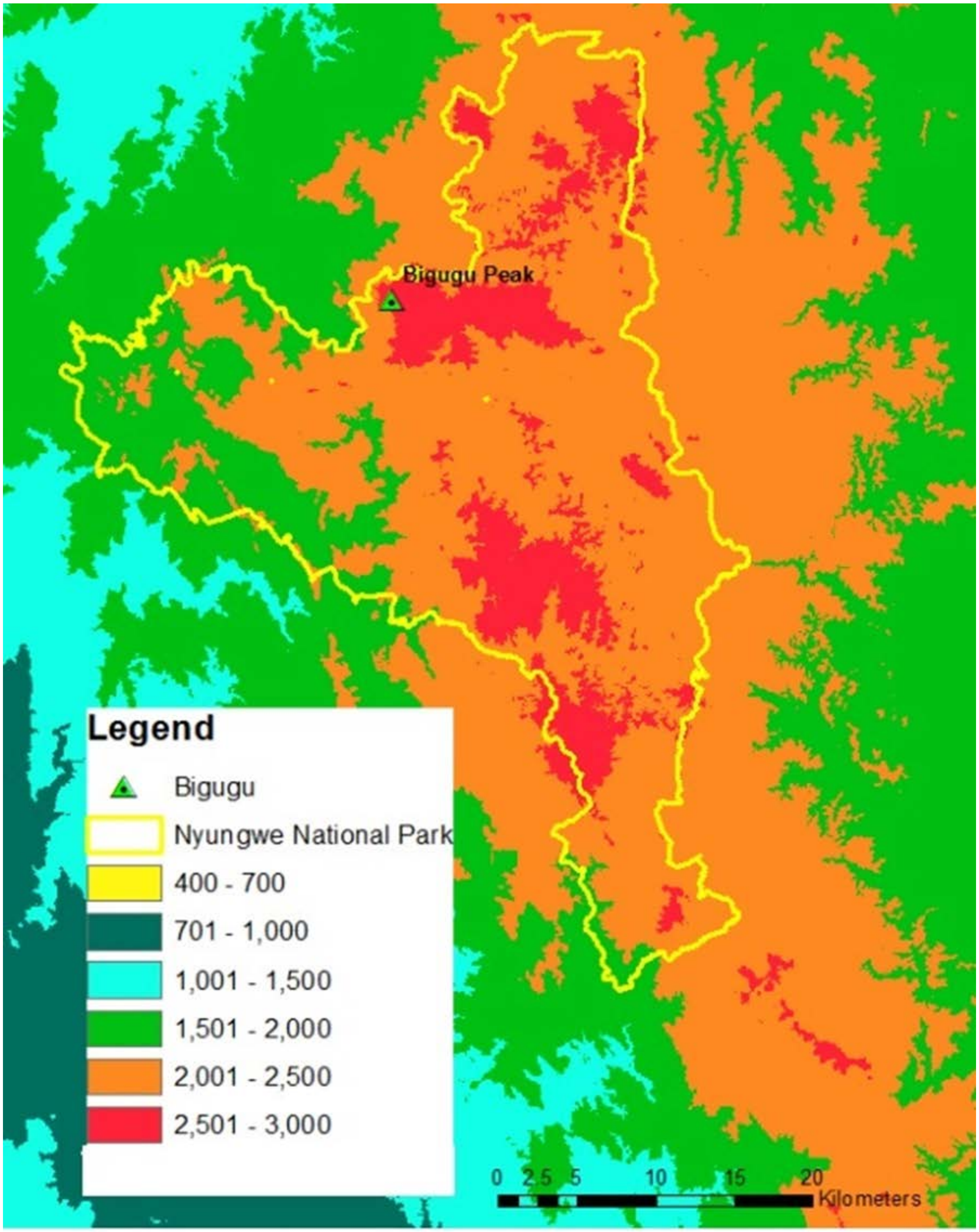


Figure 3.2. Elevation map of Nyungwe National Park, Rwanda

The vegetation of Nyungwe National Park is a mixture of trees, shrubs, herbs, ferns, and lianas. The vegetation of Nyungwe has been described by many authors including Weber (1989), Fischer (1993), Ewango (2001), Gapusi (2007), Fischer and Killmann (2008), and Plumptre et al. (2002), mainly based on physiognomic characteristics such as height, canopy cover, stem density, and environmental conditions to classify vegetation. Fischer (1993) described Nyungwe vegetation distribution based on elevation. For example, within the elevation of 1800 to 2100m, the forest is characterized by 2-3 distinguishable tree layers with a canopy layer reaching over 35m. In this forest type, the primary forest is characterized by *Parinari excelsa, Entandrophragma excelsum, Carapa grandiflora, Symphonia globulifera* and *Chrysophyllum gorungosanum* trees with a lower canopy layer of either *Psycotria mahonii*, or *Alchornea hirtella*. However, a biodiversity study conducted in Nyungwe (WCS-Rwanda, 2009) found that this kind of community can be found at a wider elevation, between 1700 to 2400m. Ewango (2001) classified the vegetation by elevation and habitat type. He used three habitats, namely primary forest, secondary forest and bamboo/savannah forest. His findings show that *Syzygium guineense* was found in all habitats and within the elevation range of 1590 -2685m while other species were found only in primary forest such as *Cleistanthus polystachyus, Chrysophyllum gorungosanum, Garcinia volkensii, Parinari excelsa, Strombosia scheffleri,* and *Symphonia globulifera.* There are areas of Ericaceous species and also a region (the Nshili area) with bamboo forest (*Sinarundinaria alpina*) along with pockets of primary and secondary forest characterized by *Chrysophyllum gorungosanum, Macaranga kilimandscharica, Rapanea melanophloeos, Nuxia floribunda,* and *Polyscias fulva*.

Visually, *Macaranga kilimandscharica* appears to dominate most of the secondary forest of Nyungwe, although the distribution has not been sampled. The northeastern part of the forest (Kitabi-Uwinka area) represents primary forest characterized by *Syzygium guineense, Parinari excelsa, Chrysophyllum gorungosanum* and *Ekebergia capensis* trees (Fischer, 1993). Similarly, Fischer (1993) described the south-western region of the forest which is at relatively lower elevation, the Bweyeye-Gasumo area, as characterized by *Entandrophragma excelsum, Parinari excelsa, Chrysophyllum gorungosanum, Prunus africana, Carapa sp.* and *Maesa lanceolata.* The high elevation Bigugu area (nearly 3000m) is characterized by Ericaceanes *(Erica johnstoniana)* with primary forest characterized by *Podocarpus latifolius, Syzygium guineense, Carapa grandiflora, Psychotria mahonii,* and *Macaranga kilimandscharica.* Most of the areas that were affected by fire in the past 15 to 20 years are dominated by *Pteridium aquilinum* today (Terra Global 2011); however, Nyungwe has a diversity of fern species, both in open areas as well as in closed canopy forests. The terrestrial and epiphytic ferns form an important part of Nyungwe vegetation.

Vegetation sampling

Two data sets have been used in this study. For the first data set, I sampled the western part of the protected area from the park edge at Gisakura tea factory east towards the Pindura-Bweyeye road (Figure 3.3) between November 2011 and July 2012. The eastern and western parts of the park are divided by the Congo-Nile watershed divide. The sampled area stretches from the central Congo-Nile divide to the western boundary of the Park covering an estimated area of about 24,327 ha which represents about 24% of the total National Park area. I used circular sample plots with a radius of 17.89 meters based on stratified random distribution within the western part of Nyungwe National Park. Each sample plot is marked with GPS northings and eastings coordinates. Within each sample plot, I recorded DBH and height of trees and shrubs with a DBH >2 cm. Trees and shrubs with DBH smaller than 2 cm were counted as stems and recorded. Names of plants were recorded in both scientific as well as in Kinyarwanda. The names were verified using the "Flore du Rwanda" books (Vol. 1 and Vol 2) (Troupin et al. 1978 and Troupin et al. 1983) and the "Illustrated field guide for plants of Nyungwe National Park" by Fischer and Killmann (2008). Species identifications were also discussed with botanists at Institut de Recherche Scientifique et Technologique (IRST) and National University of Rwanda (NUR) Biology Department botanists.

The location of each sample plot was marked by the center and I recorded eastings and northings coordinates of each sample plot center in order to spatially georeference the sample plots during analysis and mapping. I recorded the elevation of each sample plot center using the Garmin GPSMAP 60Csx GPS *(the Garmin advertisement claims that Garmin GPSMAP 60Csx GPS receiver measures elevation by barometric pressure).* Slope was measured using a Suunto clinometer and a slope correction was applied to all distances measured on slopes.

The second data set used in this study was collected as part of the 2009 biodiversity survey covering the whole National Park. The data were provided by Wildlife Conservation Society (WCS-Rwanda) where 535 species were recorded in 401 sample plots located in 41 transects. Each sample plot covered an area of about 0.125ha spaced at about 250m apart along transects (Figure 3.3). During this biodiversity survey, data collected included animal presence, human activity and vegetation. For this study, I used only the vegetation data that was recorded in each sample plot. Parameters measured include tree Dbh and tree height.

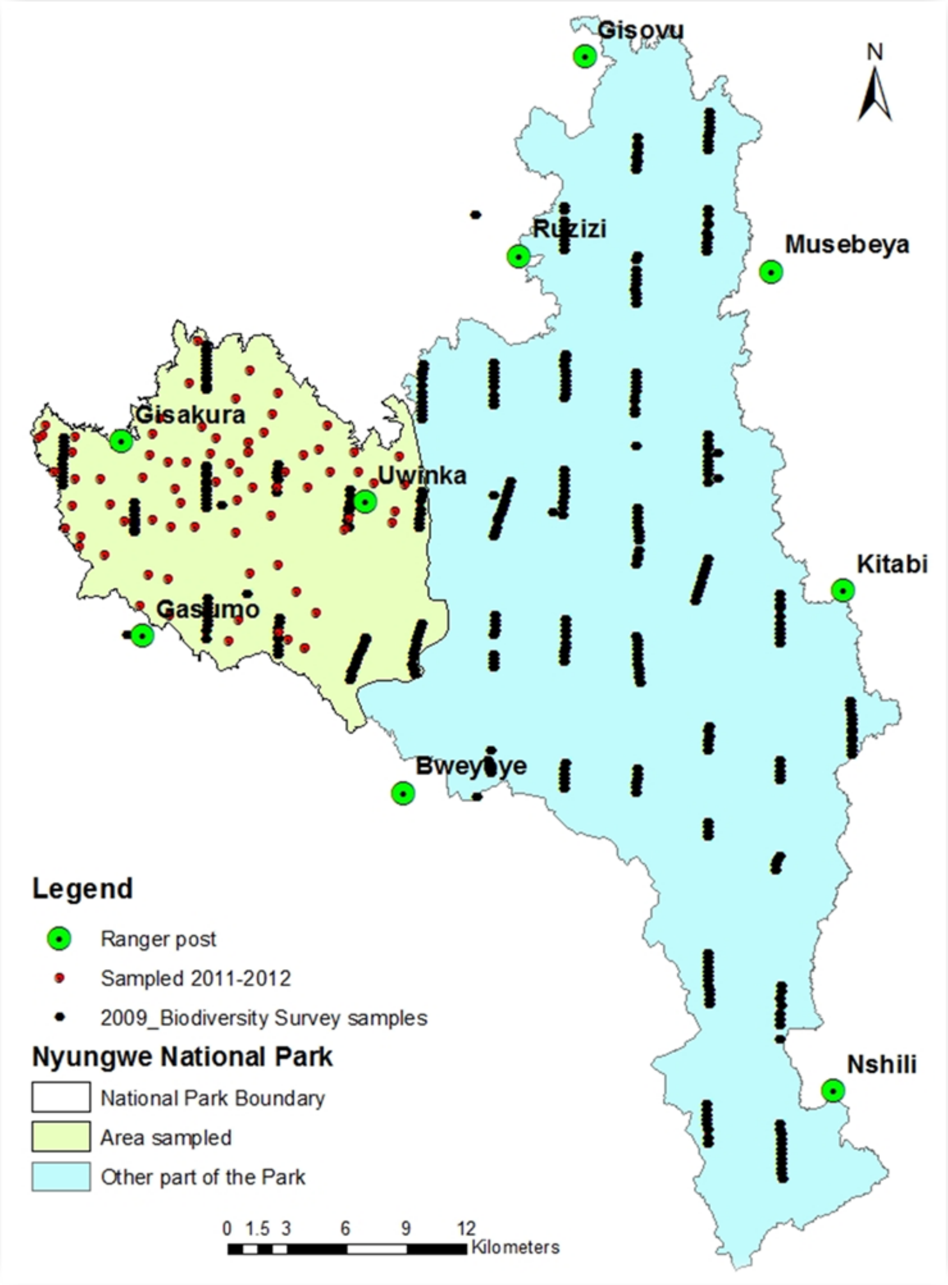


Figure 3.3. Map of Nyungwe National Park, Rwanda showing sampled area in the west of the park and 2009 WCS Nyungwe National Park biodiversity survey design.

Estimating the distribution of *Sericostachys scandens using* Maximum entropy (MaxEnt) modeling

Mapping and predicting species distributions of animal and plants has become an important tool for decision making regarding land use/land cover change and its ecological consequences. Knowing plant species distribution within a protected area is one of the important tasks for the ecologists and conservationists who plan and manage for conservation of wildlife and biodiversity resources. However, it is always difficult to estimate the spatial distribution of species. Therefore the development and use of species distribution models (SDM) to map and monitor animal and plant distributions is an important source for decision-making process. Species distribution modeling (SDM) includes climate envelope-modeling, habitat modeling, and (environmental or ecological) niche-modeling (Hijmans et al., 2017). In Nyungwe National Park, there have been several biodiversity surveys that included recording presence of *Sericostachys scandens* but this kind of information does not present the whole picture of spatial distribution of this liana. MaxEnt modeling software was used to predict spatial distribution of the liana.

MaxEnt modeling software is one of the species distribution modeling (SDM) programs that uses presence-only data as input to predict the potential distribution of a given species (Rhoden et a., 2017; Dudík et al., 2007; Phillips et al., 2006). It is based on the maximum-entropy approach for modeling species niches and distributions (Kramer-Schadt et al., 2013; Phillips et al., 2006). I used *Sericostachys scandens* species data from the 2009 biodiversity survey for Nyungwe Natioanal Park with 216 sample points that recorded present for *Sericostachys scandens.* The objective of this modeling was to estimate the distribution of the liana within the Park. Maxent was considered as an alternative tool to detailed field sampling of the liana because of its flexibility in terms of working with presence data only and also how the algorithims minimizes errors due to missing data scenarios (Elith et al., 2011; Kramer-Schadt et al., 2013). However, I also estimated area covered by the liana using integrated approach that combines multiple data sources and ecological conditions describing where *Sericostachys scandens* occurs (Schnitzer et al., 2014). Species data was prepared in MS Excel 2013 version while the covariates or the environmental variables were downloaded from WorldClim - Global Climate Data, Free climate data for ecological modeling and GIS website http://worldclim.org/version2. I downloaded a zipped file with 19 Bioclimatic variables which are derived from the monthly temperature and rainfall values in order to generate more biologically meaningful variables. In my analysis, I added a prefix of NNP to the name of the biovariables after I clipped the window covering only Nyungwe National Park. The names look as follows: NNP_Bio_01 for first bioclimate variable. Here are the list of the bioclimatic variables and their coded names:-

BIO1 = Annual Mean Temperature
BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3 = Isothermality (BIO2/BIO7) (* 100)
BIO4 = Temperature Seasonality (standard deviation *100)
BIO5 = Max Temperature of Warmest Month
BIO6 = Min Temperature of Coldest Month
BIO7 = Temperature Annual Range (BIO5-BIO6)
BIO8 = Mean Temperature of Wettest Quarter
BIO9 = Mean Temperature of Driest Quarter
BIO10 = Mean Temperature of Warmest Quarter
BIO11 = Mean Temperature of Coldest Quarter
BIO12 = Annual Precipitation
BIO13 = Precipitation of Wettest Month
BIO14 = Precipitation of Driest Month
BIO15 = Precipitation Seasonality (Coefficient of Variation)
BIO16 = Precipitation of Wettest Quarter
BIO17 = Precipitation of Driest Quarter
BIO18 = Precipitation of Warmest Quarter
BIO19 = Precipitation of Coldest Quarter

When data was prepared and was ready to run a model, I entered the sample data; the *Sericostachys scandens* MS Excel file saved in *Comma-separated values (CSV)* format and the 19 environmental variables also known as covariates. I selected 25% for Random Test Percentatge (Test data) as one way of evaluating the model performance. MaxEnt replicates number of runs and I set it at 15. Two different Replicated run type namely, "subsample" and "cross-validation" were used in running the model. I selected several outputs including creation of response curves, pictures of predictions, Jacknife to measure variable importance.

***Sericostachys scandens* sampling**

I sampled *Sericostachys scandens* by presence and absence in all the sample plots I surveyed during this study. Additionally, I extracted similar information from a 2009 WCS biodiversity survey of Nyungwe National Park. I developed guiding factors based on observations during the fieldwork, literature review and discussion with various scientists who have been working in Nyungwe National Park to estimate presence and absence of *Sericostachys scandens* in the park. Although these factors may indicate presence or absence of the liana, it remains difficult to map out precisely the extent of *Sericostachys scandens* in Nyungwe National Park. The distribution can be estimated using satellite images with high spatial resolution, or orthophotos but an accurate estimate of the distribution requires systematic sampling of the park which was beyond the scope of this study.

During a reconnaissance survey, which was carried out in November 2011, I visited all the ranger patrol areas in the park from north in Gisovu, Musebeya and Kitabi in the east, Ruzizi, Gisakura, Uwinka, Gasumo, Bweyeye in the western part and Nshili in the south-eastern part of the park. Based on observations during this survey, *Sericostachys scandens* in

Nyungwe National Park appears to have two different regeneration and die back cycles. The *Sericostachys scandens* in the northern part of the park (Gisovu area) was estimated at over 10 meters in height climbing on trees, while in the central and southern parts of the forest the liana was between 2cm and 50cm high. During the fieldwork the two different heights of *Sericostachys scandens* in the northern part of the park and the southern part of the park as presented in figure 3.4 (a & b) were estimated.

Figure 3.4 (a & b). Sericostachys scandens in Nyungwe National Park showing the differences in regeneration status. Figure 4a (left), shows S. scandens in the northern region of the park, Gisovu area, taken on 2 December 2011 by J.B. Gakima. Figure 4b (right) shows *S. scandens* in the southern region of the park; photo taken on 13 December 2011 by M.J. Mlotha.

Figure 3.5 shows the estimated boundary of the two different regions in terms of regeneration and die back status of *S. scandens* as of November 2011 in Nyungwe National Park.

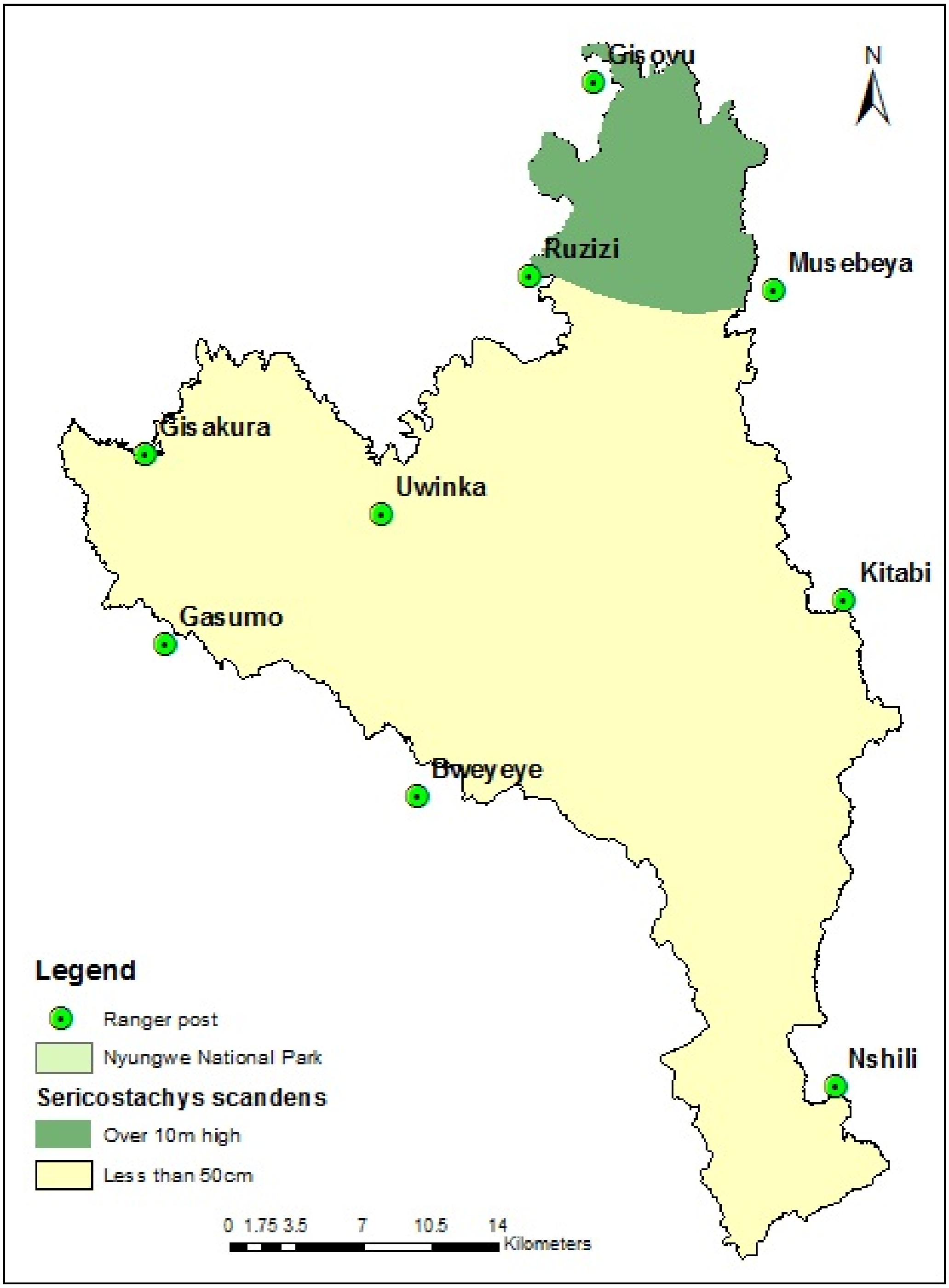


Figure 3.5. Map of Nyungwe National Park, Rwanda showing the differences in regeneration and die back status of S. scandens as of December 2011.

Estimation of spatial distribution of *S. scandens* in Nyungwe National Park was based on (1) presence and absence from the data surveyed during this study, (2) presence and absence from the 2009 WCS biodiversity survey of Nyungwe National Park, and (3) based on literature review that discussed environmental and topographic conditions of places where *S. scandens* were present and places where *S. scandens* were abscent. This information was grouped into present and absent, then using Boolean analysis within GIS environment, I selected areas that belonged to present category and separated them from those areas that belonged to absent category.

I selected all sample plots that recorded presence of *S. scandens* from the 2009 WCS Biodiversity survey of Nyungwe National Park and also from the field survey carried out during field data collection of this study and I created a new layer in ArcGIS showing only locations that recorded the presence of *S. scanden.* Grubben and Denton (2004) argued that *S. scandens* is found within an elevation range between 700-2600m. Therefore using digital elevation model (DEM) in a GIS environment I classified the elevation less than 2600m as areas of presence of *S. scanden* while areas with more than 2600m I classified as areas of absence. Using land cover layer in GIS environment I selected all rock outcrops, waterlogged areas and soil haulage sites as areas of absence to *S. scanden* (Grubben and Denton 2004; Kaplin & Martz 2008; Scholte et al. 2010). I overlaid the above mentioned characteristics on the land use/cover layer of Nyungwe National Park in order to estimate the spatial distribution of *S. scanden* in the park.

Vegetation Analysis

Presence and absence of species data were organized into a matrix of sample plots as columns with species as rows in order to be analyzed in TWINSPAN (Two Way Indicator Species Analysis) and MVSP (MultiVariate Statistical Package). Vegetation data from the sample plots were analyzed in order to identify plant communities, habitat types and vegetation structure using MVSP. I computed relative density, relative dominance, frequency, and abundance of tree species and shrubs according to Curtis and McIntosh (1950). Relative density determines the numerical strength of a species in relation to the total number of individuals of all the species in an area. Species occurrence was extracted from each sample plot and summed across plots; the number of occurrences of each species was divided by the total number of occurrence of all the species and then multiplied by 100. I determined the dominance of a species using the value of basal area coverage. Since I used the same formula to compute relative dominance, I did not separate the smaller diameter trees from trees with diameter larger than 10cm. Relative dominance was defined as the coverage value of a species with respect to the sum of coverage of the rest of the species in the area. Basal area in square meters was calculated by $\pi\ (D/200)^2$ for each tree and shrub which was measured in each sample plot. The basal area for each tree/shrub was summed to find total basal area of all species sampled. The realized vegetation communities were used in creating training sites for supervised classification of the satellite image in order to produce the map of vegetation communities. Validation of the communities was computed using the field data collected during reconnaissance and groundtruthing field work.

Remote sensing and image processing

The study utilized free access Landsat images downloaded from USGS EarthExplorer website (URL http://earthexplorer.usgs.gov/). I downloaded Landsat 5 Thematic Mapper (TM) image path 173 and row 062 captured on 24th July 2011 covering Nyungwe National Park because it was within the acceptable cloud cover limit of 10%. The associated field data were collected in 2009 during the WCS biodiversity survey therefore, I wanted to use 2009 Landsat TM data. However, the 2009 and 2010 images have more than 10% cloud cover.

The image was georeferenced and resampled to 30m spatial resolution using Erdas Imagine 9.2 and the resampling RMS (Root Mean Square) of 0.0003 for 2011 image. I used Universal Transverse Mercator (UTM) projection with 27^0 East as a central meridian for zone 35 south based on World Geodetic System 1984 (WGS84), a terrestrial reference datum. This projection is convenient for data sharing and integration because most other existing maps and data are based on this projection. However, other projections are being used in the region including the local Rwanda 1992 Transverse Mercator projection using 30 degrees East as a central meridian. Although longitude 27 degrees East is in Democratic Republic of Congo, it is the best fit for the Nyungwe National Park projection. Atmospheric correction was done in Idrisi Taiga using Cos(t) method. According to Chavez (1996) the Cos(t) model was developed as a technique for approximation in atmospheric correction that accommodates situations where not all necessary data are available.

The other data sets used in this study are 2009 color orthophotos with approximately 25 cm spatial resolution and 2009 multi-spectral SPOT (Satellite Pour l'Observation de la Terre) images with 2.5m spatial resolution. The orthophotos were already georeferenced into International Terrestrial Reference Frame (ITRF) 2005. I georeferenced and resampled SPOT images to 2.5m spatial resolution using Erdas Imagine 9.2 based on Universal Transverse Mercator (UTM) projection. I used 27^0 East as a central meridian for zone 35 south based on World Geodetic System 1984 (WGS84), a terrestrial reference datum. Although orthophotos provide highly detailed information for vegetation mapping, the common method to classify them is by visual interpretation due to inconsistencies of spectral characteristics of orthophotographs. The multi-spectral SPOT images had more than 30% cloud cover. Despite the condition of the orthophotos and SPOT images, they played an important role for fieldwork planning, verification of classification and were useful reference during groundtruthing mission.

The vegetation communities obtained from TWINSPAN output were used in image classification. The resulting image classified map was reclassified merging similar vegetation communities together. Thereafter the accuracy assessment was processed using error matrix or sometimes called confusion matrix (Eastman 2006) where errors of commission and errors of omission were identified. The final map was adjusted by incorporating the results of accuracy assessment.

Results

Distribution of all forest trees based on diameter classes follows a known forest distribution pattern where number of stems per diameter class decreases as the diameter class increases. Some understory species appeared only in the smallest diameter class including *Cinchona, Lindackeria volkensis, Oxyanthus speciosus, Lasianthus kilimandscharicus, Peddiea orophila, Maytenus undata, Celastraceae, Vernonia auriculifera,* and *Peddiea rapaneoides* which might confirm that the forest is under secondary state. Other species occurred only in the two middle diameter classes between 10 -50 cm, including *Ochna afzelii* and *Ocotea kenyensi*s, while others appeared within the last two diameter classes, thus classes that are more than 30cm including *Chionanthus africanus, Ekebergia capensis* and *Olea hochstetteri.* Species that were found in all four diameter classes included *Hagenia abyssinica, Podocarpus latifolius, Neoboutonia macrocalyx, Strombosia scheffleri, Carapa grandiflora, Syzygium guineense* and *Macaranga kilimandscharica.* Table 3.1 presents the summary of all diameter size class distributions for individual tree species measured in centimeters of diameter at breast height (dbh) in Nyungwe National Park during the 2009 biodiversity survey.

Table 3.1Diameter size class distributions of trees measured in Nyungwe National Park, Rwanda during the 2009 biodiversity survey conducted by WCS. DBH is presented in cm.

Species	**Family**	**DBH 2.5-10**	**DBH 10-30**	**DBH '30-50**	**DBH 50+**	**TOTALS**
Afrocrania volkensii	Cornaceae	19	24	21	7	**71**
Agauria salicifolia	Ericaceae	59	16	10	2	**87**
Alangium chinense	Alangiaceae	10	14	13	2	**39**
Albizia gummifera	Mimosaceae	11	12	13	2	**38**
Anthocleista grandiflora	Loganiaceae	13	6	6	1	**26**
Apodytes dimidiata	Icacinaceae	30	13	3	46	**92**
Arundinaria alpina	Poaceae	1036	2	0	0	**1038**
Aulacocalyx diervilleoides	Rubiaceae	19	6	0	0	**25**
Balthasarea schliebenii	Theaceae	9	1	8	17	**35**
Beilschmiedia michelsonii	Lauraceae	13	17	13	21	**64**
Beilschmiedia rwandensis	Lauraceae	0	4	10	8	**22**
Bersama abyssinica	Melianthaceae	2	6	4	7	**19**
Bridelia bridelifolia	Euphorbiaceae	7	5	8	1	**21**
Carapa grandiflora	Meliaceae	130	154	116	87	**487**
Casearia runssorica	Flacourtiaceae	15	26	10	3	**54**

Cassipourea congensis	Rhizophoraceae	10	13	5	0	**28**
Cassipourea gummiflua	Rhizophoraceae	0	1	1	0	**2**
Cassipourea ndando	Rhizophoraceae	0	1	2	1	**4**
Cassipourea ruwensorensis	Rhizophoraceae	24	64	6	2	**96**
Cassipourea rwandensis	Rhizophoraceae	1	6	2	0	**9**
Chionanthus africanus	Oleaceae	**0**	0	1	0	**1**
Chrysophyllum gorungosanum	Chrysophylloideae	20	**17**	21	44	**102**
Chrysophyllum rwandense	Chrysophylloideae	13	10	3	8	**34**
Cinchona	Rubiaceae	1	0	0	0	**1**
Cleistanthus polystachyus	Euphorbiaceae	33	45	44	40	**162**
Cola pierlotii	Sterculiaceae	1	1	3	2	**7**
Cremaspora triflora	Rubiaceae	20	5	0	1	**26**
Croton macrostachyus	Euphorbiaceae	1	0	2	1	**4**
Croton megalocarpus	Euphorbiaceae	2	6	4	0	**12**
Dichaetanthera corymbosa	Melastomataceae	9	18	5	8	**40**
Diospyros gabonensis	Ebenaceae	7	5	7	2	**21**
Dombeya goetzenii	Sterculiaceae	10	6	2	4	**22**
Drypetes gerrardii	Euphorbiaceae	4	0	1	0	**5**
Drypetes occidentalis	Euphorbiaceae	10	3	7	5	**25**
Ekebergia capensis	Meliaceae	0	0	1	12	**13**
Entandrophragma excelsum	Meliaceae	4	2	1	5	**12**
Faurea saligna	Protaceae	1	3	9	9	**22**
Ficalhoa laurifolia	Theaceae	9	5	6	16	**36**
Galiniera coffeoides	Rubiaceae	296	57	6	2	**361**
Galiniera saxifraga	Rubiaceae	2	1	0	0	**3**
Garcinia volkensii	Clusiaceae	44	31	4	3	**82**
Grewia mildbraedii	Tiliaceae	15	16	12	5	**48**
Hagenia abyssinica	Rosaceae	95	111	47	15	**268**
Harungana montana	Hypericaceae	18	24	10	4	**56**
Hypericum revolutum	Hypericaceae	280	19	0	0	**299**
Ilex mitis	Aquifoliaceae	18	38	45	37	**138**

Ixora burundensis	Rubiaceae	3	1	1	0	**5**
Lasianthus kilimandscharicus	Rubiaceae	2	0	0	0	**2**
Lindackeria kivuensis	Flacourtiaceae	12	2	0	0	**14**
Lindackeria volkensis	Flacourtiaceae	1	0	0	0	**1**
Macaranga kilimandscharica	Euphorbiaceae	**1526**	1206	604	80	**3416**
Maesa lanceolata	Myrsinaceae	279	121	35	9	**444**
Magnistipula butayei	Chrysobalanaceae	4	2	3	15	**24**
Maytenus acuminata	Celastraceae	74	16	9	1	**100**
Maytenus heterophylla	Celastraceae	5	2	0	0	**7**
Maytenus undata	Celastraceae	4	0	0	0	**4**
Memecylon walikalense	Melastomataceae	7	8	11	5	**31**
Musanga leo-errerae	Moraceae	7	11	2	6	**26**
Myrianthus holstii	Moraceae	28	34	21	5	**88**
Myrica salicifolia	Myrsinaceae	9	1	0	0	**10**
Neoboutonia macrocalyx	Euphorbiaceae	237	132	69	15	**453**
Newtonia buchananii	Mimosaceae	11	4	5	8	**28**
Nuxia congesta	Loganiaceae	10	6	2	0	**18**
Nuxia floribunda	Loganiaceae	14	12	3	1	**30**
Ochna afzelii	Ochnaceae	0	1	1	0	**2**
Ocotea kenyensis	Lauraceae	0	2	1	0	**3**
Ocotea michelsonii	Lauraceae	3	10	10	17	**40**
Ocotea usambarensis	Lauraceae	8	5	8	6	**27**
Olea capense	Oleaceae	14	28	5	10	**57**
Olea hochstetteri	Oleaceae	0	0	1	0	**1**
Olinia rochetiana	Oliniaceae	12	23	3	11	**49**
Oricia renieri	Rutaceae	11	5	2	0	**18**
Oxyanthus speciosus	Rubiaceae	1	0	0	0	**1**
Oxyanthus troupinii	Rubiaceae	40	2	1	6	**49**
Pancovia golungensis	Sapindaceae	0	3	2	0	**5**
Parinari excelsa	Chrysobalanaceae	30	28	20	50	**128**
Pausinystalia ituriense	Rubiaceae	5	8	5	1	**19**

Pavetta pierlotii	Rubiaceae	15	3	0	0	**18**
Peddiea orophila	Tymeleaceae	3	0	0	0	**3**
Peddiea rapaneoides	Tymeleaceae	10	0	0	1	**11**
Pentadesma reyndersii	Clusiaceae	23	26	31	16	**96**
Pleiocarpa pycnantha	Apocynaceae	10	7	3	1	**21**
Podocarpus falcatus	Podocarpaceae	0	1	0	8	**9**
Podocarpus latifolius	Podocarpaceae	73	69	50	82	**274**
Polyscias fulva	Araliaceae	68	69	42	18	**197**
Prunus africana	Rosaceae	0	3	3	4	**10**
Psychotria mahonii	Rubiaceae	226	79	22	6	**333**
Rapanea melanophloeos	Myrsinaceae	97	30	7	4	**138**
Rinorea gracilipes	Violaceae	1	6	3	0	**10**
Rytigynia kigeziensis	Rubiaceae	92	20	6	6	**124**
Sapium ellipticum	Euphorbiaceae	13	7	4	2	**26**
Senecio stuhlamnnii	Asteraceae	7	2	0	0	**9**
Sericanthe leonardii	Rubiaceae	6	15	1	0	**22**
Strombosia scheffleri	Olacaceae	30	61	75	93	**259**
Symphonia globulifera	Clusiaceae	30	22	20	45	**117**
Syzygium guineense	Myrtaceae	130	190	233	297	**850**
Tabernaemontana stapfiana	Apocynaceae	8	17	11	0	**36**
Vepris stolzii	Rutaceae	3	1	1	1	**6**
Vernonia auriculifera	Asteraceae	4	0	0	0	**4**
Vitex sp	Lamiaceae	0	1	0	0	**1**
Xymalos monospora	Monimiaceae	134	62	11	0	**207**
Zanthoxyllum gilletii	Ruraceae	0	2	1	0	**3**
	TOTALS	**5661**	**3180**	**1840**	**1260**	**11941**

The smallest diameter class representing regeneration is the largest category accounting for 47% of the entire tree species measured, followed by 10 – 30cm dbh class which accounted for 27%. This implies that 74% of the measured dbh are less than 30cm. The largest dbh class with trees larger than 50cm dbh accounted for 11% of the measured trees. In this 50+ cm dbh class, *Syzygium guineense* accounted for 23.6% of the trees measured with dbh more than 50cm followed by *Strombosia scheffleri* (7.4%), *Carapa grandiflora* (6.9%), *Podocarpus latifolius* (6.5%) and *Macaranga kilimandscharica* (6.4%).

I calculated the occurrence percentage for each tree species that were measured by dividing sum of measured stems per species divided by sum of all measured stems for all species multiplied by 100. Using the result from this calculation, I selected twenty tree species that yielded more than one percent. These selected records were then ordered based on the 2.5-10 cm dbh class to evaluate the regeneration distribution, I found out that *Macaranga kilimandscharica* accounted for 27% followed by *Neoboutonia macrocalyx* (4.2%), *Syzygium guineense* (2.3%), *Carapa grandiflora* (2.3%), *Hagenia abyssinica* (1.7%) and *Podocarpus latifolius* (1.3%). Table 3.2 shows 20 tree species selected from the largest diameter size class distributions measured in centimeters of diameter at breast height (dbh) in Nyungwe National Park during the 2009 biodiversity survey.

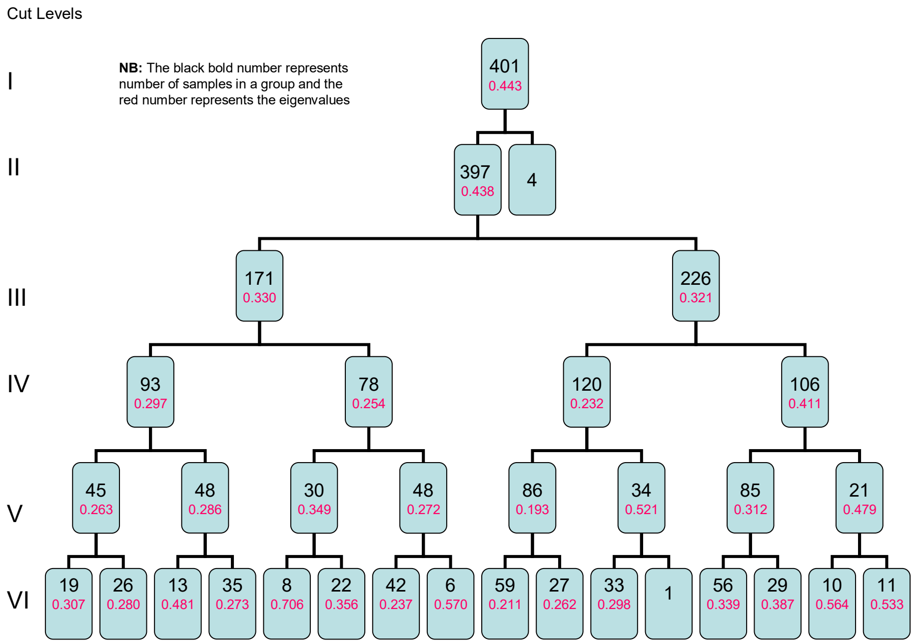
Table 3.2. Twenty selected tree species from the largest diameter size class distribution measured in centimeters of diameter at breast height (dbh) in Nyungwe National Park, Rwanda during the 2009 biodiversity survey

No.	**Species**	**Family**	**DBH 2.5-10**	**%**	**DBH 10-30**	**%**	**DBH '30-50**	**%**	**DBH 50+**	**%**
1	*Syzygium guineense*	Myrtaceae	130	2.30	190	5.97	233	12.66	297	23.57
2	*Strombosia scheffleri*	Olacaceae	30	0.53	61	1.92	75	4.08	93	7.38
3	*Carapa grandiflora*	Meliaceae	130	2.30	154	4.84	116	6.30	87	6.90
4	*Podocarpus latifolius*	Podocarpaceae	73	1.29	69	2.17	50	2.72	82	6.51
5	*Macaranga kilimandscharica*	Euphorbiaceae	1526	26.96	1206	37.92	604	32.83	80	6.35
6	*Parinari excelsa*	Chrysobalanaceae	30	0.53	28	0.88	20	1.09	50	3.97
7	*Apodytes dimidiata*	Icacinaceae	30	0.53	13	0.41	3	0.16	46	3.65
8	*Symphonia globulifera*	Clusiaceae	30	0.53	22	0.69	20	1.09	45	3.57
9	*Chrysophyllum gorungosanum*	Chrysophylloideae	20	0.35	17	0.53	21	1.14	44	3.49
10	*Cleistanthus polystachyus*	Euphorbiaceae	33	0.58	45	1.42	44	2.39	40	3.17
11	*Ilex mitis*	Aquifoliaceae	18	0.32	38	1.19	45	2.45	37	2.94
12	*Beilschmiedia michelsonii*	Lauraceae	13	0.23	17	0.53	13	0.71	21	1.67
13	*Polyscias fulva*	Araliaceae	68	1.20	69	2.17	42	2.28	18	1.43
14	*Balthasarea schliebenii*	Theaceae	9	0.16	1	0.03	8	0.43	17	1.35
15	*Ocotea michelsonii*	Lauraceae	3	0.05	10	0.31	10	0.54	17	1.35
16	*Ficalhoa laurifolia*	Theaceae	9	0.16	5	0.16	6	0.33	16	1.27
17	*Pentadesma reyndersii*	Clusiaceae	23	0.41	26	0.82	31	1.68	16	1.27
18	*Hagenia abyssinica*	Rosaceae	95	1.68	111	3.49	47	2.55	15	1.19
19	*Magnistipula butayei*	Chrysobalanaceae	4	0.07	2	0.06	3	0.16	15	1.19
20	*Neoboutonia macrocalyx*	Euphorbiaceae	237	4.19	132	4.15	69	3.75	15	1.19

Using two-way indicator species analysis (TWINSPAN) the 535 species which were recorded in 41 transects and 401 sample plots during the 2009 WCS biodiversity survey yielded 23 vegetation clusters in six cut levels. Since each plot was marked geographically, the locations of sample plots are clearly known, and as a result the spatial distribution of vegetation was determined.

The 401 sample plots were first classified into two main groups with an eignevalue of 0.443. The left arm (negative group) of the first dichotomy had 397 sample plots while the right arm (positive group) of the first dichotomy had 4 sample plots characterized by *Alchemilla johnstonii, Anagallis serpens, Cardus leptacanthus, Cyperus, Cyperus nigricans, Osmunda regalis, Senecio nyungwensis, Thelypteris confluens,* and *Xyris valida* species which belong to terrestrial herbaceous category. Three of the four sample plots were found in transect 18 thus plots 3, 4 and 5, and one plot is found in transect 22 plot 1. Since the number of samples was less than the preset dividable samples, the 4 samples could not divide any further.

The 397 sample plots were further divided with an eigenvalue of 0.438 into 171 sample plots in the negative group and 226 sample plots in the positive group. The 171 sample plots were further divided with an eigenvalue of 0.330 into 93 sample plots in negative group and 78 sample plots in positive group. The 226 sample plots were further divided with an eigenvalue of 0.321 into 120 sample plots in negative group and 106 sample plots in positive group. The dividing process continued until the pre-set cut-level of 6 was reached. The dendrogram in Figure 3.6 shows the details of the divisions realized through TWINSPAN.



NB: The black bold number represents number of samples in a group and the red number represents the eigenvalues

Figure 3.6. TWINSPAN classification of 401 sample plots in 41 transects based on 2009 biodiversity survey of Nyungwe National Park, Rwanda. Black numbers indicate the number of samples in a group and red numbers represent the eigenvalues for the division.

Similarly, the 535 species were first classified into two main groups with an eigenvalue of 0.289; the negative group had 526 species while the positive group had nine species (Figure 3.7). These nine species are the same species characterizing the four samples in Figure 3.6. The divisions of species display low eigenvalues as compared to the divisions of samples. According to Palmer (2006) eigenvalues are equivalent to correlation coefficients and are useful in interpretation of the analysis. If the division has a low eigenvalue, mostly less than 0.4, it is considered indicative of less useful division. Figures 3.6 and 3.7 display a similar pattern but differ in the range of eigenvalues. This might mean that the level of similarity among species (0.289) within the sample is lower than the similarity among the sample plots (0.443). When the similarity among species is high, the division is considered less useful.

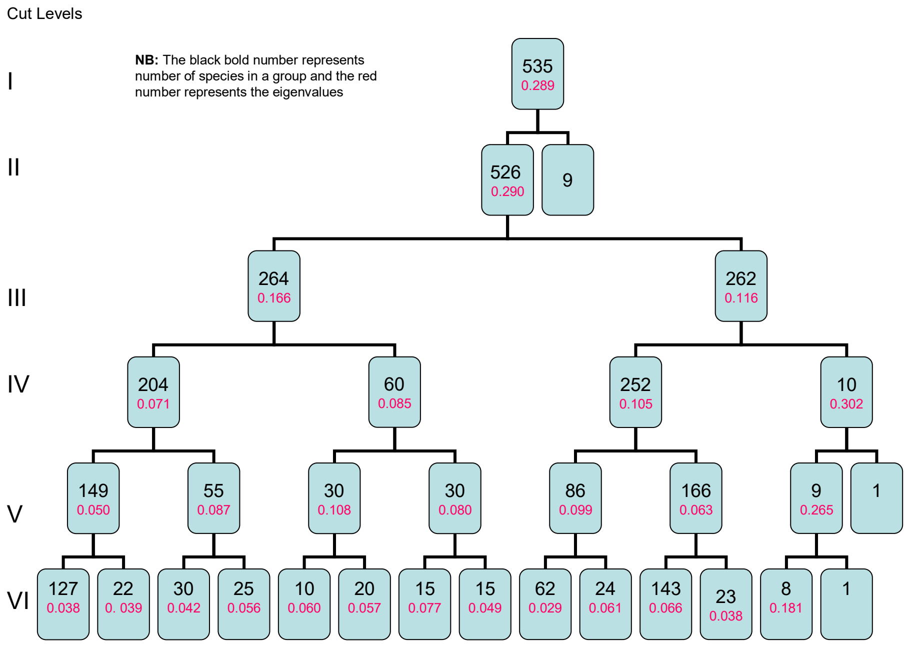


Figure 3.7. TWINSPAN classification of 535 species recorded within 401 sample plots in 41 transects based on 2009 biodiversity survey of Nyungwe National Park, Rwanda. Black numbers represent number of species in a group and red numbers represents the eigenvalues for the division.

Vegetation communities

Spatial analysis based on TWINSPAN yielded 13 vegetation communities (Figure 3.8 and 3.9). The three most common vegetation communities cover almost half (42%) of the protected area. The communities identified with the highest percent cover include Macaranga *kilimandscharica-Maesa lanceolata* (17%), *Macaranga kilimandscharica-Neoboutonia macrocalyx* (15%), and *Macaranga kilimandscharica-Dichaetanthera corymbosa* (10%). Figure 3.8 presents vegetation community cover percentages while Figure 3.9 presents the spatial distribution pattern of each vegetation community cover. The northern part of the park is most common species by *Faurea saligna, Syzygium guineense* and *Macaranga kilimandscharica, Neoboutonia macrocalyx* communities, while the area around Bigugu, the highest peak in Nyungwe National Park is dominated by *Afrocrania volkensii, Hagenia abyssinica* and *Erica johnstoniana, Hagenia abyssinica* communities. The western part is dominated by *Alchornea hirtella, Cleistanthus polystachyus, Alchornea hirtella, Carapa grandiflora* and *Macaranga kilimandscharica, Dichaetanthera corymbosa communities,* while the central part is dominated by *Macaranga kilimandscharica, Maesa lanceolate* and the southern part of the Park is dominated by *Arundinaria alpina, Macaranga kilimandscharica* (7%) and *Macaranga kilimandscharica, Dichaetanthera corymbosa* communities. When I combine all areas with *Macaranga kilimandscharica* as dominant species (42%) together with areas that *Macaranga kilimandscharica* is co-dominant species (7%), almost half of Nyungwe National Park is covered by *Macaranga kilimandscharica.*

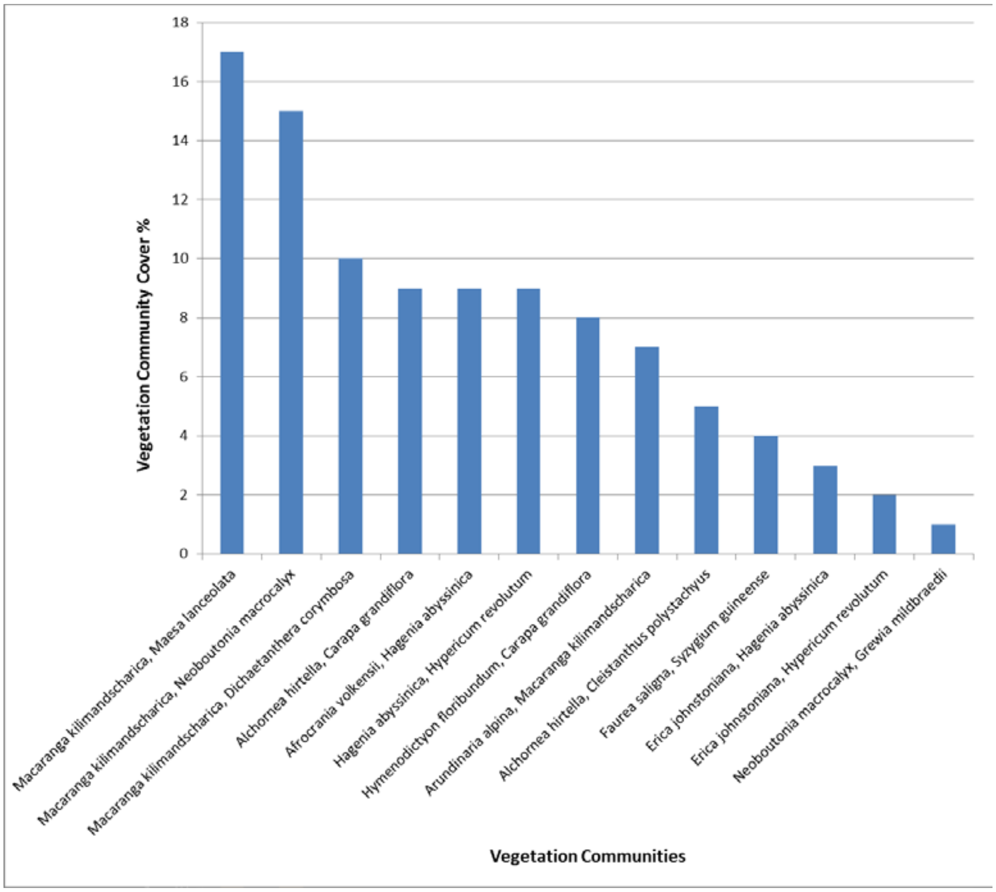


Figure 3.8. Vegetation communities identified using TWINSPAN and GIS analysis in Nyungwe National Park, Rwanda

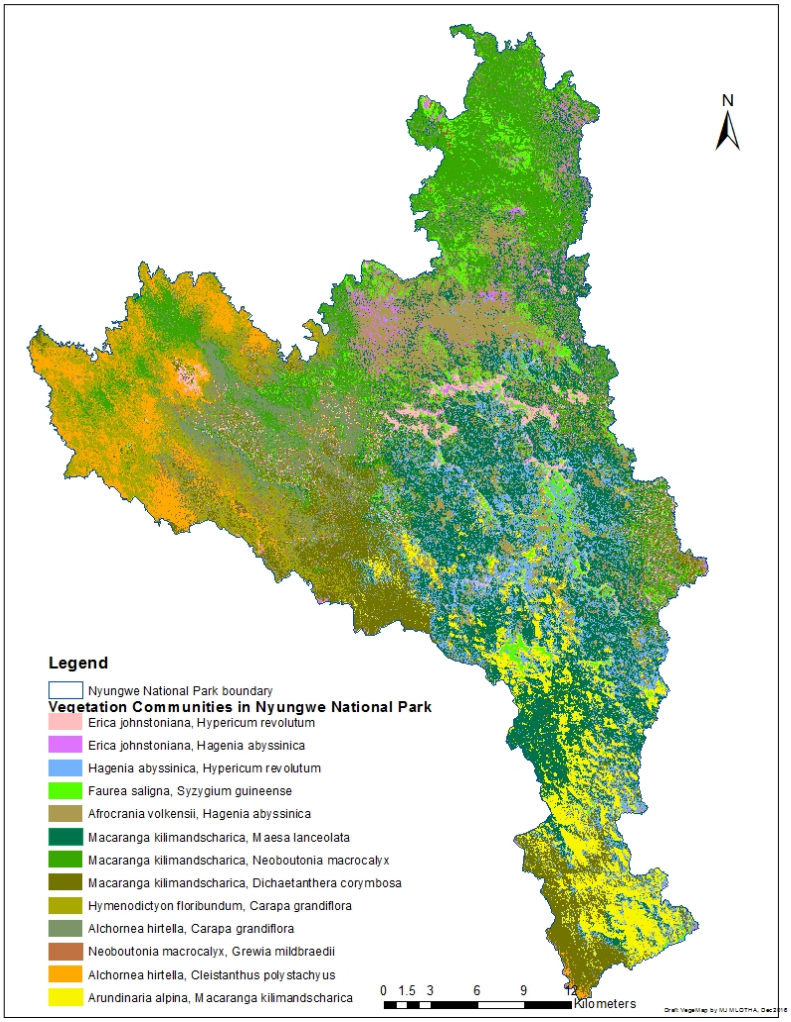


Figure 3.9. Spatial distribution of 13 vegetation communities in Nyungwe National Park, Rwanda

The western part of the Park, which was surveyed using stratified random sample plots, recorded a total of 106 species in 45 families. The Rubiaceae family was represented by 16 species, the highest number of recorded species belonging to one family, followed by Euphorbiaceae family with 10 species, and Rhizophoraceae family with six species. The average DBH was 18.5cm (SD = 18.65 at 95% CI). The maximum DBH measured was 136.5cm. *Syzygium guineense* had the largest DBH within the sampled area. The estimated average stem density for stems with ≥ 2cm was 433 stems. Relative dominance showed that

Cleistanthus polystachyus (Euphorbiaceae) had the highest relative dominance of 11.46 followed by *Syzygium guineense* (Myrtaceae) with 10.62. Spatial analysis and using the basal area calculations for dominance, showed that more than half of the surveyed area has *Cleistanthus polystachyus* (Euphorbiaceae) as the dominant species with patches of *Macaranga kilimandscharica* (dominant) and *Dichaetanthera corymbosa* (co-dominant) while *Alchornea hirtella* (Euphorbiaceae) was the dominant understory species (Figure 3.9).

Using presence and absence data from the 2009 WCS Biodiversity survey of Nyungwe National Park, 216 out of 401 sample plots recorded the presence of *S. scandens* representing 53% coverage. When all the factors listed above in methods section were taken into account the overall estimated coverage of *S. scandens* in Nyungwe National Park is 72%. Figure 3.10 presents the estimated distribution of *S. scandens* Nyungwe National Park.

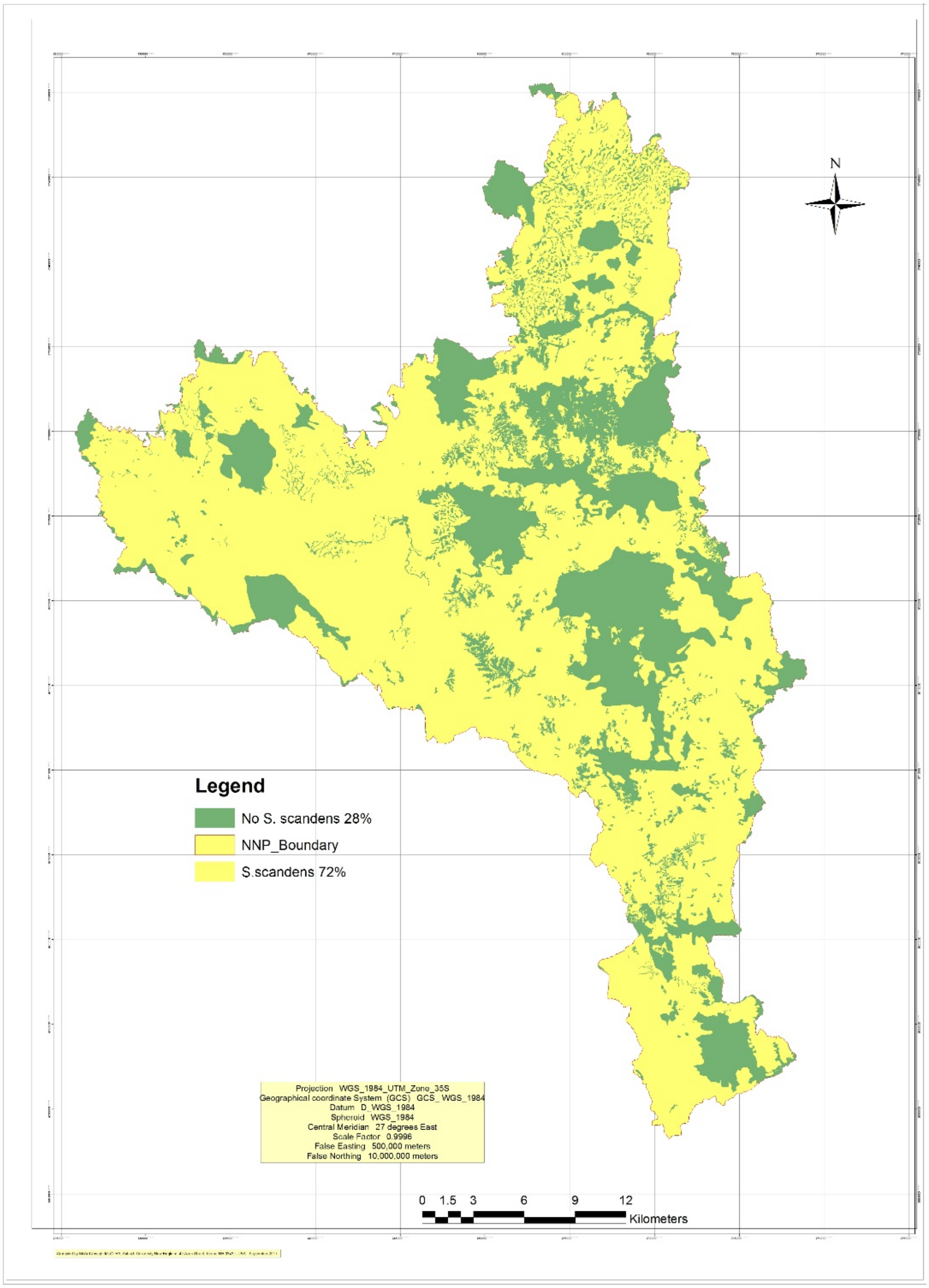


Figure 3.10. Estimated distribution of Sericostachys scandens in Nyungwe National Park, Rwanda.

The MaxEnt results summarizes the out-put of 15 split-sample models for Sericostachys_scandens using “Subsample” Replicated run type. Figure 3.11 is the analysis of omission /commission showing the omission rate and predicted area at different thresholds. The orange and blue shadings surrounding the lines on the graph represent variability measured in standard deviation. The following picture shows the test omission rate and predicted area as a function of the cumulative threshold, averaged over the replicate runs. The omission rate should be close to the predicted omission, because of the definition of the cumulative threshold.

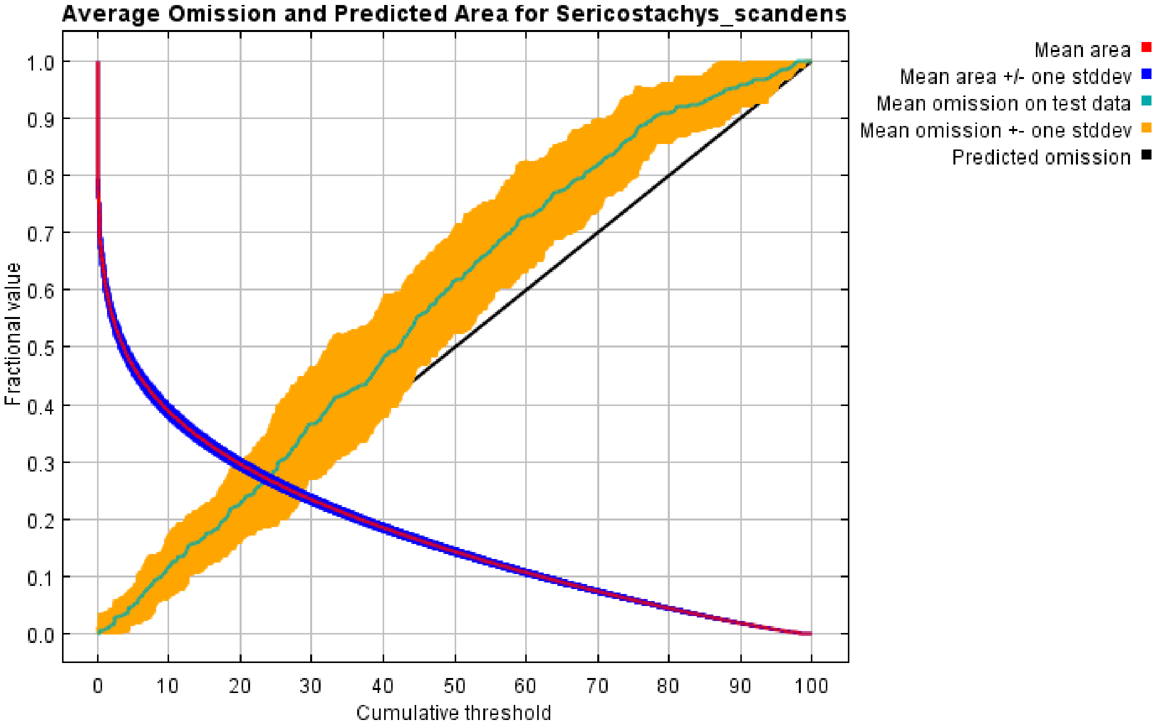


Figure 3.11. Average omission and predicted area for Sericostachys scandens at different thresholds.

Figure 3.12, presents the Sensitivity vs 1 Specificity for *Sericostachys scandens.* The graph presents the Area Under the Receiver Operating Characteristic (ROC) Curve or AUC which is important for comparing performance of models. In this model the AUC was 0.795. An

AUC value of 0.5 indicates that the performance of the model is no better than random, while values closer to 1.0 indicate better model performance.

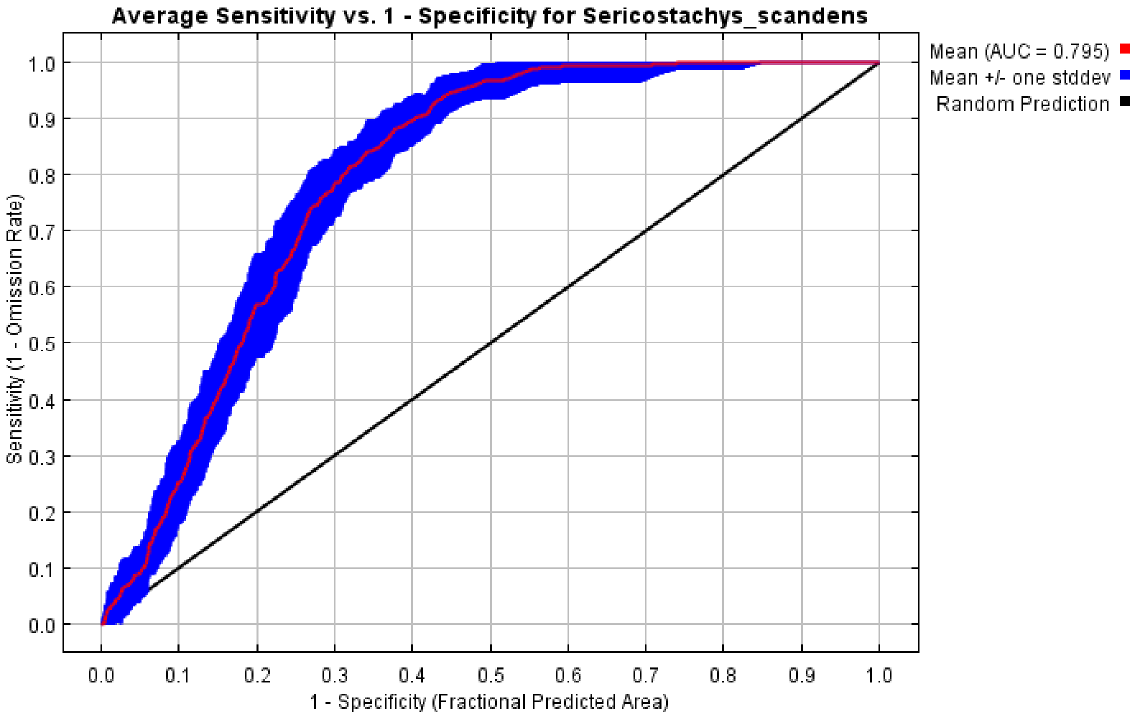


Figure 3. 12. The Sensitivity vs 1 Specificity for Sericostachys scandens.

A table is generated representing the Analysis of Variable Contributions showing all the 19 bioclimate variables used in the model and their percent predictive contribution of each variable. Table 3 shows selected six variables with highest predictive contribution. The higher the contribution, the more impact that particular variable has on predicting the occurrence of that species. In this model, Mean Diurnal Range (Mean of monthly (max temp - min temp)) had the highest Mean Diurnal Range (Mean of monthly (max temp - min temp)) highest predictive contribution of 31.3% followed by Annual Precipitation with predictive contribution of 26.6%.

Table 3.3. Six variables with highest predictive contribution on predicting the occurrence of Sericostachys scandens in Nyungwe National Park.

Variable	Percent contribution	Permutation importance
nnp_bio_02	31.3	1.2
nnp_bio_12	26.6	37.7
nnp_bio_14	10.3	4.8
nnp_bio_17	9.8	13.4
nnp_bio_18	4.3	1.5
nnp_bio_16	3.1	2.4

The results of the jackknife of Regularized Training Gain show that Annual Precipitation (nnp_bio_12) has the highest gain when used in isolation, which therefore appears to have the most useful information by itself. Additionally, the same (nnp_bio_12) is the variable that decreases the gain the most when it is omitted, therefore appears to have the most information that isn't present in the other variables. Figure 3.13 shows the Jackknife of Regularized Training Gain.

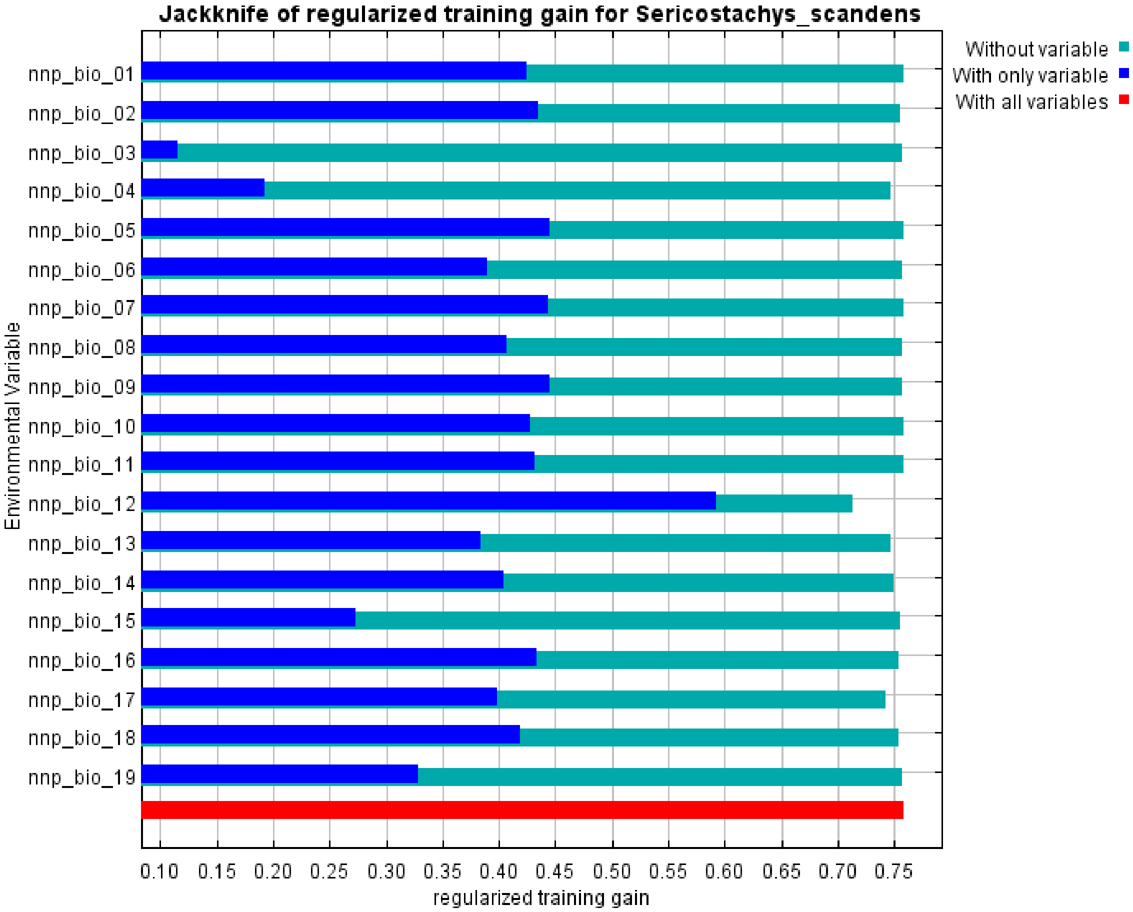


Figure 3.13. Jackknife of regularized training gain of Sericostachys scandens in Nyungwe National Park

Figure 3.14 shows the point-wise mean of the probability distribution of *Sericostachys scandens* in Nyungwe National Park. The red areas have the higher predictions of occurrence while the dark blue is the lowest prediction of occurencies.

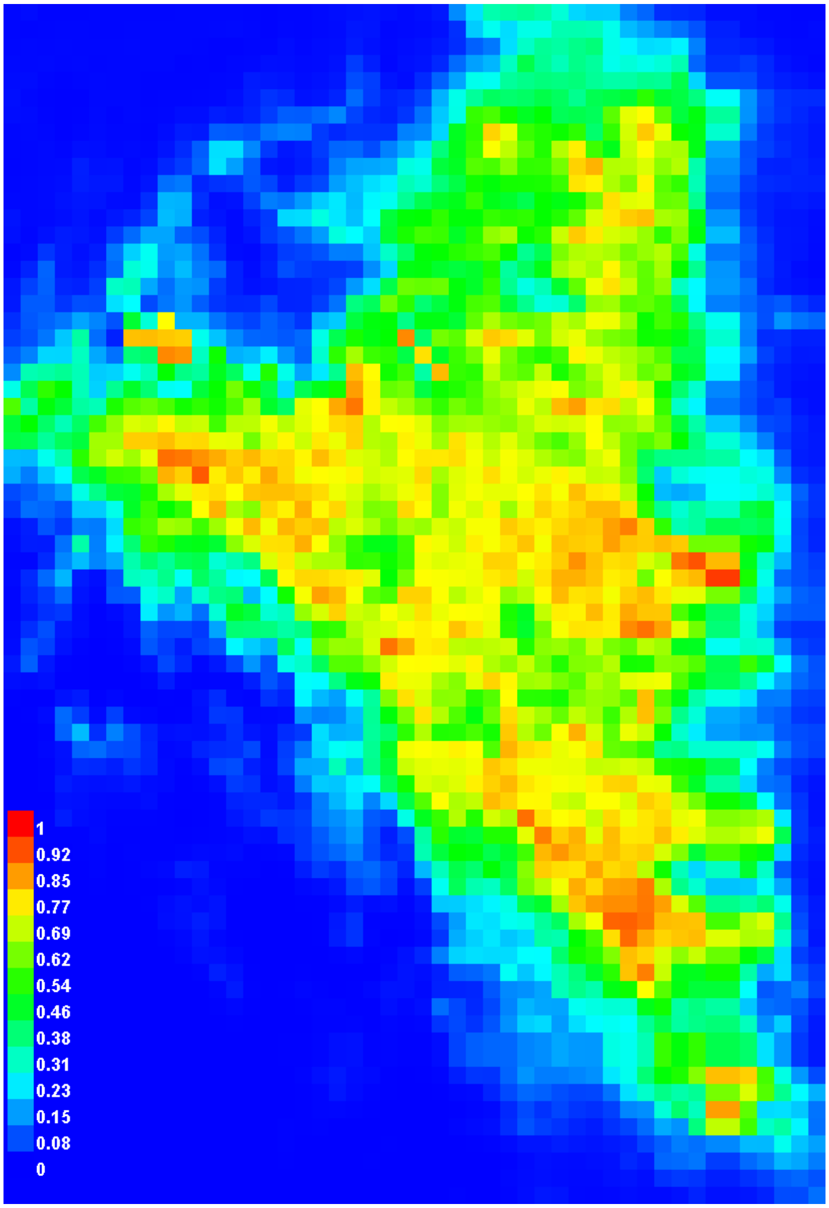


Figure 3.14. Point-wise mean of the probability distribution of Sericostachys scandens in Nyungwe National Park.

To put in context, I added the point-wise standard deviation of the probability distribution of *Sericostachys scandens* in Nyungwe National Park. I add the Park boundary to help locate areas of interest based on boundary of the Park (Fig 3.15). The red areas indicate sites that represent high probability distribution of Sericostachys scandens in Nyungwe

National Park. Most of these areas with high probability are found along the road and areas that are known to have experienced forest degradation or previously mining areas.

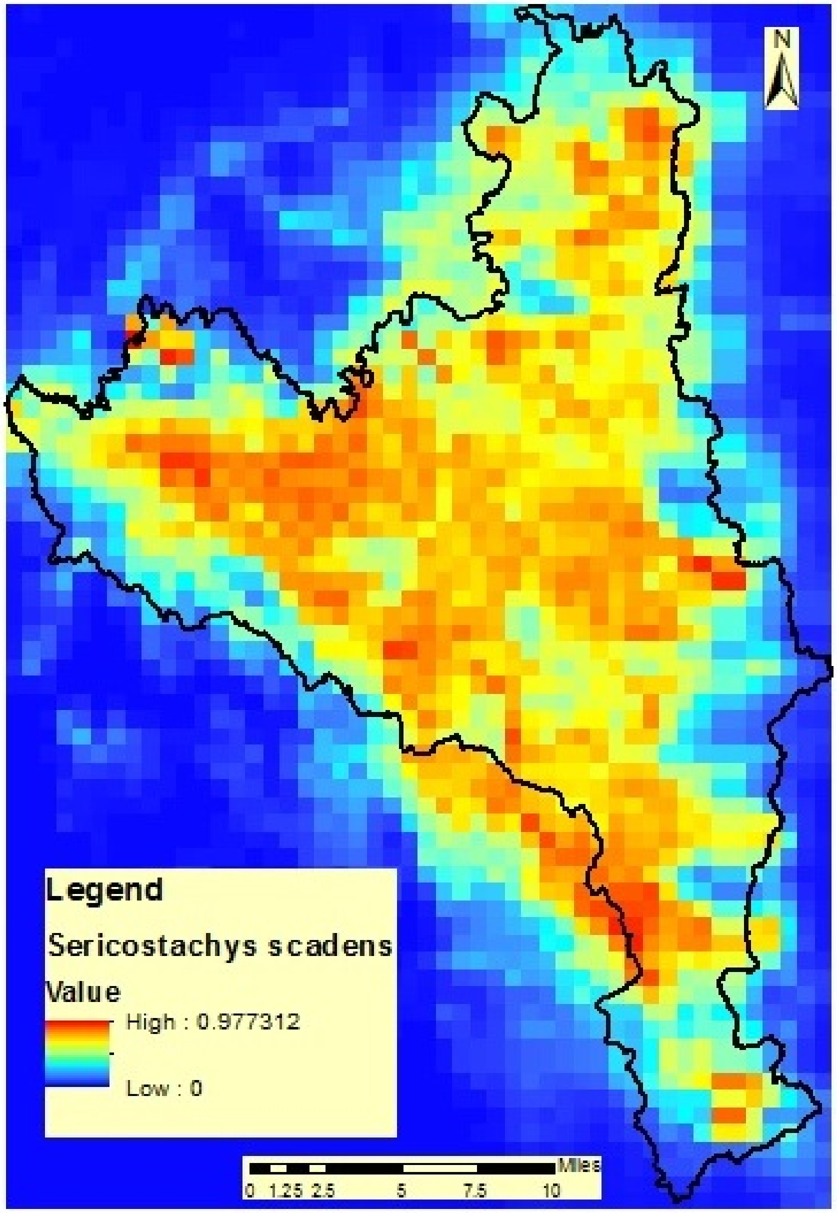


Figure 3.15. Point-wise standard deviation of the probability distribution of Sericostachys scandens in Nyungwe National Park

Discussion

The findings demonstrate that mapping vegetation communities using TWINSPAN and remotely sensed Landsat satellite imagery data can effectively be an alternative method to traditional field sampling methods. Using MaxEnt as one of the species distribution model has shown agreement with the known conditions about occurrences of *Sericostachys scandens* which concentrates within open areas including along the roads. It is clear from my results that analysis of diameter distribution conforms to tropical montane forests that are typical of self-regenerating communities. As a natural forest with mixed species, vegetation communities are determined based on dominance and co-dominance of species in a particular forest patch. Basically, dominant and co-dominant species are based on some measure of abundance although it is rarely mentioned about the abundance at which a species becomes dominant (Frieswyk et al., 2006). The advantage of using TWINSPAN, is that the results include dominant and codominant species together with indicator species. In this study, dominance and codominant species were generated by TWINSPAN.

Lewis (2006) describes tropical forest to constitute a large portion of natural forests with high biodiversity and are typically composed of comparatively dense stands of tall and evergreen broadleaf trees. Within the tropical forests, we find pioneer species and climax species. *Macaranga kilimandscharica* is one of the pioneer species which is an early successional and shade-intolerant and only grows when there is a gap in the canopy. Climax species are late successional and shade-tolerant and have the ability to grow under a closed canopy (Lewis 2006). In places where fire affected the vegetation, it was noted that *Pteridium aquilinumin* colonized and chokes regeneration. A multiple-year research of assisted regeneration by removing ferns (*Pteridium aquilinum)* for a period of five years within

Nyungwe National Park recorded 5,500 trees per hectare in areas where ferns were removed as compared to 1,100 trees per hectare within the control areas. Additionally, average tree height increased more within areas where ferns were removed than control areas (Terra Global 2011).

Maps of vegetation communities are useful tools for planning and management of natural resources and provide important information used to understand patterns of spatial distribution of species and ecological systems management. Vegetation communities are identified by two species, thus dominant and co-dominant species. The method used in this study combines remote sensing, GIS, vegetation classification in TWINSPAN and Species distribution modeling (SDM) tool, MaxEnt. Remote sensing and SDM tools provide an opportunity to use fewer fieldwork data than in a traditional vegetation mapping process which requires intensive sampling. However, the difference in methods yields different levels of accuracy. In most cases, the empirical method is superior in accuracy compared to remote sensing approach although remote sensing has many more other advantages over empirical vegetation mapping that include the ability to map vast areas within a reasonable or economical time compared to fieldwork time.

Management of natural forest ecosystems requires knowledge of regeneration and forest structure among other factors in order to make sound decisions regarding conservation and management of the forests. The findings of this study will provide such information as a spatial distribution of vegetation communities and probable extent of *Sericostachys scandens.* Using the data that was collected during the 2009 biodiversity survey presents a spatial distribution of vegetation communities which also highlighted the percentage of the total park area that is covered by the secondary species such as *Macaranga kilimandscharica* (Figure

3.9). The vegetation communities within the eastern and western sides of the park share similarities on both sides and are different from those vegetation communities along the central ridge. However, *Macaranga kilimandscharica* dominance is spread across all the areas within the Park and is found on both lower sides of the central ridge and areas on the central ridge. The results provide important information as a tool for ecological and wildlife management and scientific studies. Additionally, the vegetation communities can be used to demarcate vegetation zones based on dominant and co-dominant species (Mirkin et al., 2015).

The presence of trees within the largest dbh class typically indicate the level of forest transition, forest structure, dynamics, and capacity of forest ecosystems including biomass and forest carbon (Lutz et al., 2012). Although there had been disturbances within some parts of the forest, it is rewarding to know that some areas still have large trees as depicted by largest diameter class and this can suggest that there are areas within the park which experienced little disturbance than most of the eastern part which experienced several fires and other disturbances. Tree species diversity increases within secondary regeneration forests as we see that more species are recorded in first dbh bracket compared to the largest dbh bracket. However, forest regeneration also changes species composition dominance which might affect other wildlife and ecological systems. For example, as a home of several primates including *Pan troglodytes* the increase of *M. kilimandscharica* might affect food availability and other environmental aspects required by wildlife.

Syzygium guineense and *Macaranga kilimandscharica* are very important indicators of forest category change from primary forest to secondary forest. *Syzygium guineense* was the largest diameter tree measured within the area I surveyed during this study and represents about 24% of all tree species within the largest diameter class based on 2009 Nyungwe

National Park biodiversity survey. *Macaranga kilimandscharica* dominated communities represented about 50% of the area I surveyed during this study and it is the largest species recorded within the 2.5cm -10cm diameter class representing about 27% of all the species recorded within the diameter class. The fact that *Macaranga kilimandscharica appears in three of the 13 vegetation communities as* the dominant species and co-dominant in one of the 13 *vegetation communities covering about 50%* of Nyungwe National Park, suggests that the park is transitioning to a secondary forest status. According to Fischer and Killmann (2008), *M. kilimandscharica* is a fast-growing pioneer species of montane evergreen forest signifying forest disturbances. In the Park there are large areas of *M. kilimandscharica*, mostly in the eastern part (Figure 3.9) which also experienced fires, the largest was recorded in 1997. Large blocks of *M. kilimandscharica* are mostly found in the eastern part of the park which can be considered as a confirmation that the eastern part of the park had been subjected to forest disturbances including fire outbreaks in the past. However, *M. kilimandscharica* is found in most of the park.

The park is known to be under enormous pressure by the densely populated adjacent human communities for forest resources and need for agricultural land (Crawford 2012). I argue that the historical land uses by the early human occupants of the area together with lack of restrictions to cut or collect forest produce, forest encroachment and impacts of population growth might have contributed to forest disturbances (Oslon et al 1996; MINIRENA/CGIS-NUR 2007). For example, MINIRENA/CGIS-NUR (2007) argued that using aerial photographs, Nyungwe National Park decreased annually at an average of 750 ha due to encroachment for agricultural activities between 1958 and 1972.

The first division of all species in TWINSPAN had an eigenvalue of 0.289 which indicated that about 30% of the variance was accounted for by tree species. Similarly, the first division of all sample plots had an eigenvalue of 0.443 which indicated that 44.3% of the variance was accounted for by sample plots. TWINSPAN organize species data and sample plots data into multidimensional space according to their similarity in floristic composition (Rosales et al., 2001; Roleček et al., 2009) and the clusters of samples are presented in an order similar clusters are near each other (Šmilauer and Lepš 2014). Since vegetation mapping is recommended to be carried out in stratified random sampling, I argue that the results might have been affected by transect sampling method used in collection of this dataset. This sampling method resulted in sample plots which had higher eigenvalues (0.443) at the first division comparing the first division of species (0.289 eigenvalues) recorded in those sample plots.

Comparing results from the data collected during the survey for this study and the data collected in the 2009 WCS biodiversity survey of Nyungwe National Park shows agreement in the dominant species and vegetation communities identified. More than half of the western part of the Park I surveyed had *Alchornea hirtella* (Euphorbiaceae) as the dominant understory species while *Cleistanthus polystachyus* (Euphorbiaceae) was co-dominant, in agreement with the TWINSPAN results using the transect data and the spatial distribution results based on remotely sensed data. Despite similarities in the dominance and co-dominance in the two data sets in the western part of the park, stratified random sampling is considered to be the best approach when mapping vegetation as compared to transect sampling (Roleček et al. 2007).

The estimated distribution of *Sericostachys scandens* in Nyungwe National Park provides an indication of the extent of liana in the park. It is difficult to determine whether S. scandens is increasing its spatial presence in Nyungwe National Park without temporal change mapping, however, using the ecological behavior of this liana observed in Kahuzi Biega National Park in Democratic Republic of Congo we can assume that overtime *Sericostatchys scandens* can extend to other parts within Nyungwe National Park. Furthermore, the reproductive strategy of this liana combines both vegetative propagation and sexual reproduction, and propagule dispersal by wind (Cephas et al., 2012; Campbell et al., 2014; Schniter et al., 2002).

In this study, *Sericostachys scandens* was estimated to be present in more than half of the Park. There are concerns that the liana causes tree mortality (Scholte et al 2010) therefore mapping the extent is useful for strategic conservation planning and management. Given that this species is present in more than half of the park, it is important to monitor its distribution and potential impacts such as increased tree mortality. As the regeneration and dieback of this liana vary between the northern region and the central-southern part of the park, the divide between these two different regions of *S. scandens* ecology is not clearly demarcated. According to Gakima Jean Baptiste (personal communication, 2011), there is a two-year gap between die back in the northern region of the park versus the central-southern part of the park, similarly, the regeneration is two years apart.

Conclusion

My results show that combining remotely sensed data with data from plot sampling can produce a meaningful vegetation map; however the technical processing of such mapping requires working with remotely sensed data presented in a wide range of formats and understanding of data manipulation and data integration using various platforms. Vegetation classification tools such as TWINSPAN and the species distribution modeling programs such as MaxEnt prove to be handy when manipulating vegetation community data and predicting the extent of *Sericostachys scandens.* Spatial distribution of vegetation communities were mapped using various data sources including field sampled data and remotely sensed data. With the size of the National Park, mapping such vegetation communities would take much longer time if one team was used as we did in this research, and if the mapping was only done conventionally without integrating it with remote sensing techniques.

Nyungwe National Park is a montane tropical forest with *Macaranga kilimandscharica*, the most abundant species, covering 49% of the park. This suggests that the Park is under secondary forest status considering that *Macaranga kilimandscharica* is a pioneer species which is shade intolerant. *M. kilimandscharica* is present in three communities as dominant species and in one as co-dominant species of the vegetation communities identified through statistical analyses. The forest structure in Nyungwe National Park is represented in a reversed J shaped distribution based on diameter classes that conforms to tropical montane forests that are typical of self-regenerating communities with large number of stems within small diameter classes than in large diameter classes. The estimated presence of *Sericostachys scandens* indicates that the liana is present in over half of the Park. This study did not explore the claims that this liana is spreading in the park and is responsible for some of the tree mortality. Therefore, there is need for further research to assess whether the liana is extending its distribution within the park and if it has ecological effects on other vegetation. The resulting vegetation communities and the resulting map will be important tools for further scientific studies and also for ecological management of the Park. Vegetation communities with dominant and co-dominant species will be a helpful tool in planning and management of the Par because it provides more specific information than broad vegetation categories.

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Chapter 4: Estimation of aboveground carbon in Nyungwe National Park, Rwanda using combined methods: Remote sensing and Field measurements

ABSTRACT

Tropical forests perform a vital function in mitigating climate variation and play a key role in the conservation of biodiversity and the global carbon cycle. Forests are rich in biomass and store large amounts of carbon, estimated up to 50% of the global carbon. Any loss or negative changes in tropical forests may affect climate variations. It is thus important to estimate forest Carbon as part of monitoring climate change or patterns in forest cover. The goal of this study was to assess distribution and quantities of aboveground forest carbon in Nyungwe National Park, a tropical montane forest in southwestern Rwanda. I used generalized allometric functions and vegetation indices including Normalized Difference Vegetation Index (NDVI) based on 2011 Landsat TM images. I compared NDVI to NRVI (Normalized Ratio Vegetation Index), TTVI (Thiam's Transformed Vegetation Index) and RVI (Ratio Vegetation Index), to assess the best vegetation index for Nyungwe National Park. Additionally, I evaluated a methodology to assess forest wide carbon using Landsat TM data by calibrating the carbon derived from image analysis results based on forest carbon values obtained through field sampling of the western part of the forest. The advantage of this approach is that large areas with difficult access can be studied economically by linking remotely sensed data with field survey measurements through statistical analysis. Field sampling was carried out in 72 stratified random plots; DBH of all stems > 2cm were measured and tree height was estimated. A total of 106 species in 45 families were recorded in the plots. Among the families, Rubiaceae had the highest number of recorded species, followed by Euphorbiaceae family with 10 species. Above-ground biomass (AGB) for each sample plot was computed using an allometric equation developed by Chave et al. (2005) and results were linked to vegetation indices values for each sample plot through regression analysis. The data collected were used to calculate AGB for each individual stem in a sample plot and then summed to obtain total AGB of all stems in a sample plot in order to relate AGB and vegetation indices. Among the four vegetation indices used in this study, NDVI values showed a higher association with AGB than TTVI, NRVI and RVI indices. The study found that mapping forest carbon using combined methods of remote sensing and GIS can be a cost-effective means to assess large areas when there are limitations of time, financial resources and challenging or restricted physical access.

Key words:

Aboveground biomass (AGB), Carbon, Landsat Thematic Mapper (TM), Normalized difference vegetation index (NDVI), Nyungwe National Park

INTRODUCTION

Tropical forests play a key role in the global carbon cycle as both a carbon source and a sink (Achard et al., 2002; Bombelli et al., 2009; Bright, Hicke, & Hudak, 2012; Lu, 2005) and are home to many endangered, endemic and rare plant and animal species (Gardner et al., 2009; Schelhas & Greenberg, 1996). Houghton (2005) and Lewis et al. (2009) argued that tropical forests store up to 50% of the global carbon; consequently any loss or negative changes in tropical forests will affect climate variations. The global carbon cycle has a direct effect on global climate patterns through the amounts of carbon emissions into the atmosphere and how much is absorbed by the oceans and forests (Le Quéré et al., 2014).

Forested protected areas are one of the major areas for carbon sequestration (sink) and sources of carbon (source). They also serve as an important tool for the conservation of biodiversity (Chape et al., 2003; Deguignet et al., 2014; Naughton et al., 2005).Since carbon estimation is usually derived from biomass, therefore changes in land cover affects the carbon estimates. However, protected areas only account for a little over 12% of global land area (Chape et al., 2005) and some protected areas are experiencing negative land cover change (DeFries et al. 2005; Gross et al., 2013; Nagendra, 2008). Although forests are an important component in the global carbon cycle and climate modulation processes, the world is losing forest at an alarming rate (Ridder 2007; Meyfroidt and Lambin 2011; FAO and JRC 2012). The recent Global Forest Watch report (2014) showed that between 2000 and 2012 the global loss of forested areas was estimated at 2.3 million km^2. Despite a reduction in the annual tropical deforestation rate from approximately 16 million hectares per year between 1990 to

2000 to approximately 13 million hectares per year between 2000 to 2010 (Achard et al., 2010; DeFries et al., 2007), tropical forests are disappearing at an alarming rate largely due to conversion to pasture and agricultural lands, and for timber (Le Quéré et al. 2009, (Chapin III et al. 2000; Laurance and Peres 2006; Sudarshana et al. 2012). Various authors have estimated that most of the world's tropical forests may disappear by the middle of this century (Goudie, 2006; Sanderson et al., 2002; Seabloom, Dobson, & Stoms, 2002; Sisk, Launer, Switky, & Ehrlich, 1994; Whitmore & Sayer, 1992).

The relationship between forest biomass and forest carbon is estimated to be in a ratio of 2 to 1 (biomass to carbon); in other words carbon is estimated at 50% of forest biomass (Chave et al., 2005; Jérôme Chave et al., 2014; Houghton, 2005; Litton & Boone Kauffman, 2008; Segura & Kanninen, 2005). Carbon is stored in various pools which can be grouped into two main groups, above ground and below ground Carbon. These groups can be further classified into sub-groups; the above ground carbon pool can be divided into dead and live biomass, and litter biomass (Dong et al., 2003; Hudak et al., 2012; Potter & Klooster, 1997), while below ground biomass can be subdivided into dead and live biomass such as live and dead roots (Ekoungoulou, Liu, Loumeto, & Ifo, 2014; El-Kahloun, Boeye, Van Haesebroeck, & Verhagen, 2003; Hristovski, Melovski, Šušlevska, & Grupče, 2012; Tamooh et al., 2008). Below and above-ground carbon stocks within tropical forests also vary with space and time, due to vegetation density, age of forest, soil nutrients and slope aspects, which creates uncertainty in estimating carbon flux (Chave et al. 2008). It is important that accurate estimates for carbon stored or sequestrated by tropical forests are generated in order to understand the role of carbon in the local and global carbon cycle and also to support decision making processes.

Forest biomass information, derived from tree measurements such as diameter at breast height, can be used to compute forest carbon estimates using allometric equations (Chave et al., 2005; Houghton et al., 2012; Keller, Palace, & Hurtt, 2001). However, there is generally lack of data to analyze stored forest carbon (Pan et al., 2011), as well as lack of time and other resources to run a full carbon-biomass assessment of a forested area (DeFries et al., 2002; Hansen, Stehman, & Potapov, 2010; Nabuurs & Masera, 2007; Wertz-Kanounnikoff, Verchot, Kanninen, & Murdiyarso, 2008). Remote sensing and GIS applications have become the most economical and efficient approach to biomass and carbon estimation in tropical forests (Anaya, Chuvieco, & Palacios-Orueta, 2009; Lu, 2006a; Lu, Mausel, Brondízio, & Moran, 2004; Rosette et al., 2012). With advancements in computer technology and improved spatial, spectral and temporal resolutions of remote sensing imaging (Al-Wassai & Kalyankar, 2013; Hay, 2000; Shaw & Burke, 2003; Sinha, Jeganathan, Sharma, & Nathawat, 2015), studies have shown strong correlations between biomass and reflectance at different wavelengths (Babar et al., 2006; El-Hendawy, Al-Suhaibani, Salem, Ur Rehman, & Schmidhalter, 2015; Heiskanen, 2006; Sari, Sonmez, & Karaca, 2006; Schull et al., 2007) while others have used band-ratio indices such as normalized difference vegetation index (NDVI) using red and infra-red bands to measure levels of greenness in order to estimate biomass and net productivity (Anyamba & Eastman, 1996; Anyamba & Tucker, 2005; Eastman, Sangermano, Machado, Rogan, & Anyamba, 2013; Groten, 1993; Neeti et al., 2012; Pettorelli, 2013). However, assessing carbon stocks requires a certain level of expertise plus financial and technical inputs which are in many cases not readily available especially for large tropical forests. Combined methods using field work coupled with remote sensing analysis tend to be economical in terms of both financial and time.

When forest cover is lost there are losses and changes in accumulation of greenhouse gases (GHGs) in the atmosphere, one of the main causes of climate change (IPCC, 2006). There are many gases that form the GHG effect but one of the most important is carbon dioxide (CO_2), which has a significant influence on global warming and climate change (IPCC, 2006). CO_2 emissions have been directly linked to anthropogenic activities including land use and land cover change (Foley et al., 2005; Lambin & Geist, 2006; Lambin & Meyfroidt, 2011), and studies have shown that CO^2 emissions have been increasing since the industrial revolution and the increased use of fossil fuels (Boden, Marland, & Andres, 2010; Le Quéré et al., 2014; Peters, Minx, Weber, & Edenhofer, 2011). The main concern of scientists is the rapid decline in forested land cover and the increasing emission of greenhouse gases (GHG) into the earth's atmosphere resulting in warmer temperatures. It is to these concerns that various efforts including REDD+ were created in order to reduce emissions from deforestation and degradation within developing countries (Phelps et al., 2010). According to United Nations REDD, Reducing emissions from deforestation and forest degradation (REDD+) is a mechanism developed by Parties to the United Nations Framework Convention on Climate Change (UNFCCC) which was created in 2008 (Corbera & Schroeder 2011; Kanowski et al., 2011; Angelsen et al., 2012).

The REDD+ components include reducing emissions from deforestation, reducing emissions from forest degradation, conservation of forest carbon stocks, sustainable management of forests,and enhancement of forest carbon stocks (Phelps et al., 2010). As of January 2017, the UN-REDD+ program was supporting nationally led REDD+ initiatives in 64 developing countries, including 19 in Asia, 28 in Africa and 17 in South America. According to UN-REDD+, the design of the REDD program requires countries to complete certain tasks before they can be considered as a REDD+ country, thus, three phases to be completed namely; developing strategies, policy formulation, proposals and action plans; developing REDD projects as part of developing a more sustainable land use; lastly rewarding communities for verified emissions reductions and removals (UN-REDD 2008).

Assessing changes in land use and land cover especially within forested areas is one of the main component of REDD as a process to monitor deforestation and emissions. The challenges of developing robust and quick to use system in assessing changes in forests especially biomass and carbon values has been improved overtime such as improved remote sensing technologies and computing capabilities. Fighting deforestation and emissions can not be successful without collaboration of all stakeholders in a country at the same time address social and economic needs of the communities. During the first phase, a country is guided to identify all stakeholders and build a team to develop strategies and incorporate concerns and fears that might be associated with REDD program. For example, protected areas are often used by various stakeholders including indigenous communities and local communities that depend on forest for their livelihood, tourism, conservation and nature science education; therefore it is appropriate to include all stakeholders in the process. On the other hand protected areas are a major source of forest biomass and forest carbon mostly in countries where large forest blocks are only found in protected areas.

REDD+ requires that the drivers of deforestation and degradation must be identified and appropriate mitigation measures designed or put in place in order to reduce deforestation and increase afforestation. The processes to identify the drivers of deforestation require studies and monitoring systems that can provide data and information as a source of decision making. However, land use/land cover studies have been carried out in some countries to identify the drivers of deforestation (DeFries et al., 2010; Hosonuma et al., 2012; Kissinger et al., 2012; Meyfroidt et al., 2013). Drivers of deforestation vary from place to place but there are certain drivers common to the least developed countries such as (a) economic development including mining, urbanization and infrastructural development, (b) agriculture and food production, and (c) demand for energy sources for example fire wood and charcoal (Hosonuma et al., 2012; Kissinger et al., 2012 and Corbera et al., 2010).

The motivation for members of communities not to cut trees in REDD+ is the rewards and payments which are paid after verifications procedures are carried out, assessing that there was no deforestation over the given period. However, to get that verification requires that countries first must establish a baseline data and put in place a program to periodically assess their forestry resources and analyze the changes. In order to determine changes in forest cover, and biomass, the countries engage in activities that include monitoring and verification processes that forest resource inventory becomes a major player therefore methodology and procedures are of interest in any REDD program. The challenges faced in field data collection and monitoring varies but are dependent on planning both in office as well as in the field, research design, how well trained or prepared is the team, choice of tools to use in field for example for measuaring diameter, one can use a caliper or a diameter tape. Each of these tools have their own advantages and disadvantages, affecting accuracy and effectiveness in project performance.Other challenges depend on terrain, vegetation type and accessibility.

The purpose of this study was to highlight lessons learned and challenges of estimating carbon within a tropical montane forest and how it can be applied to the preparation process of REDD readiness. Additionally, I assessed distribution and quantities of aboveground forest carbon in a montane tropical forest protected area using generalized allometric functions and Landsat TM images using vegetation indices including Normalized Difference Vegetation Index (NDVI) based on 2011 Landsat TM images. I compared NDVI to NRVI (Normalized Ratio Vegetation Index), TTVI (Thiam's Transformed Vegetation Index) and RVI (Ratio Vegetation Index), to assess the best vegetation index (VI) for the study site. Although much work has been done in developing vegetation indices, there is still no single vegetation index that fits all situations. Jackson and Huete (1991) argued that RVI is sensitive to vegetation changes during peak growth but not very sensitive to open or sparse vegetation cover, while Sesnie et al. (2011) found that sun elevation angle negatively impacted NDVI and Enhanced Vegetation Index (EVI) values in areas of steep terrain. NDVI is considered superior to most of the indices although in areas of dense forest, this index becomes saturated (Huang at al., 2013; Pettorelli, 2013; Sesnie et al. 2011; Jiang et al., 2006; Tucker, 1979). I selected Nyungwe National Park (NNP), Rwanda, located in the Albertine Rift, a biodiversity hotspot to explore the impacts of forest cover changes and estimating above ground carbon. As a tropical forest Nyungwe National Park has thick forested areas with steep slopes and the effects of high elevations including wet and cold weather conditions (Plumptre et al., 2007; Kaplin, 2001). These might slow down the progress of fieldwork therefore, it is important to consider when planning for fieldwork

I evaluated four different vegetation indices in this study (Silleos et al. 2006). I also evaluated a methodology to assess forest carbon using Landsat TM data without fieldwork by calibrating the carbon derived from image analysis results versus forest carbon values obtained through fieldwork sampling. I assessed aboveground carbon using a combined approach of remote sensing and field measurements of forest trees. NNP is one of the largest remaining montane tropical forests in the Albertine Rift (Plumptre et al., 2007), making it an important site for biodiversity conservation and C storage in the region.

Table 4.1. Vegetation indices evaluated

No.	**Vegetation Index**	**Name**	**Formula**	**Author**
1	NDVI	Normalized Difference Vegetation Index	IR-R/IR+R	Rouse et al. (1974)
2	RVI*	Ratio Vegetation Index	R/IR	Richardson and Wiegand (1977)
3	NRVI	Normalized Ratio Vegetation Index	RVI-1/RVI+1	Baret and Guyot (1991)
4	TTVI	Thiam's Transformed Vegetation Index	√Abs(NDVI+0.5)	Thiam (1997)

**Note: Ratio Vegetation Index (RVI) (R/IR). This is different from what is called "Ratio" or Simple Ratio (SR) index (IR/R) Birth and McVey (1968) and Jordan (1969).*

METHODS

Study area

The study was conducted in Nyungwe Forest National Park, a tropical montane forest located in southwestern Rwanda. The park lies between 2°15' and 2°55' south of the equator and between 29°00' and 29°30' east of prime meridian. It is estimated to cover about 1013 km^2 of land area. The Park has a partial buffer zone of exotic tree species including eucalyptus and pines and some sections are under tea plantation or cultivation (Gapusi, 2007) (Figure 4.1). The forest extends southwards crossing the international boundary into Burundi, where it is known as Kibira National Park (Vedder, Hall, Montfort, & Wilson, 1992). The combination of Nyungwe and Kibira National Parks forms one of the largest contiguous blocks of lower montane forests in Africa (Vedder et al., 1992; Weber, 2001). The area receives an average rainfall of between 1800-2500 mm per year. The temperature ranges from 0^0 C to 30^0 C (Kaplin, 2001).

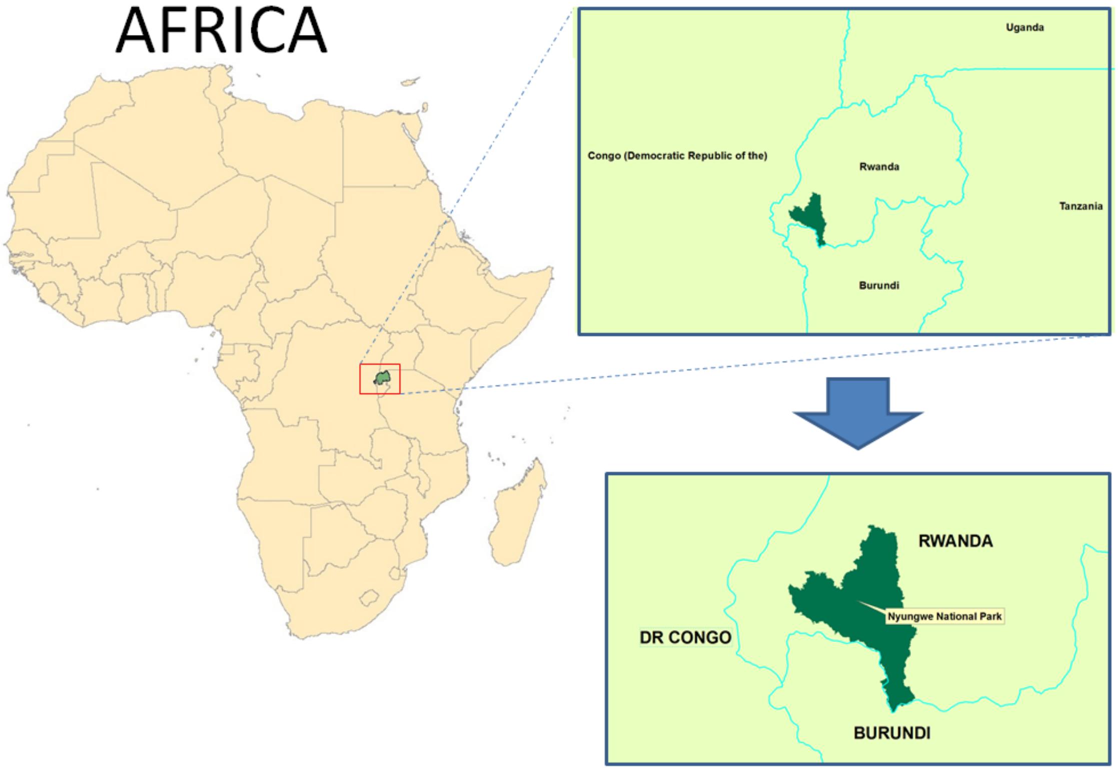

Figure 4.1. Location map of Nyungwe National Park, Rwanda

Nyungwe National Park is a montane tropical forest; these forests are found around the equator at an altitude of over 1500m elevation (Grace et al., 2014; Malhi & Grace, 2000). The Park is divided by the Congo-Nile watershed a continental divide that separates the drainage of the Nile and the Congo basins (Sreepat 2013) (Figure 4.2). Tree species typical of high this elevation forest include *Hagenia abyssinica*, *Prunus africana*, *Ficalhoa laurifolia*, *Podocarpus* spp. and *Olea* spp. (White 1983). The forest is characterized by 2-3 distinguishable tree layers with canopy layer reaching over 35m within the elevation of 1700 to 2700m (Ewango, 2001; Plumptre et al., 2002). Primary forest is characterized by *Parinari* *excelsa, Entandrophragma excelsum, Carapa grandiflora, Symphonia globulifera* and *Chrysophyllum gorungosanum* with a lower canopy layer of either *Psychotria mahonii* or *Alchornea hirtella* while the higher elevation is characterized by Ericaceous species and *Hagenia abyssinica* (Ewango, 2001; Plumptre et al., 2007; Plumptre et al., 2002). The wetlands of Kamiranzovu, Tangaro and Uwansenkoko are characterized by a mixture of short grasses, herbs like *Cyperus* species and ferns together with Ericaceous species and *Hagenia abyssinica* (Ewango, 2001). There is a section of bamboo forest (*Sinarundinaria alpina*) in NNP with pockets of primary and secondary forest characterized by *Chrysophyllum gorungosanum, Macaranga kilimandscharica, Rapanea melanophloeos, Nuxia floribunda,* and *Polyscias fulva* species (Ewango, 2001; Plumptre et al., 2002).

The Park has high biodiversity and ecological importance (Plumptre et al., 2002; USAID, 2010). It hosts more than 260 species of trees and shrubs, almost 300 bird species, about 100 orchids, and about 75 species of mammals including 13 species of primates (Kaplin, 2001; Plumptre et al., 2002; USAID, 2010). The drainage system includes Nile-Congo watersheds and it is a source of about 70 percent of Rwanda’s water supply. As a tropical forest it is an important storage of carbon stocks (USAID, 2010). Soils are humiferous, acidic, and as a result the area is classified as of moderate agricultural value. According to Ghehi et al. (2012) and Storz (1983), Nyungwe National Park soils developed mainly from schists, micaschists, quartzitic schists and granites.

Protection and conservation of Nyungwe National Park dates as early as 1933, when it was first declared a protected area by the Belgian colonial government as part of watershed protection strategy for the Congo and Nile Rivers (Vedder et al., 1992); Olson et al. 1995; Masozera 2002). This protection status allowed adjacent communities to collect wood and other forest products and also allowed grazing of animals and bamboo collection, but did not allow forest clearing (Masozera, 2002). In 2005 the protected area was gazetted as Nyungwe National Park through Rwanda Law number 22/2005 dated 21/11/2005 (Figure 4.1). The spatial area and status of the protected area has changed over time (Fischer & Killmann, 2008a; Gapusi, 2007; Olson, Manyara, Campbell, Lusch, & Hu, 1995; A. Plumptre et al., 2007). The Park follows a preservation management policy where zero extraction or harvesting is allowed. However, a lot of pressure is exerted by the human population living adjacent to the park, and illegal activities to acquire various resources from the park such as bush meat, firewood and poles, medicine, land for cultivation, mining, and raw materials for making baskets and for building continue to be carried out (Crawford, 2012; Plumptre et al., 2007; Plumptre et al., 2002).

Sample Area and Vegetation Sampling Methods

I sampled the northwestern part of the Nyungwe National Park. This area has a wide range of habitats including primary forest, secondary forest, grassland, wetlands, open and closed forest and forest regenerating following either fire or cultivation. The only vegetation category not found in the study area was bamboo forest which is found in the southern part of the Park.

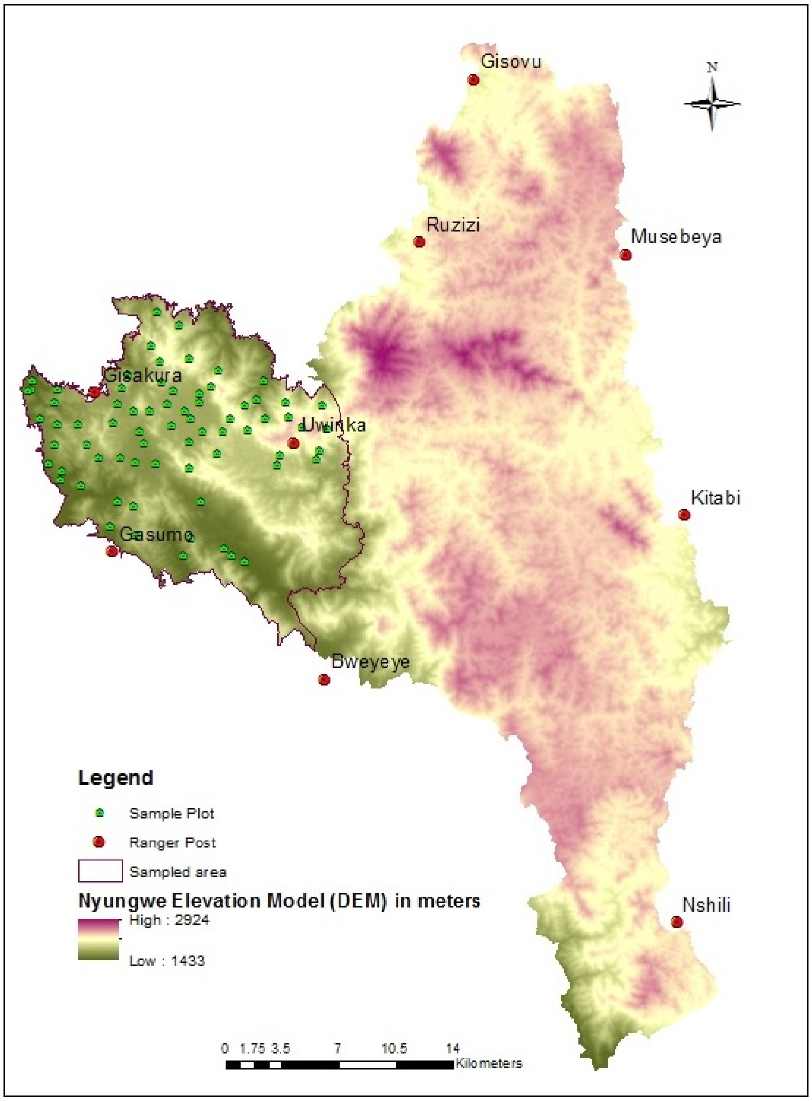

Figure 4. 2. Map of Nyungwe National Park showing sampled area

During the preliminary planning of the fieldwork I reviewed various sources of information including 2008/9 color orthophotographs, Landsat TM satellite images, topographic maps, Digital Elevation Model (DEM) and various reports and publications. I used the 2008/9 color orthophotographs to classify the sample area into four stratified vegetation classes namely, closed forest, secondary forest, ridge-top open forest, and wetland vegetation. The closed forest class covered 69% of the total sample area and was the largest class in the area followed by ridge-top open forest covering 15% of sample area. Secondary forest and wetland vegetation covered 10% and 6% respectively. I generated 100 random points which were distributed proportionally to the four vegetation classes: 69% in closed forest, 10% in secondary forest, 15% in ridge-top open forest and 6% in wetlands. Consequently, these points were marked with longitude and latitude coordinates that were used to locate sample plots in a stratified random.

Fieldwork was carried out between November 2011 and July 2012. Field data were collected in circular plots of 0.1 ha with a 0.008 ha circular plot nested within the larger plot. In the large plot I measured and recorded all trees with DBH ≥10cm and in the smaller nested plots I measured all trees/shrubs with DBH between ≥2 and <10cm. Many parameters of trees contribute to biomass assessment but DBH was selected due to many models that have been developed using tree DBH measure. Brown (1997) argued that DBH alone accounts for over 95% of the variation in aboveground tropical forest carbon stocks. At each sample plot I recorded the center point eastings and northings coordinates in order to spatially georeference the sample plot during analysis and mapping. I recorded the elevation of each sample plot center using the Garmin GPSMAP 60Csx GPS *(the Garmin advertisement claims that Garmin GPSMAP 60Csx GPS receiver measures elevation by barometric pressure).* Slope was measured using a Suunto clinometer and a slope correction was applied to all distances measured on slopes. The total sampled area was about 24,327 ha which represents about 24% of the total National Park area.

Vegetation was described in terms of family and species and their names both in scientific nomenclature as well as in Kinyarwanda, the local language in Rwanda. This information was required when analyzing species diversity, abundance and dominance in order to determine the relationship of the amount of biomass to tree species. All species identifications were verified using the "Flore du Rwanda" books (Vol. 1 and Vol. 2; Troupin, 1978, 1983) and the "Illustrated field guide for plants of Nyungwe National Park" by Fischer and Killmann (2008). Species identifications were also discussed with botanists at Institut de Recherche Scientifique et Technologique (IRST) and National University of Rwanda (NUR) Biology Department botanists.

Vegetation Community Analysis

Vegetation cover was analyzed in order to develop species distribution, estimate stocking and estimate wood volume. Data from sample plots were analyzed using MultiVariate Statistical Package (MVSP). I computed relative density, relative dominance, frequency, and abundance of tree species and shrubs according to Curtis and McIntosh (1950). Relative density determines the numerical strength of a species in relation to the total number of individuals of all the species in an area. Relative frequency describes the degree of dispersion of individual species in an area in relation to the number of all species occurrences. Species occurrence was extracted from each sample plot and summed across plots; the number of occurrences of each species was divided by the total number of occurrence of all the species and then multiplied by 100. I determined the dominance of a species using the value of basal area coverage. Since I used the same formula to compute relative dominance, I did not separate the smaller diameter trees from trees with diameter larger than 10cm. Relative dominance is the coverage value of a species with respect to the sum of coverage of the rest of the species in the area. Basal area in square meters was calculated by $\pi\ (D/200)^2$ for each tree and shrub which was measured in each sample plot. The basal area for each tree/shrub was added together to find total basal area of all species sampled.

Biomass estimation

Data collected from each sample plot were used in estimating above ground biomass (AGB). I computed carbon stocks of aboveground biomass for each tree in each sample plot using model II of the non-destructive method (Chave et al., 2005) in order to estimate AGB of each tree measured. Chave et al. (2005) developed allometric models using tree diameter (DBH) only and DBH with tree height. The models that use DBH only are convenient when the data have gaps in tree height or when tree height readings are not reliable due to difficulty of measuring in closed canopy forest. However, Chave et al. (2005) argued that using height in the equation improves the accuracy of the resulting AGB by reducing the error. I did not use height due to some missing height information in some samples. The allometric equation used to estimate AGB for each tree in every sample plot was:

$$AGB\ (kg) = \rho * \exp\left(-1.239 + 1.980 \ln(D) + 0.207(\ln(D))^2 - 0.0281(\ln(D))^3\right)$$

where

AGB = aboveground biomass in kilograms

ρ = average wood specific density in g/cm3

exp = the natural exponential function (approximately 2.718281828)

ln = natural logarithm

D = diameter in cm.

I summed the calculated AGB of each tree in each sample plot to obtain AGB per sample plot, and then obtained an estimate of AGB per hectare. This information is important when relating remotely sensed biomass values to actual measured biomass of each sample plot.

Spectral analysis and Vegetation indices

There is a wide range of vegetation indices (Table 4.1), but the NDVI using red (R) and near infrared (NIR) bands (Huang et al., 2013; Jiang et al., 2006; Tucker, 1979) has been noted to be responsive to changes in land cover, plant biomass and natural ecosystems (Anyamba & Eastman, 1996; Benliay & Altuntaş, 2014; DeFries & Townshend, 1994a; 2006; Lu, 2006b; Pettorelli, 2013). NDVI is a ratio of the difference between red band and infra-red band divided by the sum of red band and infra-red (NDVI= R-IR/R+IR). The origins of NDVI include the fact that chlorophyll in leaves tends to absorb visible light within the spectral wavelength ranging from 0.4 to 0.7 µm (Anyamba & Tucker, 2005; DeFries & Townshend, 1994b; Indeje et al., 2006; Tucker, 1979). On the other hand the near infrared (NIR) spectral wavelengths ranging from 0.7 to 0.9µm are reflected by the cell structure of the leaves. According to USGS (1985) and NASA (1999), Landsat TM spectral bands that correspond with the spectral wavelengths that absorb visible light and those spectral wavelengths that reflect near infrared (NIR) in Landsat 5 Thematic mapper are Band 3-Red with spectral wavelengths ranging from 0.63 to 0.69µm and Band 4-Near Infrared with spectral wavelengths ranging from 0.77 to 0.90µm respectively.

Data in remotely sensed vegetation assessment were captured based on spectral characteristics of the sensor, in this particular case Landsat 5 Thematic Mapper (TM). I used Landsat 5 Thematic Mapper (TM) image path 173 and row 062 captured on 24th July 2011 and obtained from USGS EarthExplorer free satellite data source (URL http://earthexplorer.usgs.gov/). The image used was close to the date of the fieldwork, and its cloud cover was within the acceptable range of less than 10%. The image was geometrically corrected in Erdas Imagine 9.2 using 3rd polynomial and resampled nearest neighbor to WGS 84, UTM zone 35 South coordinate system which covered the study area. Atmospheric correction was done in Idrisi Taiga using Cos(t) method. According to Chavez (1996) the Cos(t) model was developed as a technique for approximation in atmospheric correction that accommodates situations where not all necessary data are available. The NDVI ratio was created using Band 3 (Red) and Band 4 (InfraRed) as explained earlier in this paper (Indeje et al., 2006; Jensen, 2009; Pettorelli, 2013; Tucker, 1979). The values of NDVI range between -1 and +1. Various authors (Fensholt et al., 2012; Huete et al., 2002; Nemanill, 1997; Pettorelli, 2013; Wang, Rich, & Price, 2003) have argued that NDVI values increase with increased green biomass present in plants. Therefore higher positive NDVI values reflect high biomass and areas such as closed canopy forest, while values closer to 0 or negative values represent either water or areas with low or no vegetative cover.

Remotely sensed above ground biomass (AGB) using spectral characteristics

The sum of AGB per sample plot and the outcome of NDVI, NRVI, TTVI, RVI and Elevation processing for each plot, were regressed using SPSS remote access. These Vegetation Indices (VI) are based on a ratio of red and infra-red bands (Eastman, 2009). However the difference is on normalization and transformation. The RVI has two different formulae, one known as simple ratio (SR) or “Ratio” (RVI-SR) derived from Infra-Red/Red bands (IR/R) which according to Silleos et al. (2006), was authored by Birth and McVey (1968). The other RVI formula is derived from Red/Infra-red bands (R/IR) created by Richardson and Wiegand (1977), although UNESCO (2007) state that this formula (RVI-SR) was first described by Jordan (1969).

Although some sample plots did not have trees or shrubs $\geq$2cm causing zero DBH values for these plots which translated into zero AGB values, the derived NDVI considered the greenness of the sample plot and assigned a value to that sample plot regardless of absence of trees with $\geq$2cm. This happened for plots affected by fire where trees were eliminated or dead, and those located in wetlands where no measurable trees were found.I assessed the relationship between ABG carbon (measured in field) and vegetation indices derived from Landsat TM, namely NDVI values, NRVI values, RVI values and TTVI values using Pearson correlation tests.

I assessed the relationship between ABG carbon (measured in field) and vegetation indices derived from Landsat TM, namely NDVI values, NRVI values, RVI values and TTVI values. Correlation results can be grouped into three categories of associations whether negative or positive values, with low associations between 0 and 0.3, medium associations between 0.3 and 0.5 and strong association between 0.5 and 1 (Kozak et al 2012). Out of the four indices used, NDVI is positively correlated and it is the best index of four indices used with a correlation of 0.302, p=0.005, n=72 Using the NDVI results from the regression analysis, I generated an expression that was used to estimate AGB (Kg) as follows:

AGB (kg) = 17388 + (8092*NDVI Values)

RESULTS

A total of 106 species in 45 families were recorded from the stratified random sample plots (Table 4.2). Among the families, Rubiaceae had the highest number of recorded species

(16), followed by Euphorbiaceae family with 10 species, and Rhizophoraceae family with six species.

Table 4.2. Tree and shrub families and number of species sampled within the Nyungwe National Park, Rwanda.

Family	No. of Species	Family	No. of Species	Family	No. of Species
Rubiaceae	16	Mimosaceae	2	Ebenaceae	1
Euphorbiaceae	10	Podocarpaceae	2	Ericaceae	1
Rhizophoraceae	6	Rosaceae	2	Hypericaceae	1
Apocynaceae	4	Sapindaceae	2	Icacinaceae	1
Lauraceae	4	Theaceae	2	Loganiaceae	1
Meliaceae	4	Tiliaceae	2	Melianthaceae	1
Moraceae	4	Acanthaceae	1	Monimiaceae	1
Oleaceae	4	Aquifoliaceae	1	Myrtaceae	1
Clusiaceae	3	Araliaceae	1	Ochnaceae	1
Flacourtiaceae	3	Cannabaceae	1	Olacaceae	1
Myrsinaceae	3	Celastraceae	1	Oliniaceae	1
Rutaceae	3	Connaraceae	1	Protaceae	1
Chrysobalanaceae	2	Cyatheaceae	1	Sterculiaceae	1
Chrysophylloideae	2	Cyperaceae	1	Tymeleaceae	1
Melastomataceae	2	Dracaenaceae	1	Violaceae	1
Totals	**70**		**21**		**15**

The sampled area included primary and secondary forest. The average DBH across all sampled plots was 18.5cm (SD = 18.65 at 95% CI). The minimum DBH was 2cm and maximum was 136.5cm. *Syzygium guineense* tree had the largest DBH within the sampled area. The estimated stocking per hectare for stems ≥ 2cm was 433 stems.

The NDVI values for the whole Park based on 2011 Landsat TM data ranged from “0” to 0.347 with a mean of 0.18 and a SD = 0.05. The study area NDVI values ranged from “0” to 0.269 which is 0.08 lower than the NDVI for the whole Park, and a mean of 0.14 with a SD = 0.04 (Figure 4.4). These values showed a relationship to vegetation cover type; the highest values fell within the thick canopy-covered forest while the low values fell within cultivated areas, in area that were severely burned over, wetlands and open grasslands. Makkeasorn et al. (2006); McCleary (2013); Pettorelli (2013); Lillesand et al. (2014) have shown that dense vegetation/closed canopy vegetation have NDVI values between 0.3 to 0.8, shrubs and grassland range from 0.2 to 0.3, soils and bare land range from 0.1 to 0.2 and rocks/sand and barren areas range from 0.1 and below. Although the main focus was to assess biomass, it is clear that NDVI data can also be used to classify land cover in Nyungwe National Park by linking NDVI values to land cover classes.

Comparing the four vegetation indices used in this study (NDVI, NRVI, TTVI, and RVI), the results indicate that NDVI is positively correlated and it is the best of the four indices used with a correlation of 0.302, p=0.005, n=72 while RVI performed the least well with a correlation of -0.231, p=0.026, n=72. Table 4.3 presents Pearson correlations and a comparative analysis of the four vegetation indices used in this study.

Table 4.3. Pearson correlations and a comparative analysis of the four vegetation indices used in this study.

		ABG_Carbon	NDVI_F	NRVI_F	TTVI_F	RVI
Pearson Correlation	ABG_Carbon	1.000	.302	-.223	.226	-.231
	NDVI	.302	1.000	-.114	.119	-.126
	NRVI	-.223	-.114	1.000	-1.000	.997
	TTVI	.226	.119	-1.000	1.000	-.999
	RVI	-.231	-.126	.997	-.999	1.000
	Elevation_	.308	.486	-.063	.065	-.066
Sig. (1-tailed)	ABG_Carbon	.	.005	.030	.028	.026
	NDVI	.005	.	.171	.161	.146
	NRVI	.030	.171	.	.000	.000
	TTVI	.028	.161	.000	.	.000
	RVI	.026	.146	.000	.000	.
	Elevation_	.004	.000	.298	.295	.290
N	ABG_Carbon	72	72	72	72	72
	NDVI	72	72	72	72	72
	NRVI	72	72	72	72	72
	TTVI	72	72	72	72	72
	RVI	72	72	72	72	72
	Elevation_	72	72	72	72	72

Note: *ABG_Carbon –Above-ground carbon (kg)(measured), NDVI--Normalized Difference Vegetation Index, NRVI--Normalized Ratio Vegetation Index, TTVI--Thiam's Transformed Vegetation Index, RVI--Ratio Vegetation Index, Elevation – Altitude extracted from a 30m Digital Elevation Model (DEM), N – Number of samples*

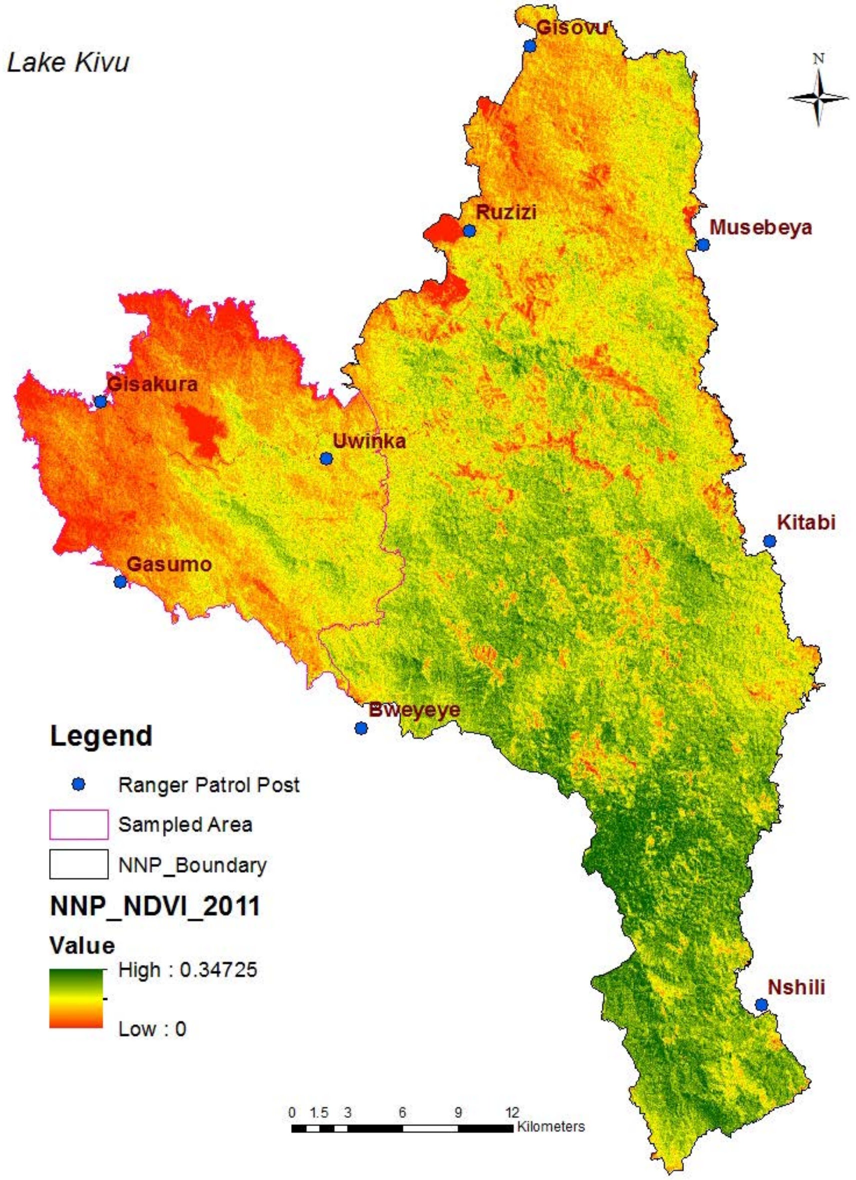

Figure 4.3. NDVI values based on 2011 Landsat TM in Nyungwe National Park, Rwanda. Orange to red areas have the lowest values while dark green areas have the highest values. The dark green areas represent thick forest cover, while the orange to red areas represent low net productivity such as rock outcrops, bare soil areas and drylands. Some of the areas with low NDVI values are cultivated areas and rock outcrop especially around Ruzizi area.

Relative dominance based on basal area indicates that the sampled forest is dominated by *Cleistanthus polystachyus* (Family: Euphorbiaceae), an understory tree identified as a Guineo-Congolian species which in some cases is considered to be an indicator of a transitional tropical forest (Lillesø et al., 2011) (Table 4.4).

Table 4.4. Relative dominance of top 26 trees and shrubs sampled in Nyungwe National Park, Rwanda.

Name	**Family**	**Form**	**Relative Dominance**
Cleistanthus polystachyus	Euphorbiaceae	tree	11.46
Syzygium guineense	Myrtaceae	tree	10.62
Strombosia scheffleri	Olacaceae	tree	9.62
Carapa grandiflora	Meliaceae	tree	9.10
Parinari excelsa	Chrysobalanaceae	tree	6.15
Chrysophyllum gorungosanum	Chrysophylloideae	tree	5.90
Symphonia globulifera	Clusiaceae	tree	4.17
Macaranga kilimandscharica	Euphorbiaceae	tree	1.56
Myrianthus holstii	Moraceae	tree	1.34
Newtonia buchananii	Mimosaceae	tree	1.07
Zanha golungensis	Sapindaceae	tree	1.00
Entandrophragma excelsum	Meliaceae	tree	0.89
Dichaetanthera corymbosa	Melastomataceae	tree	0.78
Garcinia volkensii	Clusiaceae	tree	0.78
Podocarpus latifolius	Podocarpaceae	tree	0.44
Cyathea manniana	Cyatheaceae	fern	0.39
Psychotria mahonii	Rubiaceae	tree	0.35
Alchornea hirtella	Euphorbiaceae	shrub	0.31
Chionanthus africanus	Oleaceae	tree	0.28
Polyscias fulva	Araliaceae	tree	0.25
Galiniera coffeoides	Rubiaceae	tree	0.24
Maesa lanceolata	Myrsinaceae	tree	0.23
Cassipourea rwandensis	Rhizophoraceae	tree	0.13
Cassipourea ruwensorensis	Rhizophoraceae	tree	0.06
Chassalia subochreata	Rubiaceae	shrub	0.04
Neoboutonia macrocalyx	Euphorbiaceae	tree	0.01

The open grassland sampled in this study generally had short grass mixed with herbs and short shrubs (Table 4.5).

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Table 4.5. Abundance of the top 10 tree/shrub species sampled in Nyungwe National Park, Rwanda.

Species	**Total Stem Count**	**Abundance**
Alchornea hirtella	414	0.162
Carapa grandiflora	178	0.070
Cleistanthus polystachyus	177	0.069
Syzygium guineense	175	0.069
Strombosia scheffleri	102	0.040
Macaranga kilimandscharica	67	0.026
Ficalhoa laurifolia	51	0.020
Symphonia globulifera	49	0.019
Chassalia subochreata	48	0.019
Rinorea gracilipes	48	0.019

Above ground carbon was estimated at $\bar{x}$ =93 Mg ha^{-1} (SD = 1.63) and ranged from 87 Mg ha^{-1} to 98 Mg ha^{-1}. Figure 5 shows distribution of above ground carbon in Megagram (Mg) per hectare (Mg ha^{-1}). The highest AGB carbon was found within areas that had the least ground exposure. Some areas sampled had scattered primary tree species but the understory formed a closed cover, and in turn the vegetation characteristics are reflected to the sensors, as opposed to those areas with scattered primary trees where the soil is exposed in some parts, which results in slightly lower AGB carbon readings. Although the wetlands were not measured, the advantages of using remotely sensed data apply even to those areas which were not physically visited including central parts of Kamiranzovu wetland which covers approximately 13 km^2 and is one of the largest peat bogs in Africa (Fischer & Killmann, 2008b; Kaplin, 2001). Within Kamiranzovu, the NDVI values translated to AGB ranging from 87 and 90 Mg ha^{-1} whereas the highest AGB value in forest cover areas was 98 Mg ha^{-1}. Figure 5 shows distribution of above ground carbon in Nyungwe National Park presented in Megagram (Mg) per hectare (Mg ha^{-1}).

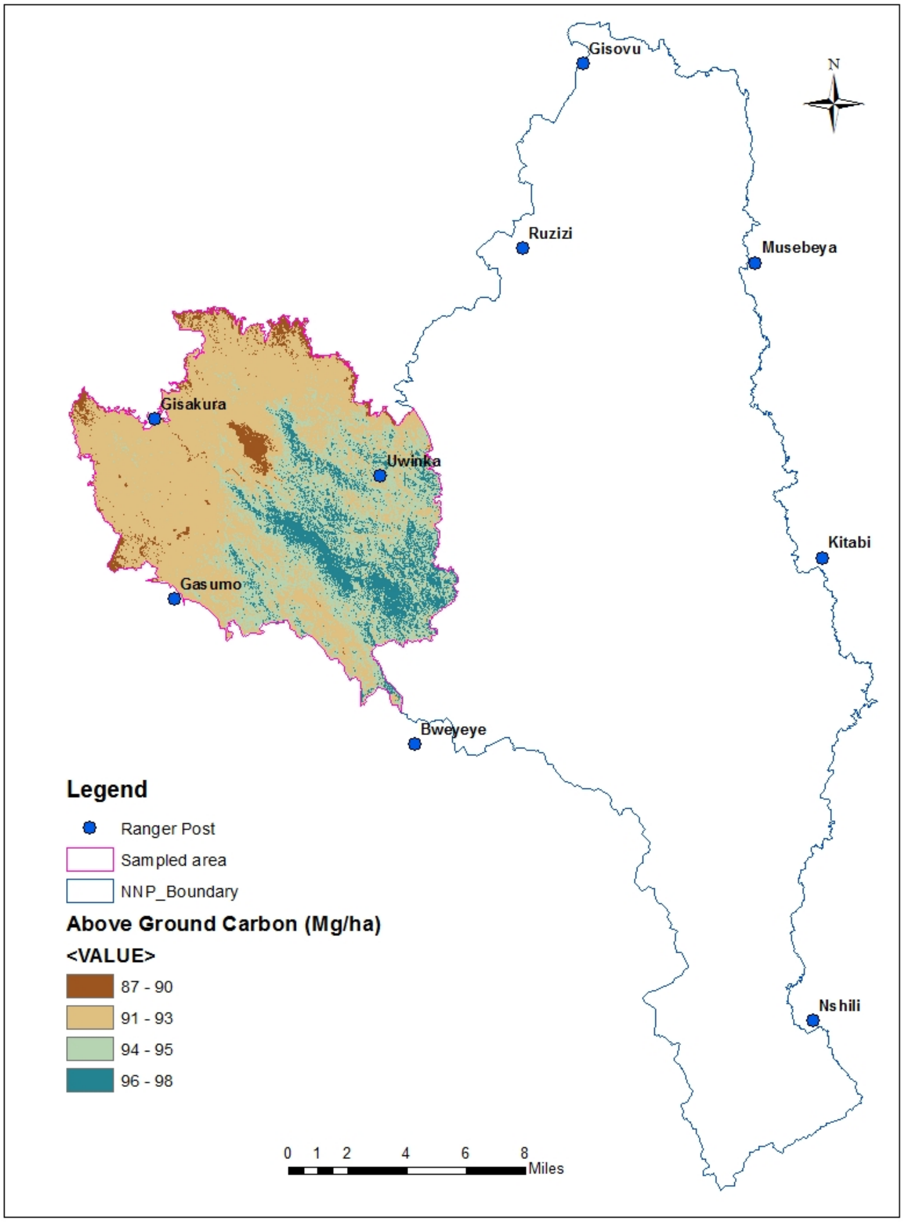

Figure 4.4. Distribution of AGB within Nyungwe National Park, Rwanda sampled area based on 2011 Landsat TM. The dark brown represents the lowest AGB and the dark blue/greenish areas represent the highest AGB. The edges of the Park area around Gisakura can be seen to have lower AGB values than the interior of the Park.

Discussion

Results from this study highlight some of the challenges of biomass and carbon estimation methods especially using NDVI in tropical montane forest. However, the lessons drawn from the study are a valuable resource for improvement in the next task or advice to others who plan to carry out similar study. Additionally, it is an important contribution for REDD+ planning where routine monitoring and assessment is a requirement for verification of the available carbon credits. Although the values for above ground biomass within the sampled area are related to NDVI, thus high biomass values correspond with high NDVI values and low biomass corresponds with low NDVI, the correlation obtained was much lower due to various possible factors described earlier in this chapter. There are numerous studies that show that there is a strong relationship between NDVI values and above ground biomass. However, the conditions in which this kind of relationship occur include a wide range of factors such as terrain, seasonality, sample size, image spectral and spatial resolution, and one time NDVI versus a time series NDVI (Huete et al., 2002; Zhu and Liu 2015; Pettorelli, 2013). AGB and NDVI yielded lower correlation which in part might be caused by effects of seasonality, sample size, terrain and shades in a rugged landscape with steep slopes. The presence of shadows and dense forest affect spectral reflectance which in turn affects NDVI values.

Edge effects were clearly shown where edge forest had lower NDVI values than the interior areas. The eastern part of the Park had on average higher NDVI values (NDVI $\bar{x}$ = 0.18) than the western part (NDVI $\bar{x}$ = 0.14). According to satellite data the eastern side of the Park shows dark red compared to the western side in a false color composite of 234 (BGR) bands of Landsat TM. This suggests that the eastern side has much greener vegetation than the western side and conforms to the NDVI values. However, the reason why the vegetation status differs is not clear. The NDVI reads the level of greenness and the deep green yields high NDVI values as opposed to brown or pale color reflectance such as unsurfaced roads or dry vegetation. Therefore, areas that show thick vegetation cover such as forest canopy, and understory and ground vegetation, play an important part when generating NDVI values (Fensholt et al., 2012; Huete et al., 2002; Nemanill, 1997; Pettorelli, 2013; Wang et al., 2003). The difference in absorbed and reflected energy from the vegetation depends on many factors including aspect, terrain, elevation, vegetation type, age and condition and spatial distribution of trees within a heterogeneous forest. In other words, NDVI measures greenness and not presence or absence of vegetation. For example when a deciduous forest loses all its leaves, the NDVI value reaches its lowest point whereas when a forest is regenerating the NDVI values increase.

Previous studies that estimated biomass in Nyungwe National Park using different methods yielded a wide range of results. The Woods Hole Research Centre used moderate resolution imaging spectroradiometer (MODIS) in combination with a large data set of field measurements to map woody above-ground biomass (AGB) across tropical Africa including Nyungwe National Park (Baccini et al., 2008). The results show that Nyungwe National Park AG biomass ranged from 0 to 317 Mg ha^{-1} which translates to AG carbon estimates ranging from 0 to 159 Mg ha^{-1} (Baccini et al., 2008). Two studies were carried out within an area of the park that is part of the area sampled in this study (Nsabimana 2008; Cohn 2011). Nsabimana (2008) found that above ground carbon range from 217 Mg ha^{-1} to 454 Mg ha^{-1} representing 57.3% of total carbon while Cohn (2011) found that above ground carbon ranged from 161 Mg ha^{-1} to 512 Mg ha^{-1} due to the presence of large diameter trees within the surveyed areas which contributed to high carbon values according to the author of that study. This study shows that using only trees with diameter larger than 2 cm yielded aboveground ground carbon ranging from 87 Mg ha^{-1} to 98 Mg ha^{-1} Two major factors affecting the results are low NDVI values compared to most parts of the Park and only stems with 2cm or larger were used to compute aboveground carbon.

Most of the fires in Nyungwe National Park occurred in the eastern side part of the Park, which in turn experienced extensive regeneration and development of thickets (a dense group of bushes or trees). The fire- affected areas in some cases were colonized by *Pteridium aquilinum*, commonly called bracken fern which creates a thick dense cover over soil; as a result there is reduced or no reflectance from soil recorded with red and Infra-red bands. On the other hand the western side has primary forest which has some openings where soil is either exposed or has sparse ground cover. However, the areas with an understory layer such as *Alchornea hirtella* and *Psychotria mahonnii* within the primary forest show higher average NDVI values. Although the large diameter trees yield large biomass, it is slightly different when using NDVI which depends upon level of greenness; thus areas with thick understory cover can yield high NDVI values especially when there is less or no reflection from soil which is common when trees are scattered and canopy is not closed (Fensholt et al., 2012; Huete et al., 2002; Nemanill, 1997; Pettorelli, 2013; Wang et al., 2003).

The process of estimating AGB using NDVI relies on the NDVI value to dictate the AGB value; however, when the NDVI value does not represent accurately what is on the ground uncertainty in AGB values is introduced. In many cases, the NDVI requires verification by ground measurements or statistical validation in order to make good sense of the resulting AGB estimates (Mundava et al. 2014; Gu et al. 2015; Congalton 2005;

Congalton and Green 2008). The correlation between the measured AGB and NDVI values may be higher if the sample size is greater, thus accommodating effects of shade and terrain.

AGB assessment for the whole National Park based on ground sampling takes significant time and resources. Remote sensing and GIS tools can facilitate assessment of the whole National Park in a given period with fewer resources. Although remotely sensed data can provide a lot of information, it is still important to verify data using field sampling methods or groundtruthing (Kamthonkiat et al. 2005; McCoy 2011; Congalton and Green 2009; Lillesand et al. 2004). In this study, reconnaissance of the whole Park and sampling of the western part of the park, specifically the Gisakura-Pindula-Bweyeye and Gasumo areas and utilization of 25cm colour orthophotos allowed verification of the remotely sensed data.

The field work provided a basis to validate the remotely sensed analysis and the data were linked statistically by regression analysis to evaluate their relationship and extend the estimation to the whole Park. However, the use of NDVI as a means of estimating AGB requires knowledge of the sensor used to capture the images, ground condition that can affect the anticipated results and understanding of the processes and systems involved in the appropriate generation and use of NDVI. Secondly, various authors (Brantley, Zinnert, & Young, 2011; Gu, Wylie, Howard, Phuyal, & Ji, 2013; Pettorelli, 2013; Viña, Henebry, & Gitelson, 2004) have argued that NDVI values tend to saturate within dense forest. This means that the NDVI readings at a certain point become unstable with the estimation.

Although NDVI has been known to saturate when working in high-density canopy cover areas (Pettorelli et al., 2005; Huete et al., 2010; Clark et al., 2011; Vescovo et al., 2012) it is a useful tool when working with remotely sensed data to derive information when estimating biomass and other reflectance-based parameters in vegetation analysis. In

Nyungwe National Park the optical images are affected by cloud cover typical of the montane tropical forest, making it difficult to find images for a particular time of the study. Some scenes might have less than 10% cloud cover which is a recommended ratio, but the clouds typically cover the protected area or the area of interest while in some scenes clouds might be scattered all over the scene.

During reconnaissance, I used the 2009 orthophotos which provided good visualization with a spatial resolution of about 25 cm. Orthophotos are mosaicked from aerial photographs which are ortho-rectified (Aggarwal, 2004; Gentili, Giusti, & Pizzaferri, 2002; Medioni, Wilson, Prohaska, & Poretta, 1989). These kind of data require specialized processes and tools to handle the issues of spectral characteristics, making it difficult to use regular algorithims in classifying the images. Although color orthophotos are a great data source to the conservation community, there are serious limitations in terms of how fast they can be used in an automated analysis. Alternatively, orthophotos offer a great source for visual interpretation of landscapes and a basis for creating classified vector maps by manual vectorization which is a tedious and time consuming process.

The lessons learnt in this study form a practical knowledge base that can help when planning and executing REDD+ monitoring and verification projects within protected areas. According to WCS (2012), various activities in line with REDD+ preparation tasks have been carried out including biomass assessment although nothing done in western part of the Park, assisted regeneration in areas that were colonized by *Pteridium aquilinum* and the Park secured an agreement to market carbon from assisted regeneration areas. Monitoring and verification of carbon stocks within assisted regeneration areas was carried out (Mulindahabi 2012) and general mapping of the forest cover.

Mapping forest cover when there are not enough resources is best done using integrated and mixed methods such as linking field surveys with remotely sensed image analysis. When linking remote sensing data and field surveys for forest resource inventory, especially in tropical montane forest with steep slopes dense vegetation cover, it is advisable to use at least three times larger sample plot to the satellite image spatial resolution and optimum sample size depending on margin of error. REDD+ preparedness for Nyungwe National Park can include strategic and action plan in order to reduce emissions and deforestation and degradadation.

Most threats are known in Nyungwe (Mulindahabi et al. 2012; Plumptre et al. 2002); however, there is need to list all possible drivers and causes of deforestation or degradation so that mitigation and proper monitoring and verification methodology can be well designed. Some of the drivers and causes of deforestation are measured directly while others are indirectly. Considering that the conservation policy followed by Nyungwe National Park does not include afforestation programs, therefeore the plans should increase protection against threats with the hope of natural regenerartion to reafforestate the deforested areas. Mitigation can include assisted regeneration, increasing patrols and protection against known threats, improving sustainable food production and soil fertility conservation, expand on electricity grid to most of rural areas especially those closer to the protected areas and promotion of sustainable development using low emission technologies (GoR 2014). The impact of human activities within the protected area can not be completely stopped although the conservation management policy followed does not allow any form of resource use from the park.

Conclusion

Mapping forest carbon using combined methods has proved to be a cost-effective means of assessing large areas when there are limitations in terms of time and money (Lillesand et al. 2004; Hatfield et al. 2008; Campbell 2002; Gibson 2013; Lillesand et al. 2014). This study benefited from using remote sensing and GIS tools for biomass estimation and carbon mapping especially when dealing with places that are either under armed conflicts or sensitive areas like common political boundary area or areas that have restrictions in access. The best estimate for biomass and carbon from a protected area is by empirically destructive method in which sample trees are cut, dried and weighed to obtain biomass estimates, however, remote sensing approach is used to protect the trees and vegetation. In this study, I considered only aboveground stems larger than 2cm. The errors generated with remote sensing data analysis which include data quality and type, resolution, georeferencing and resampling issues and the algorithims used to process. There are methods to minimize errors in the process such as using acceptable root mean square error (RMSE) when georeferencing a satellite image (Eastman 2009).

Although remote sensing has been used widely in biomass and vegetation cover mapping (Foody et al., 2001; Zheng et al., 2004; Lu 2006; Gallaun et al., 2010), I would argue that it is still not possible to assess biomass virtually without field sampling. However, when field sampling is coupled with remote sening approach, the expected remotely sensed results are improved in accuracy.In this study, the estimates are for only stems that were measured for the above ground biomass estimation. My approach did not cut and dry weigh the biomass, it was what can be called a hybrid approach using estimated allometric equations and linking to remotely sensed NDVI. However, the results are a useful estimate of how much carbon we have in the forest at a given time. Field measurements provide ground verification data for remotely sensed vegetation indices. Secondly, by avoiding the cutting of trees for weighing and measurement of oven-dried matter, the method avoids destroying what we are trying to conserve. Although the remote sensing approach is economical in deriving AGB information for a given area, the process cannot be complete without some sort of field measurements either to validate the data or provide parameters for estimating AGB.

In this study, insufficient data, small sample size and the rugged steep terrain together with amount of shadows in remotely senses data in the study area might have affected the correlation between measured above ground biomass and NDVI values. Although some models can be generated that do not require ground based measurement to estimate AGB, for these models to provide useful information, more ecological studies as well as remote sensing technological studies are needed to feed data into the models. This study highlights some of the lessons in planning for routine monitoring and verification of forest carbon as part of preparation REDD+.

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Chapter 5: Assessment of REDD+ preparedness in Rwanda focusing on Measurement, Monitoring, Reporting and Verification (MMRV)

Abstract

Developing a successful Measurement, Monitoring, Reporting and Verification (MMRV) system is a preliquisite for a successful REDD+ program. Prior to becoming a REDD+ country, countries are obliged to prepare by developing tools and policies that promote REDD+ goals and engaging local communities, community based organisations (CBOs) and local non-governmental organizations (NGO's) in REDD+ policy development and pilot projects. Rwanda REDD+ preparedness has made some progress considering that several policies focusing on REDD+ and climate change mitigation and adaptation have been developed. I evaluated REDD+ preparedness in Rwanda focusing on Measurement, Monitoring, Reporting and Verification (MMRV) system. Three capacities considered for assessing preparedness in this paper were (a) Remote sensing and GIS capacity, (b) Carbon pool inventorying capacity and (c) Baseline, intervention and monitoring capacity. Using available literature, I evaluated REDD+ MMRV preparedness in Rwanda. Rwanda has higher capacity and readiness in remote sensing and GIS than in forest inventory and carbon pools inventory. The availability of data and training institutions that teach basic remote sensing and GIS creates a recommendable capacity that can be involved in establishing MMRV. There is need to recruit and train more scientists and to expand in sampling sites for all five carbon pools in most parts of the country. Currently, studies are more concentrated within protected areas, and research sites managed by the Rwanda Agriculture Board (RAB).

Key words: carbon pool, Measurement, Monitoring, Reporting and Verification (MMRV), Preparedness, REDD+

Introduction

Forests play a critical role in mitigating climate change and environmental degradation (Anderegg et al., 2013; Giurgiu 2010; Harris et al., 2012; Prior & Heinämäki 2017). Reducing greenhouse gas emission can be enhanced by reducing deforestation and increasing sustainable afforestation and restoration program. Takacs (2012) argued that tropical deforestation contributes about 15-20% of global greenhouse gas emissions. Reducing emissions from deforestation and degradation (REDD+) was initiated through the United Nations Framework Convention on Climate Change (UNFCCC) as a key strategy for increasing the carbon stock and mitigating climate change (Corbera and Schroeder 2011). The initiative includes sustainable management of forests, restoration of degraded forest areas and community motivation through compensation for maintaining a forest for a given period of time. The REDD+ mechanism cannot succeed without effective monitoring of forest cover change, forest carbon stocks, and associated greenhouse gas (GHG) emissions and removals. Therefore measuring and documenting changes and impacts and replicating results is a focus in the monitoring REDD+ mechanism (Baker et al., 2010). The establishment of a Monitoring Measurement, Reporting and Verification (MMRV) system that works efficiently and effectively is a high priority in REDD+ preparedness. MMRV is used to track REDD+ performance and serves as a decision making tool when processing results-based payments.

Establishing a national forest monitoring system requires capacity (technical and human resources) and operational resources (funding and legal mandates). MMRV systems are data dependent and therefore can be analyzed by examining existing data from previous projects, national submissions to international organizations such as Convention on Biological Diversity (CBD) and UNFCCC, and other national reports (Joseph et al. 2014). In most cases, these reports and communications act as a source to identify gaps and deficiencies in capacity and data (Romijn et al 2012). Most MMRV systems are dependent on collaborations and partnerships to meet obligations and duty mandates such as measuring carbon emissions and lack of technical capacities, financial resources, established protocols and human resources. Some MMRV systems are project based while others span multiple projects. However, an effective MMRV system has to satisfy certain criteria in terms of capacity, which might include technical resources and methodological approach (Takacs 2012, Merger et al. 2011).

According to Joseph et al. 2014, a functional MMRV system can be evaluated using three categories: (a) Remote sensing and GIS capacity, (b) Carbon pool inventorying capacity and (c) Baseline, intervention and monitoring capacity. Remote sensing and GIS capacity focusses on availability and coverage of data, human and technical resources to manipulate data to produce meaningful products such as spatial forest and land cover maps and statistics for developing baseline reference information for monitoring REDD+. Monitoring and mapping forest cover is one of the basic requirements for assessing changes in carbon emissions and removals and relies on remote sensing and GIS capacity. Carbon pool inventorying capacity focusses on capabilities to map out the impacts of deforestation upon the five carbon pools, namely; (i) above-ground biomass (AGB); (ii) below-ground biomass (BGB); (iii) dead wood; (iv) litter, dead organic matter (DOM); and (v) soil organic matter (SOC) (IPCC, 2006). Additionally, understanding the drivers of deforestation and being able to incorporate them when developing monitoring models and strategies to monitor carbon emissions Baseline, intervention and monitoring capacity focusses on generating baseline or reference information or models that are a key source of information in developing effective intervention plans and successful monitoring strategies. Finally, a meaningful and successful

MMRV system depends on coordination and collaboration in a transparent manner with all stakeholders including government and non-governmental organizations, local and international organizations, research and academic organizations, local communities, and industry and business communities.

Lack of measurement standards and expertise, together with lack of resources to periodically assess forest cover might be a source of inaccurate estimation of forest status in some countries (Romijn et al. 2015, Westinga et al. 2013). A plan must be in place to assess forest cover periodically. When considering specific forest cover assessments for REDD+, it is important to have a clear understanding of the drivers and causes of deforestation, incorporated in the MMRV system that in turn help in designing mitigation measures. In recent years, the use of remote sensing and GIS as a tool to assess forest cover has greatly increased. While remote sensing analysis shows changes and where those changes occurred, linking remote sensing analysis to socio-economic and ground-truthing studies help to establish the causes or drivers of change (Haan et al. 2000; Mlotha 2001; Lambin et al., 2003; Lambin 2004). Although remote sensing helps overcome challenges of monitoring and measuring forest cover change for carbon emission, there are limitations associated with the fact that some emission factor data and activity data cannot be easily acquired using ordinary remote sensing technics (De Sy et al 2012).

This chapter assesses REDD+ preparedness in Rwanda focusing on the Measurement, Monitoring, Reporting and Verification (MMRV) system. Rwanda is not yet a REDD+ country, however the Government of Rwanda has increased the fight against deforestation and environmental degradation by developing plans that reduce deforestation such as introduction of alternative energy sources, improved cooking stoves, biogas in prisons, increasing natural gas usage by introducing gas stoves and discouraging charcoal traders by raising taxes (GoR 2006; GoR 2012). As a country, Rwanda has increased the effort to reduce deforestation and enhance carbon stocks and has revised most of the necessary policies and laws in support of climate change mitigation. The country is in the midst of submitting a preparedness proposal to the REDD+ Secretariat (GoR 2014). Main environmental problems in Rwanda include loss of soil fertility due to lack of agricultural rotation which is mostly caused by shortage of land (GoR 2003; Chemonics International 2008; GoR 2009). Population densities in Rwanda are one of the highest in the region. A 2012 analysis of population density estimated 415 inhabitants per square kilometer (NSIR 2012) and in 2016 the density was estimated at 483 inhabitants per square kilometer (Knoema 2017). Domestic energy especially in cities is dominantly charcoal and firewood, which drives deforestation patterns (Chemonics International 2008; GoR 2009). Rwanda faces many challenges in its efforts to reduce deforestation and environmental degradation, in part due to the steep terrain of the country, rainfall intensity, and reliance on firewood and charcoal for fuel among a majority of the population.

Methods

Country Description

Rwanda is a country known as the land of a thousand hills. It is located between 1^{0} 04’ and 2^{0} 51’South of equator, 28^{0} 45’ and 31^{0} 15’ East of Greenwich Meridian, and shares borders with Democratic Republic of Congo (DRC) in the west and north-west, Uganda in the north, Tanzania in the east and Burundi in the south. The country is divided into 30 districts, which are located in five provinces: Eastern Province, City of Kigali, Northern Province, Southern Province and Western Province (GoR, 2006). Elevation ranges from about 3,116 ft.

(950 m) located within the southwestern side (along Rusizi River) and 14,826 ft. (4,519 m) located in the Northern Province on Karisimbi within Virunga's volcanic mountains. Energy sources for domestic and industrial development include hydro-electric power supply, solar, methane gas mostly extracted from Lake Kivu, biogas mostly used in institutions like prisons and charcoal which is mostly used for domestic energy supply especially in urban centers. However, only about 8% of the rural areas have access to electricity and about 25% of the country has access to electricity (World Bank 2015) which the government projected to increase to 70% by the year 2017 (Baringanire et al., 2014; GoR 2016). Approximately 70% of the population depends on rain fed agriculture that means the country is vulnerable to climate change (World Bank 2015). It is one of the most densely populated countries in central Africa estimated at 507 people per Km^2 (Worldometers 2017). Land holdings have been reducing as population grows consequently food production to feed the growing population is not enough, and the country supplements by importing some food commodities including maize flour and tinned food (WFP 2015; GoR 2014; Weatherspoon et al., 2017; Habyarimana 2015).

Forest cover types in Rwanda are composed of natural forests and plantations, which include woodlots and agroforestry fields. Recent estimates suggest that forests cover about 16% of the dryland of Rwanda (Nduwamungu et al. 2013), an increase from about 10.1% in 2007 (GoR 2005, CGIS-NUR 2007, GoR 2007). As a densely populated country, large blocks of forest are found in protected areas or plantations. The protected areas are used for both conservation as well as tourism. The Ministry of Commerce (MINICOFIN) through Rwanda Development Board (RDB) and partner NGOs manage the four National Parks in Rwanda, including Volcanoes National Park (VNP) in the north, Gishwati-Mukura National Park

(GMNP), Akagera National Park in the east, and Nyungwe National Park (NNP) in the southwestern part of the country. Additionally there are forest reserves managed by the Ministry of Lands and Forestry through the Department of Forestry and Nature Conservation (DFNC); these reserves are not developed for tourism, and they do not have income generating activities. In some cases, communities access the reserves and collect some resources for livelihood as opposed to the national parks. However, the new Forest law prohibits collection of any forest resources in forest reserves (GoR 2010). *Eucalyptus* species account for over 85% of all species found in plantations in Rwanda (Nduwamungu et al. 2013). While Rwanda is within the Afromontane forest zone, savanna woodlands dominate the eastern part of the country towards the Tanzanian border, where Akagera National Park is located. According to Nduwamungu et al. (2013), the districts adjacent to Nyungwe National Park, within the western part of the country have the highest percent of forest cover compared to other parts of the country. All the country's National Parks except Akagera National Park are located within the western part of the country (Refer Figure 5.1).

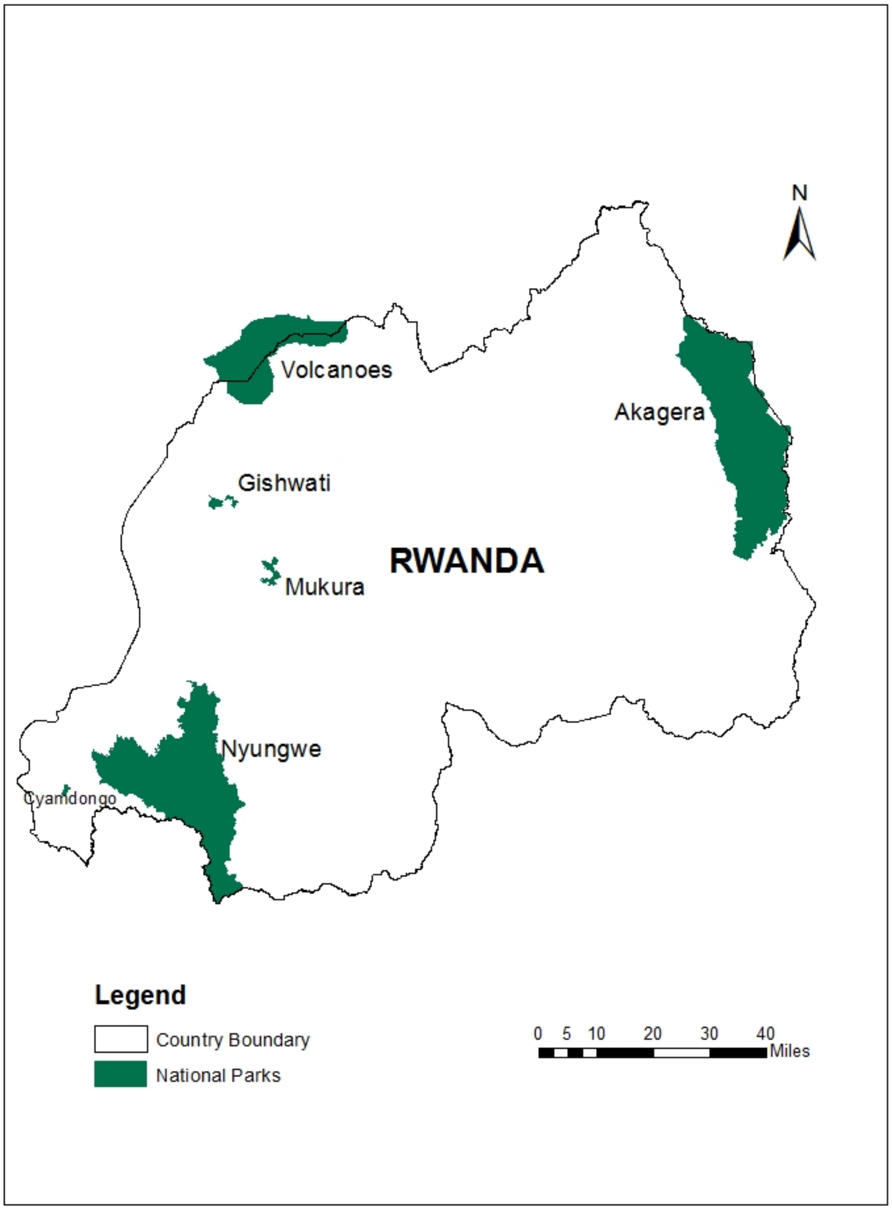

Figure 5.1. Map of Rwanda showing the National Parks.

International Treaties and Related Policies

Rwanda is a signatory to many international conventions and protocols but for this study, only those related to reducing deforestation and improving sustainable conservation and utilization of biodiversity which in turn promote goals and objectives of REDD+ and climate change. These are:

1. United Nations Convention on Combating Desertification (UNCCD), signed in 1995
2. United Nations Framework Convention on Climate Change (UNFCCC), signed in 1998
3. Kyoto Protocol to the UNFCCC, signed in 1998
4. United Nations Convention on Biological Diversity (UNCBD), signed in 2000
5. Vienna Convention for the Protection of the Ozone Layer, signed in 2001
6. The Central African Forest Commission (COMIFAC)
7. Cartagena protocol – this deals with biodiversity, genetic resources, invasives, signed in 2000

Following a famous United Nations Conference on Environment and Development (UNCED) commonly known as Earth Summit, was held at Rio de Janeiro, Brazil (June 3–14, 1992), to reconcile worldwide economic development with protection of the environment, countries increased their efforts to manage the environment as they pursuit economic development. Rwanda like many other countries revised old policies and initiated new policies as a commitment to pursue economic development in ways that would protect the Earth's environment and nonrenewable resources (Parsons et al., 1992). There are several actions that have been completed at national level in cluding the Nationally Appropriate Mitigation Actions (NAMA) and the Clean Development Mechanism (CDM) in 2006 and released the Green Growth and Climate Resilience National Strategy for Climate Change and Low Carbon Development in October 2011 (GoR 2011). The Strategy aims to build upon work done in Rwanda on climate change mitigation and adaptation and has led to a review of policies, laws and strategies for climate change mitigation and adaptation.

Most policies and laws in Rwanda have been revised in order to accommodate the need for enhanced management of environment and mitigation of climate change through sustainable development and natural resource management. Rwanda, as one of the fastest developing countries, needs to tackle the growing emissions which are part of economic growth and development (IISD, 2013). The task to reduce carbon emission cannot be successful without a complete reform of all sectors including energy sector, conservation of natural resources sector, agricultural and food production sector, industry and transportation, development and socio-economic sector. Table 5.1 presents some of the relevant policies and laws of Rwanda in relation to REDD+ and climate change mitigation.

Table 5.1. List of policies and laws that have been either revised or created in order to include climate change mitigation in Rwanda.

No.	Description	Year	Comments
1	Rwanda Environmental policy	2004	Various laws were generated including the law that created Rwanda Environment Management Authority (REMA) and law banning plastic bags
2	Rwanda National Forestry policy	2004	
3	Rwanda-National Adaptation Programs of Action to Climate Change	2006	
4	Rwanda Energy policy and National Energy Strategy	2008	
5	Rwanda Biodiversity policy	2011	
6	Establishment of Climate Change and International Obligations Unit in REMA	2009	
7	Rwanda's National Strategy for Climate Change and Low	2011	

	Carbon Resilience Development		
8	Rwanda Wildlife Policy	2013	
9	Rwanda National Forestry Law No. 47bis/2013	2013	
10	Rwanda Environment and climate change policy brief	2013	Draft

Relevant Projects and studies

Rwanda had implemented various projects as part of the fight against deforestation and environmental degradation. The projects contributed to Nationally Appropriate Mitigation Actions (NAMA) and climate change strategy in part to improve afforestation and sustainable utilization of forestry resources. Some of those projects include: Rwanda Sustainable Woodland Management & Natural Resources (CBF Fund/AFDB), Rwanda Forestry Management Support Project (AFDB), Forest Landscape Restoration Opportunity Assessment for Rwanda (IUCN), Landscape Approach to Forest Restoration & Conservation (World Bank), Support to Participatory Forest Management Pilots and Biomass Energy Production in 15 Districts of Rwanda" (PAREF NL1&2) (Kingdom of the Netherlands & the Belgian Development Agency (BDA)) and Assisted natural regeneration for forests in Nyungwe National Park through removal of bracken ferns *(Pteridium aquilinum (L) Kuhn.)* fire prevention and fire fighting and promotion of alternative livelihoods for local communities (Durschinger 2011; WCS 2015). These projects generated valuable information, which forms an important source of knowledge contributing to a progressive MMRV system due to the training component and the optimum goals of those projects. Restoration projects focused mostly on degraded land while other projects covered a wide range of areas including agroforestry, soil conservation, afforestation, monitoring and evaluation, energy resources management, sustainable utilization of forestry resources and community training in conservation and sustainability.

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National Forest Mapping

Rwanda has carried out three different national forest mapping exercises in 2005, 2007 and 2012 (Nduwamungu et al., 2013). With the help from Dutch Government through Netherlands Universities Foundation for International Cooperation (NUFFIC) and University of Twente ITC, in collaboration with, the Center of Geographic Information Systems and Remote Sensing (CGIS) at the National University of Rwanda and the Rwanda Agriculture Board (RAB), first forest mapping was carried out in 2005. During that time, Rwanda Agriculture Board (RAB) through the forest research unit carried out field forest inventory, sampling and measuring trees in the field while the CGIS and University of Twente ITC used remote sensing and GIS to classify forest cover from satellite images (Westinga and Lasry 2006). The 2005 forest mapping used eight forest classes (Westinga and Lasry 2006). Here are the classes used in 2005 forest mapping:

1. Humid natural forest
2. Dry natural forest
3. Eucalyptus plantation forest
4. Pine plantation forest
5. Young forest plantation or coppices
6. Bush (natural forest thickets)
7. Bamboo forest
8. Bush ridge forest

In 2007, the Ministry of Lands and Natural Resources asked for an updated forest cover map hence the 2005 forest cover map was revised. During the 2007 mapping, RAB carried out a forest inventory and CGIS carried out satellite image classification. The forest cover map generated by CGIS through image classification and the results of the forest inventory by RAB were used to produce a 2007 forest cover map. The methodology and classification categories did not change much during subsequent mapping. The 2007 mapping used a combination of satellite data, including Aster (15m spatial resolution), Landsat Thematic Mapper (30m spatial resolution) and SPOT multispectral (20m spatial resolution). With the difficulties to find cloud free images, mapping was done using different sensors, which are also different in spatial and spectral characteristics.

The 2012 mapping used color orthophotos, (25cm spatial resolution) derived from aerial photographs by the Swedish Survey (2008/2009) (Nduwamungu et al 2013). Image processing and interpretation was done at the CGIS while RAB carried out forest inventories. The minimum mapping unit in 2007 was 0.5 ha while in 2012 the minimum mapping unit was 0.25 ha. The classification did not change between the two dates. The difference of the two map sets is drawn from the data used for image processing, thus 15 to 30m resolution for 2007 and about 25cm for 2012. The 2012 mapping included a class of shrubs into forest class considering contribution of the class to forest carbon and biomass assessment (Nduwamungu et al 2013) and this increased the forest cover percentage for the country. These three forest cover maps provide a basis to establish monitoring deforestation and carbon emission.

Evaluation approach

Baker et al. (2010) argued that countries joining REDD-plus need scientifically robust forest carbon estimates, probably Tier 3 based on IPCC scale, with an MMRV system that provides consistent results that meet international standard accuracy. For Rwanda, it would be difficult or impossible to start with this high a level of accuracy, although after gaining experience it would be possible to progress from Tier 1 to Tier 2 then to Tier 3. In order to assess country MMRV system preparedness, I considered three broad categories as described in Joseph et al. (2013). The functions of a MMRV system can be divided into these three broad categories: (a) Remote sensing and GIS capacity, (b) Carbon pool inventorying capacity and (c) Baseline, intervention and monitoring capacity. Each of the three broad categories was further subdivided into three categories: Data, Tools/methods/models and In-house capacity/human resources expertise, then these were again subdivided further depending on condition that there was still room to further subdivide the categories for evaluation purposes.

Remote sensing and GIS capacity

Data resources

When evaluating remote sensing data for MMRV, I considered six important factors: (a) data availability, or whether data are easily accessible either with or without cost; (b) data coverage, or whether data covers the whole country or parts of the country; (c) data resolution (Spatial, Temporal and spectral), including pixel size and presence of a routine cycle of data capture (e.g., Landsat data cycle is every 16 days) and number of bands or channels; (d) data quality and clarity (most high elevation areas tend to have weather that brings frequent cloud cover, while acceptable images for certain analyses need to be at least 10% cloud free); although atmospheric restoration can be done, it is important that an image is clear for use; (e) how many points in time are data available; multiple data points over time allows change detection and if more than two points in time data are available, baseline model can be developed to detect trends of change; (f) archiving and use of a clearinghouse mechanism for organized access to data for either replicate studies or other uses within MMRV systems.

Tools, methods and technical resources

Adequate remote sensing and GIS software and hardware need to be available for effective monitoring systems. With advancement in computing technology, large amounts of data can be handled and processed to solve complex analyses (Chen and Zhang 2014). Consequently, remote sensing and GIS processing software have been improved with more capabilities to manipulate large amounts of data at remarkable processing speeds (Mustafa and Zhong, 2014). The list of remote sensing and GIS software has increased since the 1990s, with more free software being developed. In this evaluation, I considered some of the most common programs that can be used for image processing to analyze and model vegetation cover changes. These image processing and GIS software include ArcGIS, ERDAS Imagine, IDRISI, ENVI, MapINFO, and TNTmips. The free image processing and GIS programs include Quantum GIS (QGIS) by Open Source Geospatial (OSGeo) Foundation, Oregon, USA, The Integrated Land and Water Information System (ILWIS) developed by (ITC) Faculty of Geo-Information Science and Earth Observation of the University of Twente, Netherlands; Geographic Resources Analysis Support System (GRASS GIS) developed as a project of the OSGeo Foundation. Most of the remote sensing and GIS programs include multivariate analysis capabilities that are important in algorithms to classify and model forest cover change or levels of biomass and carbon from remotely sensed data (Wang et al. 2010).

Human resources

Human capacity to develop and maintain monitoring systems is crucial. The target is to have internal capacity to manipulate remote sensing data and carry out GIS work to implement routine monitoring and data analysis for the MMRV system. In this regard, it is important that members of REDD+ MMRV teams have at least remote sensing and GIS capability to understand and interpret remote sensing and GIS results or models and ability to create such products from raw data. The most important capacity is to model and classify correctly the satellite images for carbon mapping. Depending on organizational structure, it is important that MMRV both at headquarter level and at district level should have remote sensing and GIS capacity; however the headquarters must have advanced capacity to lead and guide the districts while the districts should be prepared to have such understanding and knowledge to analyze and interpret models. Similarly, when proposing REDD+ projects, technical specialists in remote sensing and GIS should be considered at the beginning of the project and continue monitoring until after the project ends.

Carbon pool inventorying capacity

IPCC guidelines stipulate that capacity exists to inventory and map carbon pools, and to assess the impacts of deforestation upon the five carbon pools: above-ground biomass (AGB), below-ground biomass (BGB), dead wood, litter, dead organic matter (DOM), and soil organic matter (SOC) (IPCC, 2006). Research to develop allometric equations and volume tables have concentrated to a greater extent on production forest species rather than indigenous forests, and as a result most indigenous forest tree species do not have allometric equations. In order to compute accurate volumes, biomass and carbon from trees, allometric equations are vital in most calculations (Chave et al., 2014). Indigenous forests such as tropical Afromontane forests are comprised of numerous tree species from many different families. The task to develop allometric equations requires long term studies through which tree growth is linked to soil and environmental conditions and requires understanding taxonomy and phylogeny of the species (Jara et al. 2015: Huy et al. 2016).

Baseline data for Estimation of Greenhouse Gas Emissions (GHGs) in Rwanda

An MMRV system is data driven and requires reference data and time series or baseline data for estimating emission and removals of GHGs. The Second National Communication (SNC) to UNFCCC (GoR 2012) provides insights about some of the baseline data compilation in Rwanda. However, the SNC argues that Rwanda does not have a methodology of its own to generate the GHG emission estimates and data uncertainty is as high as 40 percent (GoR 2012). Although several studies (Boden et al 2009; GoR 2012; Stiebert 2013; CAIT Climate Data Explorer. 2015; Faostat 2015) have presented estimated GHG emissions for Rwanda, there is a need to establish baseline data for estimation of GHGs emission and removals with high accuracy. Most Rwandan research centers do not have complete assessment of emissions due to lack of data and existing models to replicate (Stiebert 2013). International Institute for Sustainable Development (IISD) carried out a study using FAO (2010) data to establish baseline for GHG emissions in Rwanda. I would argue that a detailed study should be done in order to establish baseline data with high accuracy. Models require good data for validation, which is long term data collection, is important in order to develop a baseline of GHG emissions and model development.

Status of country’s preparedness

Rwanda is currently waiting for approval from UN-REDD to launch REDD+ MMRV project, with the assumption that it will rely on human resources available in collaborative institutions and stakeholders, including partners that participated in previous forest inventories, carbon research projects and GHG emissions analysis programs. Plans are in place to recruit suitable people for all required sections as leaders in their fields while working with staff from the Ministry of Lands and Forestry, Department of Forestry and Natural Resources, District Forest Offices, University of Rwanda and research institutions such as Rwanda Agriculture Board. The team can benefit from the current District Forest Office staff who have completed courses in remote sensing and GIS during their University study and those who have worked in districts with projects that included capacity-building programs in GIS and remote sensing. For example, District forest staff in 15 out of 30 districts completed some courses in GIS through the capacity building component of the Participatory Forest Management Pilots and Biomass Energy Production project (PAREF) funded by the Government of Rwanda, Kingdom of Belgium and Kingdom of Netherlands (Habimana, 2017). The University of Rwanda's CGIS, founded in 1999 to enhance regional capacity in conservation science and related technologies and to provide support in teaching, learning, research, management and community development remains a major source of human resources in geoscience research (Shilling et al 2005). CGIS supports all faculty and colleges of University of Rwanda in teaching GIS and remote sensing as part of geoscience human resource development in the country.

The most recent available high-resolution data covering the country of Rwanda are the 2009 color orthophotos created by the Swedish Survey from color aerial photography with approximately 25cm spatial resolution (Nduwamungu et al. 2013). The data are archived at the Rwanda Land Management and Use Authority. These high-resolution 2009 orthophotos are available for only one point in time, which makes it low quality in terms of performance indicators. Landsat (30m spatial resolution) and ASTER (15m spatial resolution) data are available for several points in time and can be downloaded free of charge from several websites, including the United States Geological Survey (USGS), Global Visualization Viewer *(*GloVis*),* EarthExplorer (EE), the Land Processes Distributed Active Archive Center (LP DAAC), the Global Land Cover Facility (GLFC) of University of Maryland and NASA/Japan/Jet Propulsion Laboratory (GISGeography, 2017). Cloud cover is a major problem affecting most Landsat and ASTER images for Rwanda; however, there are few clear days in some months. In addition to the 2009 aerial surveys conducted in Rwanda, there were three surveys conducted in 1959, 1974 and 1980; however, 1980 covered only urban areas (Royal African Kings Museum, 2007).

As mentioned earlier, most of the remote sensing and GIS software programs are capable of doing most of the MMRV required work. These programs vary in cost and operability but the bottom line is if they can do the intended tasks, they can be considered for MMRV system. Furthermore, other programs can be acquired either free or with a charge, or at a reduced price through partnerships and affiliations. ArcGIS is a common example in Rwanda because of the ESRI/Government of Rwanda and University of Rwanda partnership through which most GIS trainings are conducted using ESRI products. ILWIS and QGIS are freely available for MMRV and ERDAS Imagine is considered important but the cost is prohibitive.

Most of natural forest tree species do not have allometric tables, despite that natural forests represented 33% of forested areas by 2007 mapping. Henry et al. (2011) compiled allometric equations for sub-Saharan tree species including those of Rwanda. The study was in response to the growing interest in estimating carbon stocks in forests as part of REDD+ programs and the equations were incorporated into an open-access database on the

Carboafrica website (http://www.carboafrica. net). According to Henry et al. (2011) there are 22 equations for five tree species of Rwanda, which are all non-native forestry species.There is need to develop specific allometric equations for most of the tree species found within Rwanda natural forests. MINIRENA/RAB (2008) presented volume models of major plantation tree species in Rwanda but nothing for natural forest. The species with volume models include: *Pinus spp., Callitris robusta, Grevillea robusta , Acacia melanoxylon , Eucalyptus spp. (High forest) , Eucalyptus spp. (Coppice) , Eucalyptus spp. (Coppice with standards).* Generalized allometric equations (Chave et al. 2005; Chave et al. 2014) are used to estimate biomass and carbon due to lack of allometric equations for natural tree species in Rwanda. However, it would be much more precise and accurate if the allometric equations were developed based on Rwanda conditions.

The SNC represent most of the reference data, which was used to generate projections of GHG emissions in Rwanda. Few sources present estimates of GHG emissions and removals in Rwanda. The estimates are compiled from various sources using different methods and time period. Some of these GHG emission data sources include World Resources Institute (WRI) website (CAIT Climate Data Explorer. 2015) which presents data for Rwanda for the period from 1990 to 2013. Boden et al., (2009) presents CO_2 Emissions from fossil-fuel burning, cement manufacture and gas flaring and for Rwanda, the data cover 1962 to 2006; FAO (2015) presents data including Agriculture, Forestry and Other Land Use (AFOLU). The most recent study to develop projections of GHG emissions baseline data was carried out by the International Institute for Sustainable Development (IISD) in 2013 (Stiebert 2013) using data from the FAO (2010). Ucertainties associated with data and data sources were acknowledged in this study. There might be more uncertainties in using 2010 data as opposed to the most recent forest cover mapping data of 2012 (Nduwamungu et al. 2013) because the 2012 forest cover mapping utilized high resolution (25cm spatial resolution) color orthophotos with a minimum mapping unit of 0.25ha (Nduwamungu et al. 2013). As mentioned earlier, comparing forest cover data by FAO with that of CGIS-NUR and ISAR for Rwanda reveals uncertainties or discrepancy especially when comparing data and statistics by FAO versus the empirical studies by RAB in collaboration with CGIS-NUR (Westinga et al 2013).

Apart from the first map of tropical Africa's aboveground biomass derived from satellite imagery (Baccini et al. 2008), there is no other biomass or carbon mapping covering the whole country of Rwanda. However, there had been several studies covering small areas mostly within protected areas and research stations (Nsabimana 2009; Cohn 2011; Durschinger 2011; Nyirambangutse et al, 2017). The findings in those studies have informed, to some extent, the status of carbon information. However, not all carbon pools had been empirically assessed. Lack of data and lack of countrywide empirical studies in sampling all carbon pools present challenges to a proposed MMRV system that aims to monitor the whole country. Currently, there is no in-house capacity to carry out such studies due to lack of technical, financial and human resources; however, the Government of Rwanda is implementing programs to improve the education and training sector and providing scholarships to Rwandese nationals for trainining at overseas universities as part of developing capacity (Byamukama et al., 2011).

At the country level, there are experts that can help the initial study and training of prospective MMRV staff, mostly experts from RAB and the University of Rwanda. Although emission factors specifically for Rwanda are not yet developed, there are emission factors that can be adopted from IPCC guidelines and from other countries that are within the same environment.

Forest Cover Change and Human Population dynamics

Rwanda has the highest population density in the region, estimated at 1,277 people per mi^2 with a population growth rate estimated at 2.8% per year. If no intervention or change in trend, the population is expected to reach 26 million by 2050 from current 12 million, which is double the current population (Government of Rwanda. 2011). Although deforestation cannot be directly linked to population growth and population density, there is a clear pattern that as the population increased overtime; forest cover was decreasing (Figure 5.2). Masozera and Avalapati (2002) argued that in 1960, forest cover was at 30% and the population was estimated at 2.77 million (World Bank 2013). It is not clear what the trend had been, between 1960 to 2000 since there was no specific periodic assessment of population increase and deforestation but the linear progression of deforestation indicates that forest cover continued to be lost as population increased. With the changes in policies and strategies developed through the 2006 NAPA and plans for Vision 2020, the target is to bring back the 1960 forest cover percentage by 2020. Figure 5.2 shows the negative relationship between population increase and forest cover, suggesting that population growth may be a driver of deforestation in Rwanda.

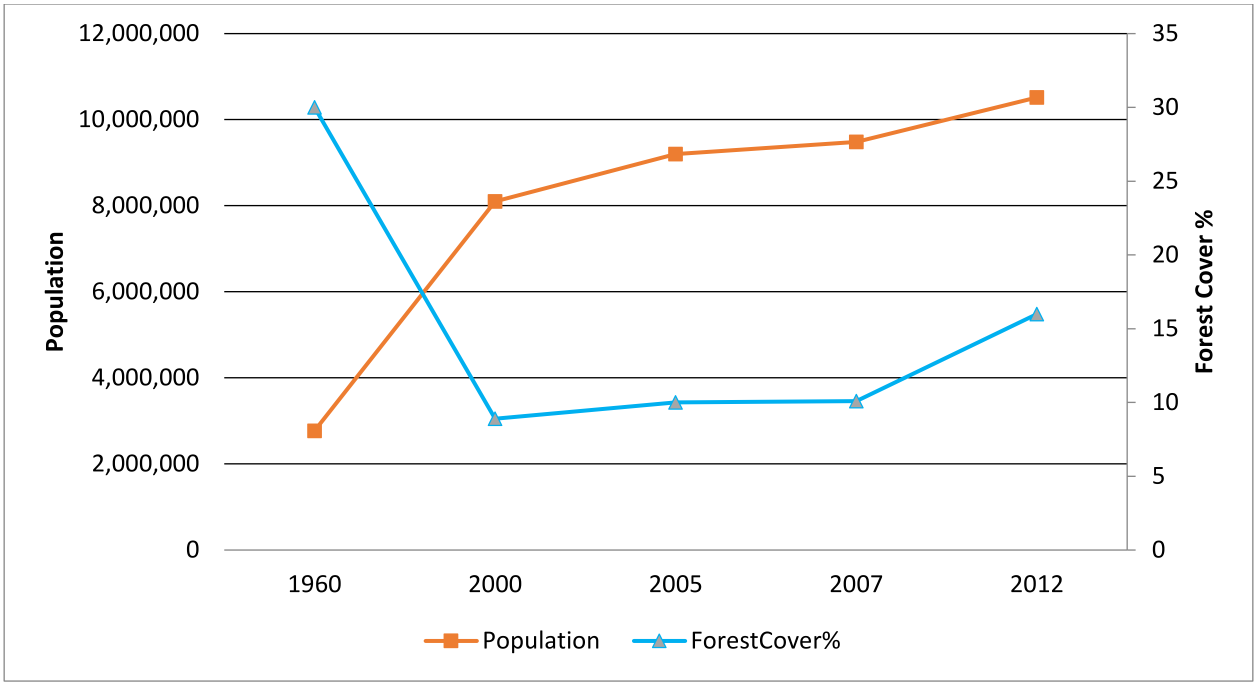

Figure 5.2. Relationship between population growth and forest cover in Rwanda

Food production for both humans and animals is one of the major sources of gas emissions. Smith et al (2008) argued that agricultural lands occupy 37% of the earth's land surface accounting for about 52 and 84% of global anthropogenic methane and nitrous oxide emissions. When population increases, demand for many essential products increases especially food and raw materials sometimes proportionally or exponentially. Increased agricultural productivity uses chemical fertilizers that contribute to increased emissions of greenhouse gases from agricultural industries (Smith et al 2007). In Rwanda, agriculture forms a major part of the country’s economy, contributing about one-third of the nation’s Gross Domestic Product (GDP) and employs approximately 70 percent of the country’s working population (Alinda and Abbott 2012; Argent et al 2014). Sustainable land use for agriculture, using compost manure and improved farming practices that promote soil conservation and soil fertility are important elements when developing a carbon emissions monitoring system (Tubiello et al., 2015). Rwanda as a country, especially the western highlands, the landform is hilly with steep slopes and most of the slopes are under cultivation (Rushemuka et al., 2014). The combination of steep terrain and rainfall intensity in Rwanda and agricultural activities practiced within steep slopes causes' serious soil loss and land degradation (Oppong & Gritzner 2009; Kagabo et al., 2013). In order to increase agricultural productivity especially for rice farming, many wetlands in Rwanda are cleared for farming that means wetland vegetation is removed and planted with rice (Nabahungu and Visser 2011). Consequently, the functions of wetlands as collectors of uphill runoff are disturbed, hence soil loss. Karamange et al. (2016) estimated a total soil loss rate of approximately 595 million tons per year within Nyabarongo catchment and an average of 250 million tons per year for the whole country of Rwanda. In order to reduce deforestation, the agriculture sector needs to be improved especially to control soil loss, which in turn helps reduce land degradation so that the land can be used for a longer time than shifting to a forested area for fertile soils. The government of Rwanda embarked on various projects to improve soil conservation through agroforestry and sustainable forest management projects. Examples of such projects are "*Forest landscape restoration opportunity assessment for Rwanda*" in collaboration with IUCN and WRI. The project identified degraded lands and restoration opportunities available to carry out forest and landscape restoration. Additionally, the project discussed and presented opportunities for scaling up pilot projects supporting the government of Rwanda to achieve multiple goals in forest and landscape restoration. The results were considered a tool to influence international forest financing mechanisms for both forest restoration activities and avoided deforestation, through mechanisms such as the Forest

Investment Program (FIP), Forest Carbon Partnership Facility (FCPF), and Reducing Emissions from Deforestation and forest Degradation (REDD+) (GoR 2014). The *Rwanda Sustainable Woodland Management and Natural Forest Restoration* project funded by Africa Development Bank under Congo Basin Forest Fund was carried out with an objective to reducing deforestation and poverty in the Congo Basin focusing on increasing forest cover and improving the living conditions of forest area dwellers as part of developing country's eligibility for carbon market benefits and payment for ecosystem services (GoR 2012). The project planted over 8 million trees, trained farmers and technicians from forestry and natural resources sector.

Discussion

Establishing a functional and effective MMRV system to achieve REDD+ is a major component of mitigation plans and actions within the forestry sector (Herold and Skutsch 2009; Pratihast et al., 2013). Monitoring changes in biomass and carbon estimation within forested areas generates important information and data which are a requirement for a functional MMRV system. Since an MMRV system is data-driven, the major concern in developing the system should focus on methodology and quality of data (Angelsen et al., 2007; Baker et al., 2010) and of course the capacity to manipulate data. An effective MMRV system acts as an auditor to track changes in carbon stocks that are caused by changes in land use and land cover. In order to achieve the goals of MMRV, there must be a base or a reference point so that the assessment can be compared to that point in time. This requires data together with capabilities to manipulate data using sound methodologies and algorithms. MMRV system can be designed as an independent, stand-alone system or integrated with other systems. In Rwanda, most of the climate matters have been coordinated through the Rwanda Environmental Management Authority (REMA). REMA prepared the first and the second national communication to UNFCCC and other international organizations. The proposed location of the REDD+ unit for Rwanda is within Forestry department under the Rwanda Water and Forestry Authority (RWFA). RWFA was created by splitting the former Rwanda Natural Resources Authority (RNRA), forming three organizations namely, Rwanda Water and Forestry Authority (RWFA), Rwanda Land Management Authority (RLMA), and the Rwanda Mines, Petroleum and Gas Board (RMPGB). As the government of Rwanda work to improve operations and communication regarding REDD+ activities REMA is closely collaborating with other institutions working towards achieving climate change and adaptation strategies for Rwanda.

Although Rwanda has made some progress in preparing for REDD+MMRV, there are still a long list of activities to be accomplished before the MMRV system could effectively yield the expected results. For example, there is need to train human resources who can manage the programs, developing methods and tools for assessing and analyzing land use and changes in carbon pools. The needed human resources are being trained locally as well as internationally however, there is a cross movements by qualified experts in developing countries including Rwanda where people change jobs for better conditions such as high pay and work benefits. This kind of brain drain leaves developing countries continuously training for experts and the developed countries take most of the best brains from developing countries. As the country is still developing REDD+ preparedness, they held various meetings involving local communities, non-governmental organizations and government departments, academic institutions and stakeholders. The local communities in Rwanda have been sensitized about green economy and REDD+ during various project meetings, however, there is need to plan for several meetings and community training to keep updating them with the developments in REDD+MMRV preparedness.

In the absence of national data sets to use as baseline data and to test the methodology and other approaches, there is need for Rwanda to develop a baseline data that can meet internationally recognized IPCC Tier 3 category. In such a data collection program, the country can be stratified according to altitudinal zones, also called Agro-Climatic Zones or Agro-Ecological Zones; however, it would be very useful if the forest cover and forest category are used in stratifying the country to be precise when planning for monitoring forest cover change. The most recent forest mapping used 0.25ha minimum mapping unit which of course does not include individual large trees that contribute significantly carbon emission/removal. Therefore the methodology employed in MMRV system should consider an approach that could include these large individual trees and other smaller forest blocks (<0.25ha) (Stephenson et al. 2014).

Both existing and proposed data to be collected need to be subject to standard testing for Quality Assurance and Quality Control (QA/QC) from data collection design through all processes to data analysis and presentation of results. Problems of determining data QA/QC is more difficult when dealing with existing data, which in some cases do not have associated metadata, and there is minimal information to understand data design and data collection methods (Michener and Jones 2012). Although data design is specific to the objectives for that particular project, it is possible that other questions can be answered with the same data in a different project. However, missing metadata makes it difficult for data to be used effectively in another study. For example, during research in Nyungwe National Park, there were data to map vegetation in the Park. The available data did not come with a metadata and the methodology used to collect was determined from the data itself to be in transects. Vegetation mapping is recommended to be carried out in stratified and random sampling, hence data issues were encountered when running analyses. In order to incorporate existing data sets in REDD+MMRV, the data must have metadata and details of how the data was collected.

Most of the data needed to establish an MMRV system for REDD+ in Rwanda are located in various organizations that have been involved in data collection and analysis such as forestry inventory data is with Rwanda Agricultural Board (RAB) and forest cover spatial data analysis is located in the University of Rwanda at the center for GIS. The creation of the Department of Lands and Mapping in 2011 (GoR 2012) created a clearinghouse for spatial datasets by harmonizing all spatial data which were scattered in different organizations. The recent national aerial survey (Swede Survey 2009) provides the most recent high-resolution color orthophotos covering almost the whole country. The areas that were security sensitive such as border areas with DRC and Burundi were filled in using high-resolution Quick Bird images (Nduwamungu et al. 2013). The forest cover mapping was carried out through collaboration between Rwanda Agricultural Board (RAB), formerly known as Institut des Sciences Agronomiques du Rwanda (ISAR).and the Center for GIS and Remote Sensing (CGIS) at University of Rwanda. Satellite images were downloaded from USGS websites and some images were provided through partnerships between CGIS and international organizations including partner Universities. The National Institute of Statistics Rwanda (NISR) collects many data and many different indicators that can be very useful in MMRV system. Population and other census data are updated periodically by NISR (NISR 2015). REMA has been a major player in environmental and climate change data management in

Rwanda. One of the jurisdictions of REMA is to coordinate national communication to UNFCCC and therefore REMA hold a certain amount of data that is important for MMRV system for REDD+. There are also other organizations involved in GHG emission monitoring focusing other sectors such as Agriculture, Transportation, energy and industry (Stiebert 2013).

Data alone do not tell the whole story, and there is need for human resource capacity to manipulate the data into meaningful products that can be used for decision-making. Funding to hire experts with specialized skills is an important part of readiness for a functional MMRV. Rwanda has not yet hired such experts but has identified the preliminary required qualifications for human resources needed as part of the MMRV system (GoR 2013). It is important that the REDD+ MMRV system start with acceptable capacity to lay baseline data and design the national MMRV projects. The established district forestry offices will play an important role in the Rwandan MMRV system. Capacity building programs through which staff can be trained are important but recruiting qualified staff as initial in-house capacity is required for a functional MMRV system.

The existing data, mainly forest inventory data, carbon pool inventory data and remote sensing and GIS data, need to be organized and archived in an accessible database or a clearing house with well documented metadata that provides information about the limitations of available data. Prior to 2011, the CGIS at National University of Rwanda was the major source of spatial data and country mapping since the ministry of infrastructure did not have capacity to carry out cartographic works. As a research and training center CGIS collected and compiled various remote sensing and GIS data that can be a source of reference in developing baseline data sets; however, creation of the National Land Center, later renamed

Department of Lands and Mapping and then Rwanda Land Management and Use Authority (RLMUA) has shifted responsibility and mandates of managing national spatial data in Rwanda. The RLMUA had a task to harmonize spatial data from various organizations since data was scattered in many organizations (GoR 2013).

Guidelines for forest inventory and biomass assessment methods for estimating carbon emission are ambiguous with regards to setting emission level reference points for REDD+ (Angelsen and Verchot 2009; Dutschke 2013). There is little agreement on the appropriate methods for determining a reference point (IPCC 2006); data about historical changes in forest cover can provide a basis for determining a reference level. Although simple linear regression using historical forest cover changes can help to set a reference point, (Shoch et al. 2011) recommends logistical regression to minimize problems that arise when simple regression is used. Challenges in mapping forest cover to develop baseline data and cover change need to be addressed for accurate assessments. For example, when using remote sensing approach to classify images in Rwanda, there are land cover classes that can be easily confused such as the banana plantations that surround some of the many houses and in some cases they have a similar reflectance signature as forest cover. Similarly tea plantations and *Pteridium aquilinum* could be easily confused if classified without prior knowledge of the area (Olson 1994; Palmer and Oxfam 2001; Uwimbabazi and Lawrence 2011; Ansoms et al. 2017). Furthermore, the mountainous landscape of Rwanda creates shadows that may affect remote sensing data analysis and interpretation.

Conventional methods to measure and verify biomass or carbon are time consuming and require reasonable planning in choosing appropriate methodologies and tools (Petrokofsky et al. 2012; Brown (2002). Most tropical forests do not have adequate data available and any data collection in such forests requires a significant investment of resources. Westinga et al., (2013) carried out a study comparing consecutive forest cover assessment results by FAO versus image-based inventories by the CGIS of the University of Rwanda and the results shows serious inconsistencies. These known data inconsistencies between FAO data and locally processed data in Rwanda can be minimized if the methodology and data collection have been up to date as opposed to estimated data variation over time. A routine national forest assessment using standardized method should be used to collect data and if possible permanent sampling sites for long term data collection should be established in order to consistently assess changes in biomass and carbon and also ease the problem of data shortage.

In order to calculate emission or removal of CO2, we need to know activity data, thus the magnitude of human activity resulting in emissions or removals taking place during a given period of time and emission factor which is defined as the average emission rate of a given GHG for a given source, relative to units of activity (Tubiello et al., 2015).The importance of activity data and emission factor cannot be overemphasized because the two are primary inputs for calculating emission or removals. Allometric equations developed specifically for Rwanda involving the common indigenous species and all the plantation species would improve accuracy of estimates and assessments. Use of generalized allometric equations has limitations when targeting the results to meet accuracy of international standards. Brown (1997) produced a list of wood density for some of the tropical tree species sample from tropical America, Asia and Africa, however there were no samples collected from Rwanda, therefore, there is need to develop specific wood density and biomass expansion factor based on Rwanda environmental conditions. If the initial plan is to adopt existing wood density and biomass expansion, I argue that the list should be tested and to determine if the densities are consistent with the changes in altitude and time of the year. Below ground carbon pools might require the development of root-shoot ratios and AGB-BGB ratios for specific environments and forest cover types.

Although I did not evaluate funding resources for MMRV system in Rwanda, the country is dependent on donor support to run such programs. Financial resources might affect level of preparedness in many forms including recruitment of human resources that are capable for specialized tasks, and operations including data collection and day to day running of the system. As the country will be developing proposals for funding, it would be important that the project includes human development component for re-training staff together with workshops and refresher courses. Some project start at a smaller scale in order to study the system for improvements and modifications to project proposal. The availability of funds, together with technical resources and human expertise are always used when determining the scale of monitoring.

Conclusion

This study reveals that Rwanda has higher capacity and readiness in remote sensing and GIS than in forest inventory and carbon pools inventory for establishment of an MMRV system. The availability of data and training institutions that teach basic remote sensing and GIS support the development of capacity needed for the establishment of MMRV. However, advanced remote sensing and GIS training for Rwandan staff is mainly obtained from overseas training which might affect the continuation of capacity when scholarship opportunities phase out. With the shortage of local experts in relevant fields, Rwanda employs experts from other countries with a hope that the locals will be trained and takes over the management of the projects. Although international experts are helpful when involved in establishing MMRV system, it is very important that Rwanda nationals should be equipped and supported to run the MMRV system and all operations. Universities and other training institutions should develop programs to support capacity building required for MMRV system at all levels. This training can support the expansion of monitoring from project scale to national scale.

Although the figures reported for emissions and removals in Rwanda, forest cover over time, there show some inconsistencies in statistics found in different reports, it is important that systematic data compilation and analysis should be organized for forest inventory; carbon pools inventory and GHG emission baseline data. Lack of allometric equations, and lack of data on biomass expansion factor and wood density together with lack of previous national carbon pools inventory, affects the readiness in developing MMRV system. Since Rwanda has not yet established a National Forest Monitoring System (NFMS), however, the exisiting systems that saw forest cover change mapping and estimation of GHG emissions used in second national communication to UNFCCC should be used as a basis to build an effective NFMS. A functional MMRV depends on accurate and reliable data of forested area and changes of forest area over a given period of time.

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Chapter 6: Conclusions and Recommendations

Changes in land use and land cover in montane forest can come about through increases or decreases in vegetation cover which in turn affect the exchange of greenhouse gases including forest carbon between ecosystems on land and the atmosphere (Wu et al., 2012; Hansen et al., 2013). This study found that almost half of the vegetation communities of Nyungwe National Park are dominated by *Macaranga kilimandscharica.* This implies that the forest has been going through ecological disturbances. As a pioneer species, *Macaranga kilimandscharica* colonizes forested areas that experienced disturbance such as fire or by extraction of forest products. The history of Nyungwe National Park shows that fires and land clearings for livestock pasture were some of the causes of land cover change in Nyungwe forest before it became a National Park.

Although the protection status increased from forest reserve to national park the protected area is still under enormous pressure from the adjacent communities. The relationship of forest cover and population shows a common trend: as population increases, forested area is reduced. The population density of the communities adjacent to Nyungwe National Park are high and continue to pressure the park through increased demand for natural resources that are found in the park. Vegetation cover changed mostly along the road that cut the Park from east to west. This implies that construction of the road had an impact on vegetation and habitats.

The results from study of vegetation communities and estimated distribution of presence of *Sericostachys scandens* indicate that the liana is present in over half of the Park.

However, I did not explore the claims that this liana is spreading in the park and is responsible for tree mortality.

The results from REDD-MMRV preparedness research for Rwanda revealed that Rwanda has higher capacity and readiness in remote sensing and GIS than in forest inventory and carbon pools inventory. There is a serious deficiency of carbon pools inventory data and some discrepancies of forest cover data reported by FAO versus the Government of Rwanda figures generated by the National University, Centre for GIS in collaboration with Ministry of Lands and Natural resources. There is lack of allometric equations and lack of data on biomass expansion factor and wood density together and also lack of previous national carbon pools inventory data affects the readiness in developing MMRV system in Rwanda.

Future directions

Periodic assessment of spatial distribution of vegetation and forest disturbances creates opportunities for further research questions. The research done in this dissertation will benefit for comparative analysis of vegetation cover distribution and changes through long-term research using permanent sample plots. Understanding tropical ecosystems and functions of montane forest of Nyungwe brings an important dimension to ecological planning and management. Regarding carbon emission and sequestration studies, long-term monitoring would create a source of data for modelling and other remotely sensed analysis. This research forms a basis for further studies to understand the ecological implications of *Sericostachys scandens* on tree mortality within the Park and the vegetation dynamics as patches of primary forests are being colonized by *Macaranga kilimandscharica*.

Forest openings and tree mortality are important aspect of ecological studies in forest ecosystems. I am particularly interested to study how the forest has been changing over hundreds or thousands of years. The use of paleo-environment investigation tools such as using spore cores sampling should be utilized to study long term changes in vegetation and creation of current open spaces in Nyungwe National Park. Historical and social developments should be included in developing a comprehensive study to understand underlying factors leading to vegetation species distribution within the National Park. One important land cover class that needs to be well understood regarding its formulation is open spaces within a montane forest. There are large montane grassland and they play an important role in wildlife habitat, ecological functions and processes. The remnants of primary forest show some tree species that might have dominated the area several years before but a structured long term study can help to establish the historical vegetation progression to current status.

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