# STAND STRUCTURE AND CARBON STORAGE IN THE NILO NATURE RESERVE, EAST USAMBARA, TANZANIA

**BY**

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# ABSTRACT

Understanding forest stand structure is necessary for predicting losses and storage of carbon in forests. However, there is scanty knowledge on relationship between stand structure and carbon storage. This study assessed stand structure and its relationship with carbon storage in Nilo Nature Reserve. The specific objectives were to determine the forest stand structure, above ground and soil carbon stock and their relationship. The forest was stratified into four elevation bands. Four marked permanent sample plots of size 0.4 ha with 80 subplots of size 20 $\times$ 10 m one in each elevation band was established. In each plot, the following information was collected: tree diameter at breast height, wood cores, and soil samples. The data was used to determine species richness, stem density, basal area, volume and carbon stock. ANOVA was used to test variation in stand structure and carbon stock with elevation bands while regression analysis was used to determine their relationships. A total of 77 species of trees and shrubs belonging to 29 families were identified. Shannon index was 3.60 indicating high plant species diversity. The stand density, average diameter, basal area and volume were 299 ± 26 stems $ha^{-1}$, 26.07 ± 2.88 cm, 38.08 ± 3.61 $m^2ha^{-1}$ and 488.35 ± 56.32 $m^3ha^{-1}$ respectively. Above ground and soils carbon stocks were 291 ± 32.81 and 247.13 ± 73.38 t $ha^{-1}$ respectively. There was significant correlation (P = 001) between carbon stocks and tree diameter, basal area and volume. Average diameter, basal area, volume and above ground carbon stock were significantly higher at high elevation than mid-high elevation band. It is concluded that stand structure correlated with carbon stocks and NNR has high potential for carbon storage in above ground biomass and soils. The stand structure parameters can be used adequately for prediction of carbon stock in similar forests.

## DECLARATION

I, Emmanuel Japhet, do hereby declare to the Senate of Sokoine University of Agriculture, that this dissertation is my original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

________________________ __________________

Emmanuel Japhet Date

MSc. Candidate

The above declaration is confirmed

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Prof. P.K.T Munishi Date

(1) Supervisor

________________________ __________________

Dr. E.F. Nzunda Date

(2) Supervisor

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# DEDICATION

This work is dedicated to my parents, my father the late Japhet Mwainunu and my mother Ester Abraham, who built a strong foundation for my education.

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## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AFIMP | - | Amani Forest Inventory and Management Plan |
| $CO_2$ | - | Carbon dioxide |
| CoP | - | Conferences of Parties |
| DBH | - | Diameter at Breast Height |
| FAO | - | Food and Agriculture Organization (of the United Nations) |
| Gt | - | Gigatonnes (equals one billion or $1.0 \times 10^9$ tonnes). |
| IPCC | - | Intergovernmental Panel on Climate Change |
| HE | - | High elevation |
| LSD | - | Least Significance Difference |
| LE | - | Low elevation |
| m *asl* | - | Metre above sea level |
| MHE | - | Mid-high elevation |
| MLE | - | Mid-low elevation |
| MNRT | - | Ministry of Natural Resources and Tourism, Tanzania |
| MSc | - | Master of Science |
| NFP | - | National Forest Programme |
| Mt | - | Megatonne (equals one million or $1.0 \times 10^6$ tonnes |
| NNR | - | Nilo Nature Reserve |
| REDD | - | Reducing Emissions from Deforestation and forest Degradation |
| SOC | - | Soil Organic Carbon |
| SPSS | - | Statistical Package for Social Sciences |
| SUA | - | Sokoine University of Agriculture |
| TAFORI | - | Tanzania Forest Research Institute |
| UNFCCC | - | United Nations Framework Convention on Climate Change |
| URT | - | United Republic of Tanzania |

# CHAPTER ONE

## 1.0 INTRODUCTION

### 1.1 Background Information

Climate change is caused by an increase in atmospheric temperatures due to upsurge in concentration of greenhouse gases (GHGS) (Ngeleja, 2008). Greenhouse gases refer to gases that absorb and emit infra-red radiation in atmosphere, warming the earth's surface and the lower part of the atmosphere (Reay and Hogen, 2010). Carbon dioxide ($CO_2$) is the most predominant of all the greenhouse gases accounting for nearly half of the atmospheric warming (Mwandosya, 1999). Other greenhouse gases include methane, nitrous oxide, water vapour, ozone and chlorofluorocarbons (Mwandosya, 1999; Ngeleja, 2008).

Carbon is accumulating in the atmosphere at a rate of 3.5 Pg (1Pg = $10^{15}$ g or one billion tons) per annum (Mackey *et al*., 2008). Fossil fuel use and land-use change contribute to the rise in global carbon concentration in the atmosphere resulting in raising concentrations of $CO_2$ (Shah, 2009). About 20 percent of carbon dioxide emitted to the atmosphere results from loss of tropical forests through deforestation and forest degradation (IPCC, 2007; Mackey *et al*., 2008; Jorgensen and Milledge, 2009).

Increase in $CO_2$ concentration in the atmosphere will subsequently change the earth's temperature and weather system (Brown, 1997; Munishi, 2001; Munishi and Shear, 2004; Yanda, 2008). Mackey *et al*. (2008) stressed that due to atmospheric rise in $CO_2$ concentration, the mean global temperature will increase by between 1.4 and 5.8°C over the coming century causing changes in rainfall distribution, extreme weather events and sea-level rise. Recently, adverse impacts of climate change on the environment, human health, food security, human settlements, economic activities, natural resources and physical infrastructure are apparent in many countries, including Tanzania.

With this increase in atmospheric carbon dioxide and its implication on global climate change, the role of forests management has received attention as a means of mitigating carbon emissions and climate change (Munishi, 2001; Munishi and Shear, 2004; Munishi *et al.*, 2008). This is because forests remove $CO_2$ from the atmosphere through photosynthesis and store in its biomass and soils (Gurney and Raymond, 2008). The total carbon stored in the natural forest ecosystem globally is 638 Gt with 283 Gt of carbon in its biomass, 38 Gt in dead wood and 317 Gt in soils (top 30 cm) and litter (FAO, 2006; Yanda, 2008). It is because of this, that the contribution of forests to carbon storage was acknowledged at Earth Summit on Environment and Development held in Rio de Janeiro in 1992. At the Summit, sustainable management and conservation of all types of forests were emphasized in order to combat desertification, land degradation and deforestation and to reduce emissions from land use and land-use change activities.

Despite the fact that, large percentage (20%) of carbon emission results from loss of tropical forests, protection of existing natural forests and woodlands was excluded in the Kyoto Protocol (Grace *et al.*, 2006). The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) is the first step by the world's nations to limit the emissions of carbon dioxide and other greenhouse gases in order to reduce global warming. The Protocol came into force in February 2005 and adopted by the UNFCCC in 2007 (Grace *et al.*, 2006; Lawuo, 2008). The protocol is based on the fact that, atmospheric greenhouse gases have global effects regardless of where they are released. For this reason, the Kyoto protocol include several 'flexible mechanisms' permitting industrialized nations to reduce global GHG emissions by investing in emission reduction activities in other countries (Ladue, 2008). One of these flexible mechanisms was the Clean Development Mechanism (CDM) which serves the first commitment period (2008- 2012) and was limited to afforestation and reforestation projects (Lawuo, 2008; Zahabu *et al*., 2008).

Though protection of existing natural forests and woodlands was excluded in the Kyoto Protocol, international negotiations focusing on reducing emissions from deforestation and forest degradation (REDD) started at eleventh Conference of Parties (CoP 11) in Montreal, Canada in 1995. This was continued at CoP 12, in Nairobi in 2006, CoP, 13 in Bali in 2007, CoP 14 in Bozma, Poland in 2008 and CoP 15 in Copenhagen 2009. The decision at UNFCCC CoP 13 in Bali expressly focused on REDD post 2012. The decision for re-negotiation of the climate change policy for the post 2012 to include REDD policy has been prompted by the evidence of the contribution of natural forests to global carbon emission and carbon storage (Mackey *et al*., 2008; Lawuo, 2008). This came after studies supported that natural forests also sequester carbon and have a long term storage capacity compared to plantation forests (Lawuo, 2008).

Natural forests are defined as forests that have not been disturbed by intensive human land-use activities including commercial logging (Mackey *et al*., 2008). The forests are characterized by high heterogeneity in their stand structure (Merino *et al*., 2007). Stand structure refers to parameters such as tree species composition, diversity, diameter size class distribution, basal area, volume, stem density, forms and canopy layers of the forests (Adam and Ek, 1974; Husch *et al.*, 1982; Valkonen 2007; Isango 2007; Mbwambo *et al.*, 2008). Stand structure is the result of the species' growth habitats, environmental conditions and management practices under which the stand originated and developed (Husch *et al*., 1982). Understanding forest structure is necessary for predicting potential losses and storage of carbon (Merino *et al*., 2007). This is because altering forest structure may affect carbon stored in biomass and soil causing emission to the atmosphere (*ibid*).

Tanzania has about 34 million hectares of natural forest (MNRT, 2001, Zahabu, 2008). Categories of the natural forests in Tanzania, which fall under different managements, include, forest on public lands (54 percent), Government Forest Reserves (37 percent), and private and community forests (9 percent) (MNRT, 2001). However, alarming rate of deforestation and degradation of natural forests in the country is a threat to the existence of these forests. It is estimated that deforestation in the country ranges from 130 000 to 500 000 ha per annum (MNRT, 1998; FAO, 2006; Miles *et al*., 2009). Reducing Emissions from Deforestation and forest Degradation (REDD) initiative has, therefore, been pointed out as a solution to deforestation and forest degradation as a well as carbon emission (Yanda, 2008).

## 1.2 Problem Statement and Study Justification

Reducing atmospheric carbon emission and concentration through forest management has recently become an important issue in many countries including Tanzania. This is due to the fact that living trees and soils in natural and semi-natural forests constitute major long-term stocks of organic carbon (Merino *et al*., 2007).

The ability of forests to store large amounts of carbon depends heavily on the tree species growing in them and their stand structure (Munishi, 2001; Shanahan, 2005). Structural attributes of forest stand are important in understanding and managing forests ecosystems because they have direct value as a product or in providing a service (in storage of carbon) (Franklin *et al*., 2002). Therefore, understanding the relationship between stand structure and carbon storage is essential.

Few studies have estimated carbon storage in natural forests of the Eastern Arc Mountains (Munishi 2001; Munishi and Shear, 2004). Furthermore, most of these studies focused on assessment of carbon storage potential, sequestration and carbon monitoring by local communities (Munishi 2001; Munishi and Shear, 2004; Zahabu 2008). However, none of these studies has assessed the relationship between stand structure and carbon storage. Moreover, limited information (if any) is available on variations between stand structure and carbon stock across elevation in the Eastern Arc Mountain. Therefore, this study aims at filling these knowledge gaps. The results of this study will be useful to forest managers, scientists, planners and policy makers in understanding potentials of natural forest ecosystem in storage of carbon. The results will equally be critical in understanding not only how stand structure parameters relate to carbon storage potential of the forests but also variation of stand structure and carbon stock across elevation. Information from this study will obviously form the basis for proper planning of forest management for reducing deforestation and forest degradation which contribute to alteration of stand structure and carbon dioxide emission to the atmosphere. In addition this study will add value to national and global strategies (REDD, REDD+) geared towards reducing emission and mitigation of climate change.

## 1.3 Objectives

### 1.3.1 Overall objective

The overall objective of the study was to assess stand structure and its relationship to carbon storage in Nilo Nature Reserve, East Usambara, Tanzania.

### 1.3.2 Specific objectives

The specific objectives were to:

i. Determine the stand structure in Nilo Nature Reserve.

ii. Determine the above ground and soil carbon stock in the Nilo Nature Reserve.

iii. Determine the relationship between stand structure and carbon stock in the Nilo Nature Reserve.

## 1.4 Research Questions

1. What is the stand structure (tree species composition, tree species diversity, diameter size class distribution, stem density, basal area and volume) in the Nilo Nature Reserve?
2. How much are the above ground and soil carbon storage in the Nature Reserve?
3. What is the existing relationship between stand structure and carbon storage in the Nature Reserve?

# CHAPTER TWO

## 2.0 LITERATURE REVIEW

### 2.1 Overview of Carbon Storage in Natural Forests

Natural forests play a significant role in the global carbon cycle (Mackey *et al*., 2008). These forests are important not only in terms of total net carbon emissions but also in global storage capacity, important for climatic regulation (Terakunpisut *et al*., 2007). This is due to the fact that vegetation biomass and soils store approximately three times the amount of carbon that is currently found in the atmosphere. Moreover, the annual exchange of carbon between the atmosphere and natural forests is 10 times more than the annual global carbon emissions from burning fossil fuels (Mackey *et al*., 2008).

The amounts of carbon stored globally differ widely among forest biomes (Lorenz and Lal, 2010). Forest biome includes areas that are dominated by trees and other woody vegetation (Klappenbach, 2011). The major forest biomes are the boreal, temperate and tropical forest biomes (Lorenz and Lal, 2010). Forest carbon stocks vary between forest biome due to difference bioclimatic gradients (temperature, precipitation and geologic substrate) slope, elevation, drainage class, soil type and land-use history (Gibbs *et al*., 2007). Estimates show that tropical forests store largest quantities of carbon in vegetation and soil (Baishya *et al*., 2009; Lorenz and Lal, 2010). These forests account for 37% of the total 90% of the world's terrestrial carbon that is stored in forests (Baishya *et al*., 2009).

### 2.2 Stand Structure of Natural Forests and Carbon Storage

#### 2.2.1 Species composition

Composition is expressed as the assemblage of plant species that characterize the vegetation (Martin, 1996). Vegetation composition refers to the relative amounts of a particular species as a percentage of the total number of species in a community (Munishi, 2001). Species composition can change over time due to variations in moisture levels associated with unpredictable disturbance and environmental contrast (Munishi *et al*., 2007). Understanding species composition is important as it helps to determine forest condition and trend which are valuable tools of judging the impact of previous management and guide future decisions as well as carbon storage (Billheimer *et al*., 2001; Chen, 2006; Mbwambo *et al*., 2008). This is because plant species composition is an important driver of carbon accumulation in forest ecosystems. Composition on the other hand influences above-ground carbon storage and total carbon storage (Jonson, and Wardle, 2009).

**2.2.2 Tree species diversity**

Species diversity refers to the number of different species in a particular area (Arrison *et al*., 2007). Tree species diversity in tropical forest varies greatly from place to place mainly due to variation in biogeography, habitat and disturbance (Huang ***et al*., 2002).** Moreover, harvesting and other disturbances in the forests change the relative composition of tree species and strongly influence species diversity (Elliott and Hewirr, 1997). The diversity of trees is fundamental, simply because trees provide resources and habitats for almost all other forest species and play a role in carbon storage of forests (Huang ***et al***., **2002).** Increasing plant species diversity contributes to greater ecosystem carbon sequestration as well as total storage. Furthermore diversity of species increases the likelihood that in the face of climate change, some species will be capable of adapting to those changes (Shanahan, 2005; Jonson and Wardle, 2009).

### 2.2.3 Tree size distribution

Trees size distribution contributes to the structural pattern characteristic of forests (Huang ***et al*., 2002**; Franklin *et al*., 2002). Carbon storage of trees correlates with DBH size class (Terakunpisut *et al*., 2007). Large trees have large capacity for carbon storage whereas small trees especially the young ones have low carbon storage capacity, though they have high rate of carbon sequestration (Franklin *et al*., 2002). In tropical rain forest and dry evergreen forest, the main tree size classes that had a great potential in carbon sequestering from small up to medium tree size at 4.5–20 up to >40–60 cm (Terakunpisut *et al*., 2007). However, it has been noted that, old trees that highly contribute to carbon storage are less abundant compared to young trees. In a study on examining the abundance, growth and mortality of very large trees (>70 cm diameter above buttresses) at La Selva Costa Rica, it was found that very large trees are a minor fraction (2%) of the stems, but contain a significant fraction of the above-ground biomass (27%) (Terakunpisut *et al*., 2007). In other study, Huang ***et al*. (2002) found that t**he diameter size class distribution of trees is very variable and some forests have large numbers of trees of 40–60 cm dbh and highly contribute in carbon storage.

### 2.2.4 Stem density

Stem density usually defines the stocking of the stand and it indicates the degree of rowdiness of stems in a given area (Husch *et al*., 1982; Njana, 2008). Stem density varies widely between forest reserves and forest types. Studies of montane rain forest in Tanzania showed that average stocking level range from 650 to 1161 stems per hectare for East Usambara (Munishi 2001; Munishi and Shear, 2004; Kajembe *et al*., 2004; Luoga *et al*., 2005; Kajembe *et al*., 2008). In Miombo woodlands stems per hectare range between 618 and 980 (Zahabu 2001; Malimbwi and Mugasha, 2002; Mohamed, 2006; Kajembe *et al*., 2008). Factors controlling tree density in forests included natural and anthropogenic disturbance, soil conditions and elevation (Huang ***et al.,* 2002;** Kumar *et al*., 2006). Tree density is normally significantly higher in high elevations in tropical forests than in low (Kumar *et al*., 2006).

**2.2.5 Basal area**

Stand basal area is the total basal area of all trees or of specified classes of trees per hectare (Hush *et al*., 1982; Philip and Gentry, 1993; Njana, 2008). Basal area in plantation forest is useful parameter in comparing stocking of two stands of the same species, age and height while in natural forest, is a good measure of site potential (Philip, 1983). Various reports show that basal area per ha is not constant but vary between and within forest types as well as forest reserves. Basal area in montane forests may range between 30 and 51$m^2ha^{-1}$ (Wass, 1995; Malimbwi and Mgeni, 1991; Munishi, 2001; Munishi and Shear, 2004; Kajembe *et al*., 2004; Kajembe *at al*., 2009). In most miombo woodlands, the basal area ranged between 7 and 120 $m^2$ per hectare (Lowore *et al*., 1994; Nduwamungu and Malimbwi, 1997; Zahabu, 2001; Mafupa, 2006; Mohamed, 2006; Njana, 2008). With respect to carbon storage in the forest, basal is important in understanding the carbon stock in the forests. This is because increases of basal area lead to increase in carbon storage of the forest and vice-versa (Bunker *et al*., 2005).

**2.2.6 Volume**

Tree volume is linearly related to basal area (Lowore *et al*., 1994). Various reports show that volumes per ha are not constant but vary between and within forest types. Volume in montane forests range between 67 and 560 $m^3ha^{-1}$ (Kajembe *et al.,* 2004; Kajembe *at al.,* 2009). In most miombo woodlands, standing volume ranged between 11 and 88 $m^3ha^{-1}$ Nduwamungu, and Malimbwi, 1997; Zahabu, 2001; Luoga *et al*., 2005; Mafupa, 2006). With respect to carbon storage in the forest, volumes are important in understanding the carbon stock in the forests. This is because increase in volume leads to increase in carbon storage of the forest and vice-versa (Bunker *et al*., 2005).

### 2.3 Biomass and Carbon Stock

Biomass refers to the total amount of living matter present at a given moment in a biological system (Luhende, 2003). Tree biomass is a key variable in the annual and long term changes in the global terrestrial carbon cycle as wood biomass is involved in the regulation of atmospheric carbon concentrations (Terakunpisut *et al*., 2007). Therefore, maintenance and enhancement of natural carbon stocks in land vegetation is considered a key climate change mitigation measure (Miles *et al*., 2009). Carbon storage in vegetation varies from one forest reserve to another due to a number of factors including variation of stand characteristics. Due to variation of forest stand characteristics, forest reserves have different carbon storage potentials. Previous study showed that carbon stock in tree biomass including roots ranged between 126 and 640 $tha^{-1}$ while organic carbon ranged between 237 and 520 $tha^{-1}$ (Munishi, 2001; Munishi and Shear, 2004; Terakunpisut *et al*.,2007; Mackey *et al*., 2008; Miles *et al*., 2009).

### 2.4 Carbon Storage in Soils

Soil represents the largest carbon reservoir in terrestrial ecosystems (Schimel, 1995). It is estimated that the soil contains two times that of the atmosphere and 2.3 times that of the total terrestrial vegetation (Yang *et al*., 2006) Hence, even relatively small changes in soil carbon storage per unit area could have a significant impact on the global carbon balance (Rice, 2010). In natural forest reserves, carbon content in the soil varied between 280 $tha^{-1}$ and 418 $tha^{-1}$ (Munishi, 2001; Munishi and Shear, 2004; Mackey *et al*., 2008 The variation of carbon stock in soils between forest reserves might be attributed to tree species composition, richness and anthropogenic disturbance. Trees influence soil properties in diverse ways, as tree litter, root decay and continuous sloughing-off, as well as decomposition of dead trees are a major source of soil organic matter (Nair, 1984; Ngegba, 1998), which contribute to organic carbon in the soil. On the other hand, anthropogenic disturbance reduces vegetation cover and exposes soil organic carbon to temperature that may lead to an increase in carbon emission and hence reducing carbon stock in soils (Brown, 2010; Yang *et al*., 2010)

**2.5 Variation of Stand Structure and Carbon Stock across Elevation Bands**

Elevation is the vertical distance measured from a point to a reference surface while elevation bands are subunits within the elevation (Horning *et al*., 2010). Elevation plays a key role in stand structure and carbon storage in soils. A numbers of scholars have pointed out elevation as a key factor in tree density and distribution in the forests (Elliott and Hewirr, 1997; Munishi, 2001; Huang ***et al***., **2002;** Kumar *et al*., 2006). For instance, Kumar *et al*. (2006) reported that tree density and basal area were significantly greater in higher elevation bands in tropical forests of Garo hills (Kumar *et al*., 2006). On the other hand it has bee reported that high elevation bands forest soils store relatively large quantities of organic carbon than lower elevation bands in Eastern Arc Mountain, Austria and Spain (Munishi, 2001; Karhu *et al*., 2010). This is attributed by low organic matter decomposition rate experienced in high elevation bands because of low temperature contributing to accumulation of organic matter forming soil organic carbon (Munishi, 2001; Karhu *et al*., 2010).

# CHAPTER THREE

## 3.0 MATERIAL AND METHODS

### 3.1 Study Area Description

#### 3.1.1 Location

The study was conducted in the Nilo Nature Reserve which covers an area of 6025 ha. The nature reserve is made up of three forest reserves namely Ludindi, Kilanga and Nkombola forest reserves. The Nature reserve is situated between latitudes 04˚ 50’ - 59’ S and longitudes 038˚37’- 41’ E at an elevation of 400 - 1506 Metres above sea level (m *asl*). It is in the North West of the East Usambara Mountain. It falls under jurisdiction of three districts namely Korogwe, Muheza and Mkinga in Tanga Region. The East Usambara Mountains form part of a chain of Mountain known as the ‘Eastern Arc’, which stretch from Southern Kenya to Southern Tanzania (Frontier Tanzania, 2002).

#### 3.1.2 Climate, soil and topography

The climate of East Usambara is monsoon (Edward, 2007). The rainfall distribution pattern is bi-modal, peaking between March and May and between September and December. Rainfall is higher at higher altitudes and in the southeast of the mountains, increasing from 1200 mm in foothills to over 2200 mm annually (Hamilton and Bensted-Smith, 1989; Frontier Tanzania, 2002). Average monthly temperature is 20ºC which varies considerably during the year with a difference of 5ºC between the hottest and the coldest month, that is, March and July, respectively (Lema, 2000; Richard, 2007).

Soils of East Usambara originated from biotite-hornblende-garnet gneiss rock with much quartz and mainly belonging to the Precambrian Usagaran system (Edward, 2007). The soils are deep, reddish clay-loams, with nutrient concentrated in topsoil less than 20 cm deep (Rechard, 2007). The upper altitude soils are highly acidic (pH 4 — 5) while lowland soil tend to be more neutral (pH 6.5 - 7) (Hamilton, 1989; 1998; Edward, 2007). Topography of Nilo Nature Reserve is undulating ridge system with steep sided slopes. The nature reserve forms two main peak areas namely Nilo peak at an elevation of 1506 m *asl* and Lutindi with a height of 1400 m *asl* (Frontier Tanzania, 2002).

### 3.1.3 Vegetation

The main types of vegetation in East Usambaras are the lowland rain forests and submontane rain forest which occur below and above 880 m *asl* respectively (Hamilton, 1998; Richard, 2007). The East Usambara Mountains support ancient and unique forests, rich in endemic species (Hamilton, 1989). It is estimated that approximately 45 137 ha of the East Usambara Mountains remain as natural forest which is divided into two types: submontane rain forest and lowland forest. In Nilo Nature reserve, large part contains endemic, near endemic and threatened species. The indigenous tree species are *Cynometra brachyrrahchis, Couratari longipedicellata, Placodiscus amanuenses, Uvariodendron oligocarpum* and Uvariodendron *pycnophyllum* (Frontier Tanzania, 2002).

### 3.1.4 Communities adjacent to Nilo Nature Reserve

The Nilo Nature Reserve is surrounded by a total population of 28 960 people, whereas 13 784 are male and 15 176 female living in 6430 households in sixteen villages. The villages around the nature reserve include Kwenkeyu, Kizara, Kilangangua, Bombo maji moto, Magunganzia, Folofolo, Kifango, Kitivo, Makumba in Korogwe. Other villages inclu de Kazito, Kizerui and Zirai in Muheza District and Kuze, Kibango and Bosho kumtindi are in Mkinga District (Fig. 1). The dominant tribe in the villages is Sambaa, other tribes include Ngoni, and Pare. The main stay of all these communities is agriculture: growing maize, beans, bananas and cardamom. It was also observed that people in mentioned villages depend much on the NNR for their livelihoods. Water, firewood, fruits and medicines used by these communities are sourced from the forest reserve. Furthermore, some people conduct illegal activities such as cultivation of *Cannabis sativa*, tobacco and cardamom in the nature reserve.

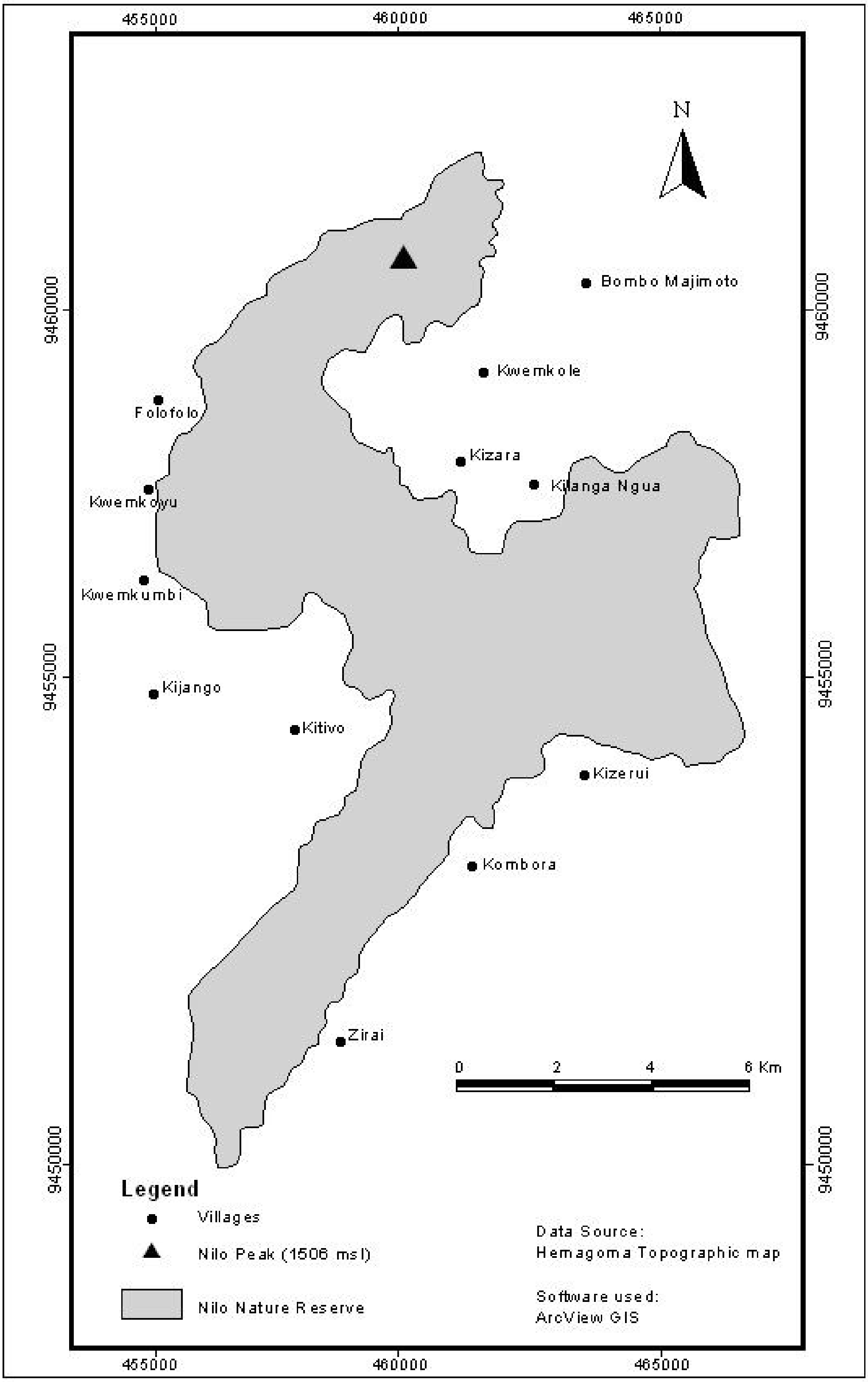


**Figure 1: Map of Nilo Nature Reserve**

## 3.2 Data Collection Methods

### 3.2.1 Sampling design

The reserve was divided into four elevation bands (ranges): 400 - 667 m *asl*, 667 - 992 m *asl*, 992 - 1228 m *asl* and 1228 - 1504 m *asl*. One 100 × 40 m (0.4 ha) permanent plot marked on the ground was located randomly by the aid of topographic map in each elevation range. The average distance between plots across contour was 246 m (Appendix 1). In each 0.4ha plot twenty sub-plots with 10 x 20 m sizes were systematically distributed (Fig. 2). In order to minimize variation within a plot, they were laid out with long axis perpendicular to the direction of the slope or environmental gradient.

The rationale of stratifying Nilo Nature Reserve into elevation bands is due to the fact that the Nature Reserve has wide range of elevation (400 m to 1504 m). According to Hamilton *et al*. (1998) there is continuous variation in the vegetation along an elevation gradient. Therefore, Nilo Nature Reserve was stratified into elevation bands in order to capture information in a short range of elevation regarding stand structure and carbon stock. This is essential not only for understand condition of the stand structure and carbon stock at each elevation band but also for planning appropriate management or restoration aiming at reducing deforestation and forest degradation. This is because, understanding how plants distributed within an elevation band, is critical for on designing restoration and biodiversity conservation programme (Munishi, 2001).

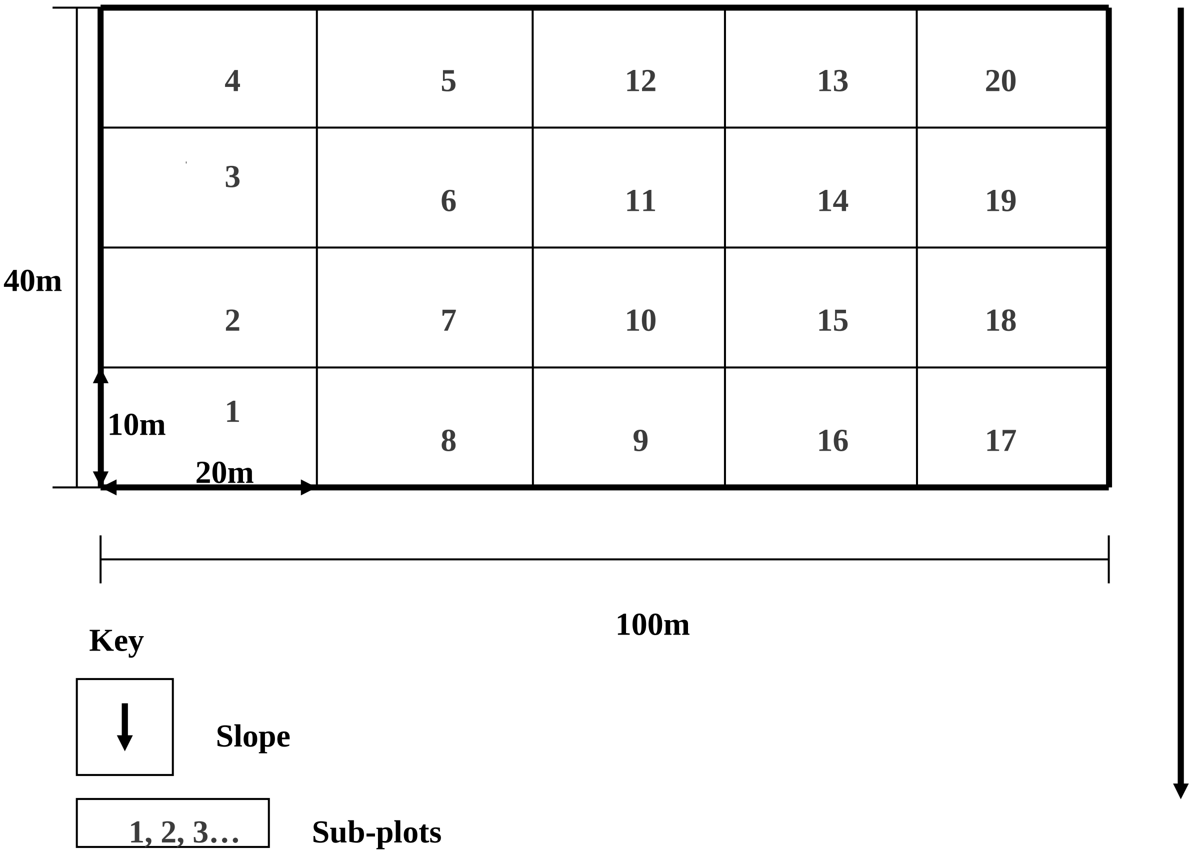


**Figure 2: Plot layout in the Nilo Nature Reserve.**

### 3.2.2 Determination of stand structure and carbon

In each plot information on elevation (m) and diameter at breast height (dbh) in centimetre for all trees with dbh ≥ 5 were collected. The dbh was measured using a caliper and a dbh tape for big trees which could not be measured by a caliper. Tree species were identified in the field for botanical name by a qualified botanist from Tanzania Forestry Research Institute (TAFORI). For species that were not identified in the field, voucher specimens were collected for identification in Lushoto Silvicultural Station Herbarium.

### 3.2.3 Determination of above ground carbon stock

Wood cores were extracted from each of the sample trees using increment borer at 1.3 m from the ground for determination of wood density. The wood core volume was determined by using Archimedes principle. Wood core density was computed as core oven dry weight to the wood core volume for each tree species.

### 3.2.4 Determination of soil carbon stock

In each sample plot, three points at the middle of the plot perpendicular to the slope were selected systematically for collection of soil samples. Soil samples were collected at 15 and 30 cm depths. The three samples from each depth were combined, air dried, finely grained and sieved through 2 mm sieve. Percent soil carbon was determined as described by Andeson and Ingram (1993).

Soil cores for determination of bulk density were collected at the middle of each plot (0 -15 and 15 - 30 cm depth) using bulk density core samplers. The bulk density cores were oven dried to constant weight in the laboratory. The soil bulk density was computed as the ratio of the soil oven dry weight to the soil core volume for each sample.

## 3.3 Data Analysis

Data analysis involved determination of tree species composition, richness, diversity, stem density, basal area and volume as well as above and below ground carbon stock. This was followed by the analysis of variation in stand structure parameters with elevation and the relationship of stand structure parameters with carbon stocks.

### 3.3.1 Tress species composition

Identified individual tree species were arranged alphabetically in spreadsheet and thereafter the list and number of species in the forest were obtained. The dominant tree species was determined on the basis of their Important Value Index (IVI). This is because IVI gives a combined standard measure of abundance, density and dispersion for each species (Kent and Coker, 1992). The higher the IVI the more ecologically dominant and important the tree species in a given plant community (Shrestha *et al*., 2000; Reddy *et al*., 2008). The IVI for each individual tree species was determined using the formula (Mueller-Dombois and Ellenberg, 1974; Munishi *et al.*, 2007; Nzunda, 2008).

IVI = (RD + RDo + RF)……………………………………………………………….(1)

Where:

RD = 100 × number of individuals of the species/ number of individuals of all species

RDo =100 × total basal area of the species/ total basal area of all species

RF = 100 × number of occurrence of the species/number of occurrences of all species

### 3.3.2 Tree species diversity

Shannon Wiener index (H’) was used to determine trees diversity for the forest. The index can be described mathematically as follows:

$$H' = -\sum^{s} pi \ln pi \quad \text{……………………………………………………………(2)}$$

$i=1$

Where;

$H$ = Shannon–Wiener index

$P_i$ = the proportion of all individuals in the sample that belong to species i.

s = total number of species

ln = $\log_e$ = natural logarithm of pi (e = 2.71828 ).

$P_i$ is best estimated as $\frac{n_i}{N}$ , the maximum likelihood estimator (Kent and Coker, 1992);

Where,

$n_i$ = total number of individuals in the $i^{th}$ species

N = total number of individuals of all species

The Shannon Wiener index assumes that all the species from the community are included in the samples. The value usually lies between 1.5 and 3.5 although it can occasionally exceed 4.5 (Kent and Coker, 1992).

### 3.3.3 Diameter class distribution

Eleven tree diameter (DBH) classes of interval of 10.9 cm up to 100cm were established. Stem density, mean DBH, basal area, volume and carbon per hectare were used to characterize the forest and determine the contribution a species and diameter class have on carbon storage in the forest.

### 3.3.4 Stem density

Stem density was computed by using the following formula;

$$N = \sum \frac{n_i}{a} \text{.........................................................................................} 3$$

Where:

N = Number of stems per hectare

$n_i$ = number of trees counted,

a = plot area in ha.

### 3.3.5 Basal area

Basal area ($m^2$/ha) was calculated from measured dbh (1.3 m) for all woody individuals in all plots. This was expressed mathematically as follows:

$g_i = \Pi dbh^2/4$

$$G = \sum \left( \frac{g_i}{A \times n} \right) \quad \text{...........................................................................}$$

(4)

Where;

G= basal area of the $i^{th}$ plot ($m^2ha^{-1}$)

dbh = Diameter at breast height (cm)

$\pi$ = Pi

A = Plot area (ha)

n = Number of plots

$g_i$ = Basal area of a tree ($m^2$)

### 3.3.5 Volume

Tree volume was estimated using the formula developed for some forests in the Eastern Arc Mountains (Munishi, 2001; Munishi and Shear, 2004):

$$V = 194.8803 \times DBH^{2.3982} (r^2 = 0.99, p < 0.0001) \ldots\ldots 5$$

Where; $V_i$ = tree volume ($cm^3$), DBH = diameter at breast height

### 3.3.6 Wood density and above ground carbon stock

The tree wood density was computed as a ratio of dry mass to green volume. Tree bole biomass was computed as the product of wood density and tree volume. A biomass expansion factor (BEF) of 29% was used to estimate the biomass of the branches and foliage (Hall, 1980; Munishi *et al*., 2000; Munishi, 2001; Munishi and Shear, 2004). Root biomass was estimated as 22% of the above ground biomass (Brown and Lugo, 1992; Malimbwi *et al*., 1994). Individual tree species biomass was aggregated to plot biomass and divided by the plot area to obtain biomass density ($tonsha^{-1}$). Tree biomass was converted to carbon through multiplication by 0.49 (Colman and Cote, 1968; quoted in (Munishi *et al*., 2000, Munishi, 2001; Munishi and Shear, 2004 and Zahabu, 2008).

### 3.3.7 Soil carbon stock

The soil bulk density was computed as the ratio of the soil oven dry weight to the soil core volume for each sample. Soil carbon density in the forest was computed as the product of volume of soil per unit area (ha), bulk density and percent of carbon in the soil (%SOC).

### 3.3.8 Variation of stand structure parameters between elevation and their relationship with carbon stock

Analysis of variance (ANOVA) was used to compare stand structure parameters and carbon stock between elevation bands while simple correlation analysis was used to examine relationship other stand structure parameters (species diversity, diameter distribution, stem density, basal area and volume per hectare) with carbon stored in the forest. The coefficient of correlation $R^2$ was employed to depict the relationship. A value of $R^2$ near or equal to 0 implies little or no linear relationship between variable Y (stand parameter) and X (carbon stock), the closer the value of $R^2$ to 1 or -1 implies the stronger the linear relationship between stand parameter and carbon stock. The aim here was to check whether carbon stock has any relationship with stand structure parameters. Microsoft Office Excel computer programme were used for generation of descriptive statistics and correlation while and Stastical Package for Social Sciences (SPSS) was used to test variations between stand structure and carbon stock across elevation in the Nature Reserve.

# CHAPTER FOUR

## 4.0 RESULTS AND DISCUSSION

### 4.1 Stand Structure

#### 4.1.1 Tree species composition

A total of 713 trees and shrubs were measured, comprising of 73 and 4 species of tree and shrubs respectively in 29 families (Appendix 9). The most dominant tree species were *Sensypallum msolo, Tabarnaemontana usambarensis, Macaranga capensis, Leptonychia usambarensis, Strombosia scheffleri, Newtonia buchananii, Cylicomorpha parviflora, Albizia zimmermannii, Albizia gummifera and Drypetes subdentata* accounting for 54.1% of the basal area (Table 1 and Appendix 2). The higher Importance Value Index for these tree species is an indication that they have wide range of growth, adaptability and evenly distributed in the forest (Kent and Coker, 1992; Reddy *et al*., 2008).

**Table 1: The most dominant tree species based on species IVI in the Nilo Nature Reserve**

| S/n | Species | IVI |
|---|---|---|
| 1 | *Sensypallum msolo* | 30.44 |
| 2 | *Newtonia buchananii* | 15.96 |
| 3 | *Cylicomopha parviflora* | 15.25 |
| 4 | *Strombosia scheffleri* | 17.15 |
| 5 | *Albizia gummifera* | 10.04 |
| 6 | *Albizia zimmermannii* | 10.79 |
| 7 | *Tabarnaemontana usambarensis* | 20.50 |
| 8 | *Myrianthus hoistii* | 9.37 |
| 9 | *Drypetes subdentata* | 9.54 |
| 10 | *Macaranga capensis* | 20.40 |

#### 4.1.2 Tree species diversity

On average, Shannon-Wiener diversity index (H') was 3.60. The high value of Shannon-Wiener index shows that Nilo Nature Reserve has high tree species diversity. This is because an ecosystem with H’ value > 2 has been regarded as medium to high diverse in terms of species (Kohli *et al*., 1996; Isango, 2007).

### 4.1.3 Stem density

The mean stem density was 299 ± 26 stems $ha^{-1}$ for trees with dbh ≥ 5cm. The stem density observed in this study was much less than that obtained by Munishi, 2001; Munishi and Shear (2004); Kajembe *at al*. (2004) and Luoga *et al*. (2005) respectively in montane forests of Uluguru, West Usambara, Kwizu forest reserve and South Kilimanjaro Catchment Forest Reserves respectively. The low stem density in Nilo Nature Reserve might be caused by human disturbance particularly selective logging. Illegal timber harvesting and fire wood cutting noted in the forest during the field work. This may also indicate a continuing degradation in Nilo Nature Reserve (Fig. 3).

**Figure 3: Tree remnants from illegal timber and firewood cut as observed in Nilo Nature Reserve.**

### 4.1.4 Diameter size class distribution

The overall mean diameter of the trees in Nilo Nature Reserve was 26 ± 2.88cm. There are higher numbers of small diameter trees with low DBH size class (< 20 cm) compared to those with large DBH sizes class. The number of trees in the DBH size class decreased with increasing DBH size class conforming reverse 'J' shape (Fig. 4) which is an indication of active recruitment and regeneration. According to Phillip (1994), a reverse 'J' shape is common for natural forests with active regeneration and recruitment. The high regeneration in the forest of Nilo Nature Reserve indicates that the forest is undergoing normal recruitment and regeneration or recovering from previous anthropogenic disturbances. It has been reported that during colonial era timber logging was intensive in Nilo Nature Reserve. This might be one of the factors that have resulted into the present status.

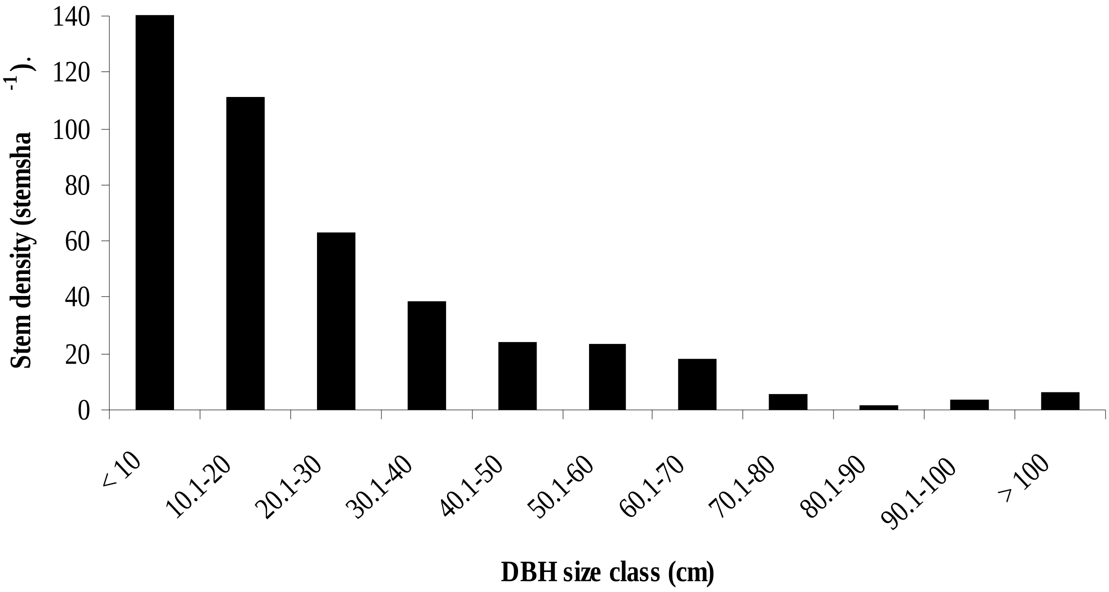


**Figure 4: Stem density across DBH size classes distribution in Nilo Nature Reserve.**

### 4.1.5 Basal area

The overall mean basal area was 38.08 ± 3.61 $m^2ha^{-1}$. This figure is lower than that reported by Malimbwi and Mgeni (1991); Munishi (2001); Munishi and Shear (2004) Mazumbai Forest Reserve in West Usambara and higher than that reported by Munishi (2001); Munishi and Shear (2004) and Kajembe *et al*. (2004) in Urugulu and Kwizu Forest Reserve respectively. This might be caused by difference in tree sizes between the forest reserves since big size classes contributed higher basal area (Fig. 5).

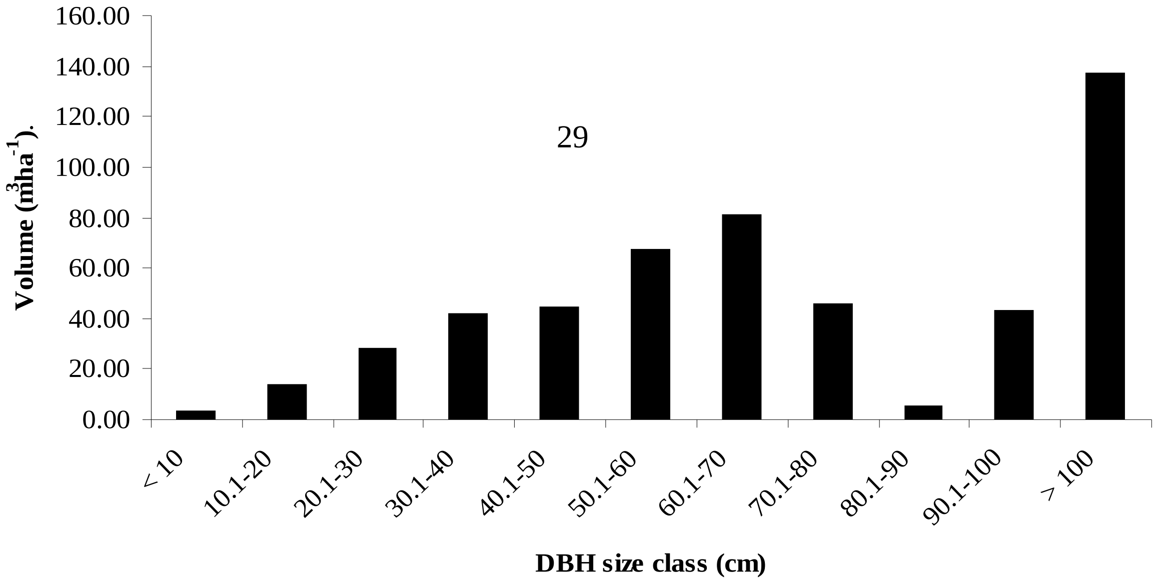


**Figure 5: Distribution of basal area by DBH size classes in the Nilo Nature Reserve.**

### 4.1.6 Volume

The overall mean standing volume was 488.35 ± 56.32 $m^3ha^{-1}$. This volume was slightly less than that reported by Kajembe *et al*. (2004) and higher than that reported by Wass (1995) in Kwizu Forest Reserve and in Mount Kenya respectively. This might be caused by differences in tree sizes between the forest reserves as the big trees contributed to high volume (Fig. 4 and 6). Exploitation history and recovering rate of tree species from previous anthropogenic disturbances may account for the difference.

**Figure 6: Distribution of volume by DBH size classes in the Nilo Nature Reserve.**

## 4.2 Above Ground and Soil Carbon Stock

### 4.2.1 Above Ground Carbon Stock

The mean biomass density was 593.91 ± 66.97 $tha^{-1}$ which translates to mean carbon density of $291 \pm 32.81$ $tha^{-1}$. Ten trees had highest contribution to carbon storage include, *Sensypallum msoo*, *Sensypallum cerasiferum*, *Newtonia buchananii*, *Strombosia scheffleri*, *Albizia gumifera*, *Albizia zimmermanii*, *Tabarnaemontana usambarensis*, *Drypetes subdentata*, *Macaranga capensis* and *Polyscias fulva* (Table1 and Appendix 2). These tree species contributed about 62% of the total carbon storage in the forest. Compared with other studies, the average carbon density obtained in this study, was less than that reported by Munishi (2001); Munishi and Shear (2004) in West Usambara and Uluguru Mountains. The low biomass and carbon stock in Nilo Nature Reserve might be caused by anthropogenic disturbance caused by local communities living around as well as previous industrial exploitation in Nilo Nature Reserve. Differences in species composition, tree sizes and the physical environment might have also caused the difference in carbon stocks between the forest reserves.

#### 4.2.2 Soil Carbon Stock

Average carbon stock was 247.1 ± 73.4 $tha^{-1}$. The soil carbon stocks in Nilo Nature Reserve is much lower than that reported by Munishi (2001); Munishi and Shear (2004); Mackey *et al*. (2008) in similar forest types. The reason for this variation carbon stock might be differences in tree species composition, vegetation density and soil characteristics. This is because the higher the species richness and vegetation density the higher the accumulation of litter and hence the higher the input of organic carbon in soils (Sheikh ***et al***., **2009)**. Difference in temperatures and precipitation between the forest reserves may also likely be cause of variation in soil carbon stock as they facilitate decomposition of soil organic carbon stored within forest ecosystem and released into the atmosphere (Sheikh ***et al***., **2009;** Brown, 2010; Yang *et al*., 2010). On the other hand, variation of soil characteristics between the forest reserves may also account for the variation carbon stock. According to Walker and Desanker (2004), clay dominated soils and soils with lower bulk densities have the highest carbon levels.

### 4.3 Relationship between Stand Structure and Carbon Storage

It was observed that diameter distribution, basal area and volume had a positive and significant correlation with carbon storage ($p = 0.001$) (Fig. 9, 11, 12 and Appendix 4). Other studies have shown that stand basal area, volume and diameter are correlated with carbon storage in Thailand (Huang *et al*., **2002;** Franklin *et al*., 2002; Terakunpisut *et al*., 2007). On the other hand, there was no significant relationship between carbon storage and neither tree species composition and diversity nor stem density, though carbon stocks increased slightly with increase in the stand parameters (Fig. 7, 8, 10 and Appendix 4).

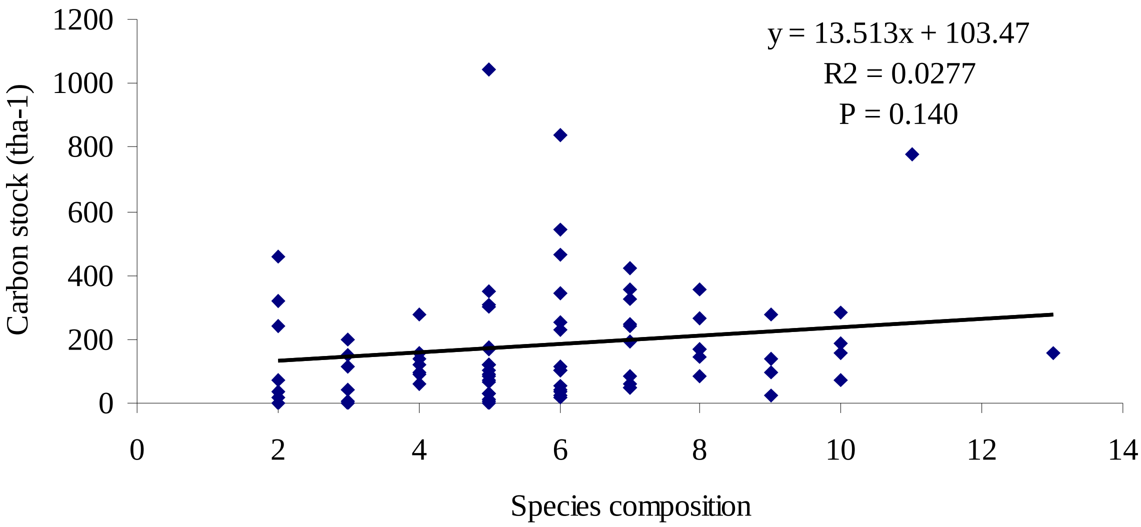


**Figure 7: Relationship between species composition and carbon stock in Nilo Nature Reserve**

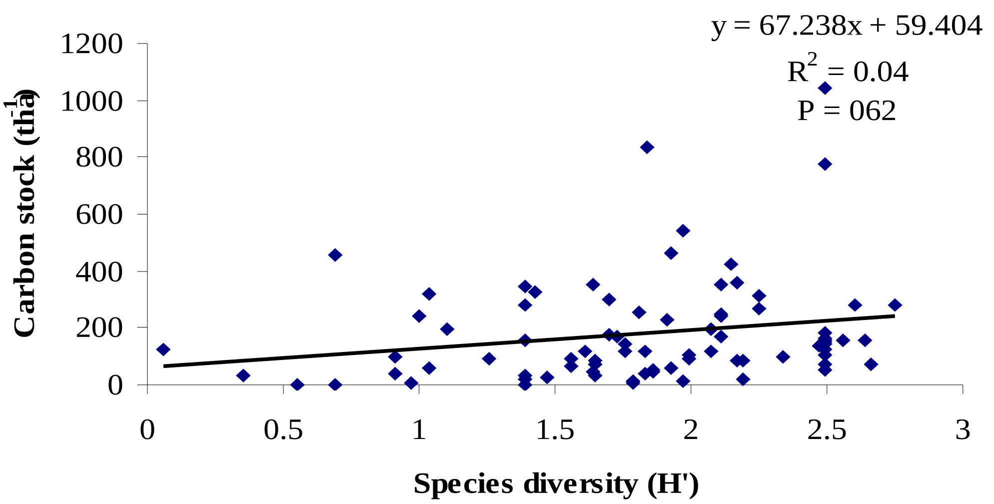


**Figure 8: Relationship between species diversity and carbon stock in Nilo Nature Reserve.**

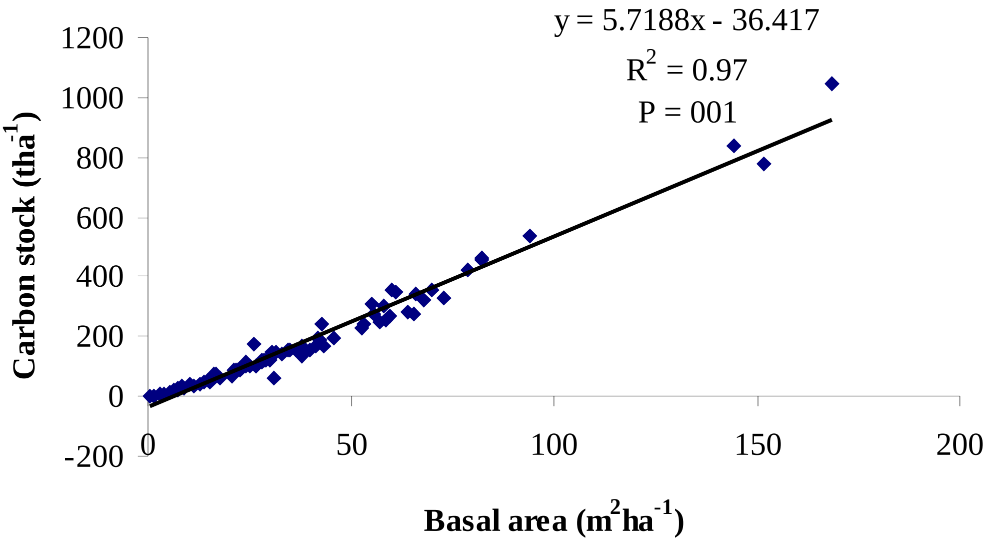


**Figure 9: Relationship between average DBH and carbon stock in Nilo Nature Reserve.**

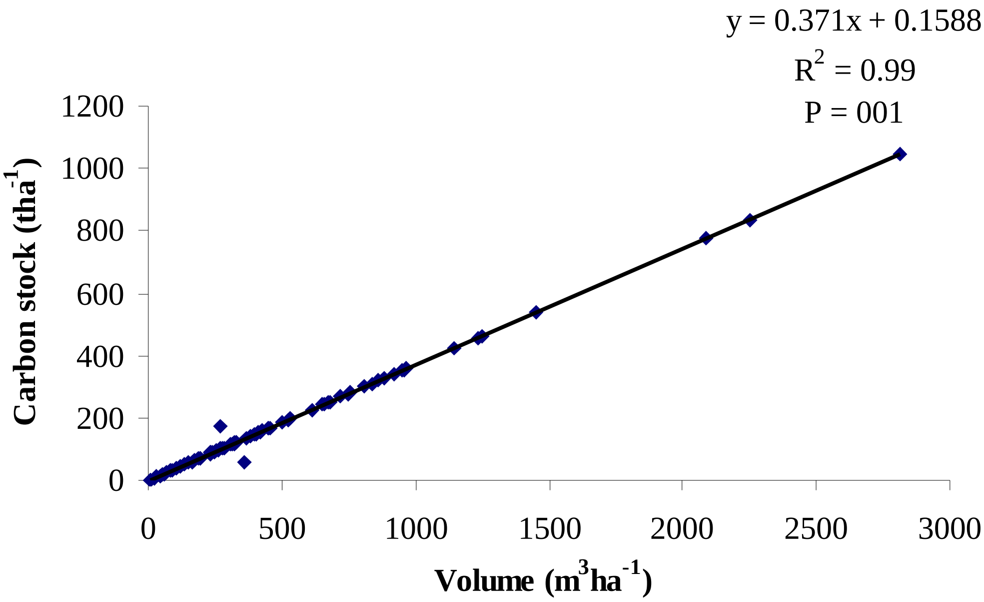

**Figure 10: Relationship between stem density and carbon stock in the Nilo Nature Reserve.**

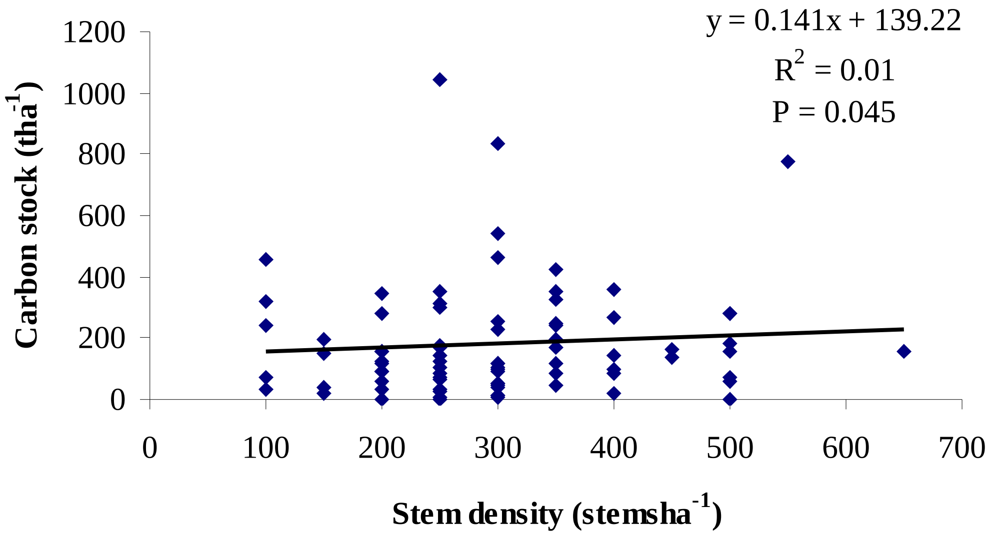


**Figure 11: Relationship between basal area and carbon stock in Nilo Nature Reserve.**

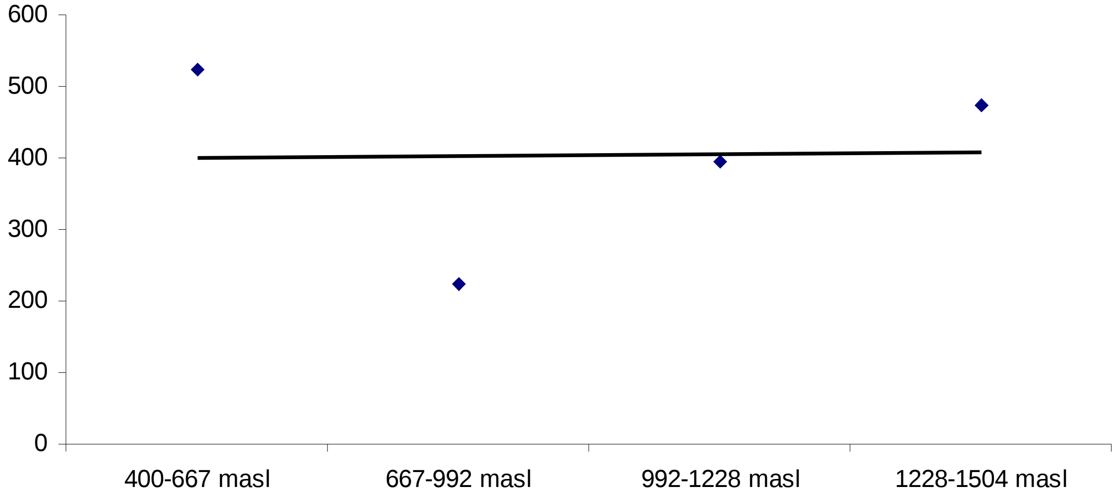

**Figure 12: Relationship between volume and carbon stock in the Nilo Nature Reserve.**

## 4.4 Stand Structure Parameters and Carbon Storage across Elevation in Nilo Nature Reserve

### 4.4.1 Change of stand structure with elevation

Generally, there was no significant difference in number of species (species richness), tree species diversity, stem density, average DBH, basal area and volume across elevation gradient though mid-high elevation band (992-1228 m *asl*) differed significantly from high elevation band (1504 - 1228 m *asl*) in average diameter, basal area and volume (Table 2 and Appendices 5, 6 and 7). The difference might be attributed to the lower DBH class size trees in the mid-high elevation band compared to high elevation band (Fig. 13 and 14). The area in the mid-high elevation band was previously logged heavily and encroached for farmland by villagers living in Kwamkeyu village located about 1000 metres above seal level. Villagers from the aforementioned village had been conducting illegal activities such as cultivation of *Cannabis sativa,* tobacco and cardamom within the nature reserve at past.

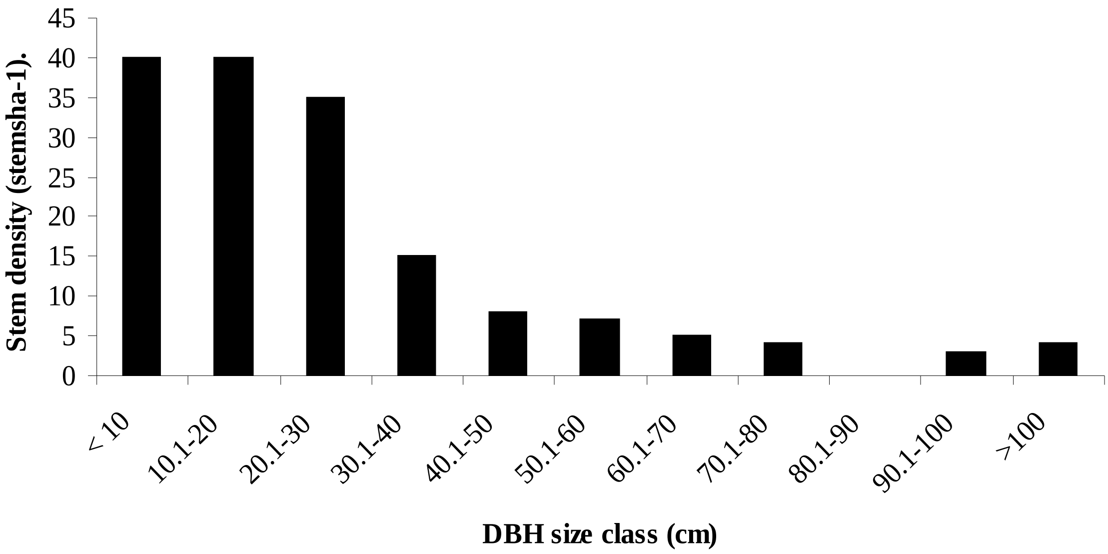


**Figure 13: DBH size class distribution at mid-high elevation band (992 – 1228 m *asl*) in Nilo Nature Reserve.**

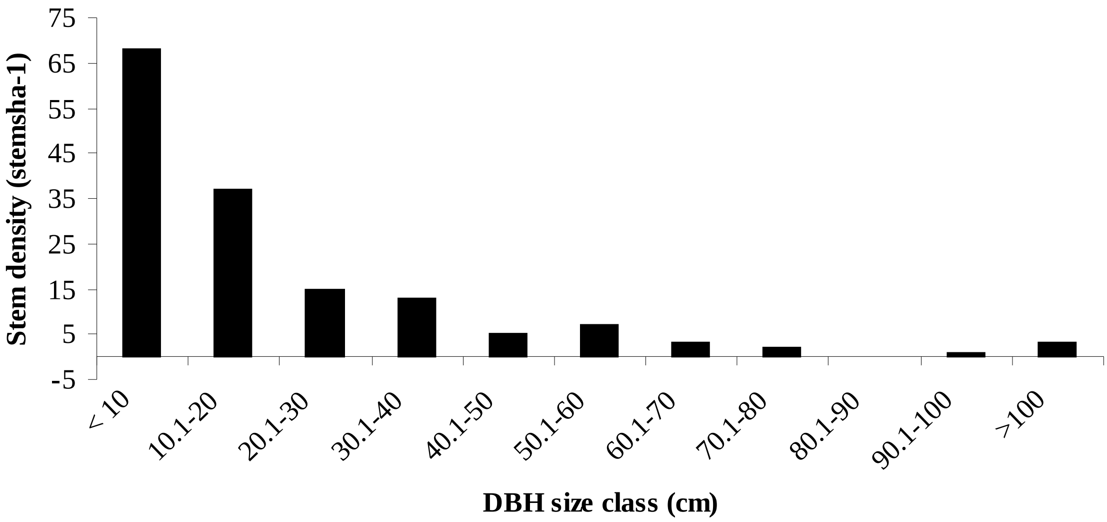


**Figure 14: DBH size class distribution at high elevation band (1228 – 1504 m *asl*) in Nilo Nature Reserve.**

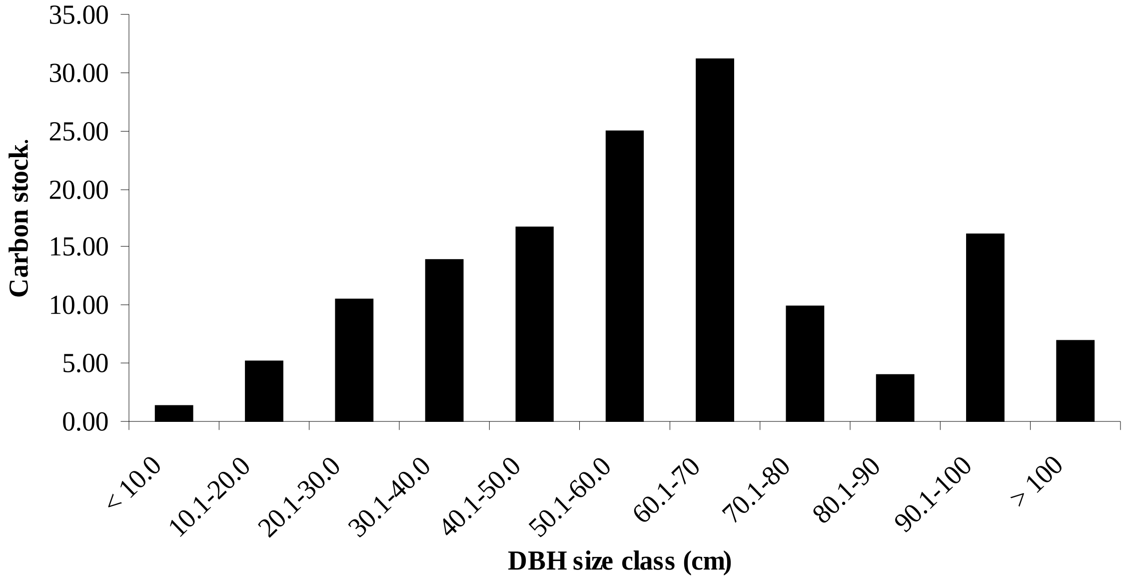


**Figure 15: Distribution of carbon stock in trees by DBH size classes in the Nilo Nature Reserve.**

### 4.4.2 Change in above ground carbon stock across elevation

Generally, carbon stock was not significantly different across elevation gradients though higher elevation band had relatively higher carbon than other lower elevation bands (Table 2). The difference was caused the lower elevation bands having large number of trees of small DBH size classes which contributed less basal area and volume which led to low carbon stock. This was because the larger the DBH, basal area and volume the higher the capacity of carbon storage (Figures 4, 5, 6, 14 and 15). Other studies have shown that large trees have high capacity for carbon storage whereas small trees especially the young ones have low carbon storage capacity (Franklin *et al*., 2002; Terakunpisut *et al*., 2007).

**Table 2: Stand parameters and carbon stock across elevation bands in Nilo Nature Reserve**

| Elevation band | | | |
|---|---|---|---|
| 992-1228 m | 1228-1504 m | F-value | P-value |
| 32 | 22 | 1.45 | 0.239 |
| 3.2 | 2.5 | 1.30 | 0.280 |
| 20.8± 4.3 | 31.5± 7.4 | 2.90 | 0.040 |
| 333 ± 6 | 263 ± 6 | 1.60 | 0**.197** |
| 28.1±12.6 | 44.4±18.5 | 2.10 | 0.107 |
| 366.2±192.6 | 601.2± 311.8 | 1.89 | 0.139 |
| 135.9±35.8 | 223.2± 57.9 | 2.15 | 0.101 |
| 241.9±211.3 | 289.9±158.8 | 1.39 | 0.369 |

| S/n | Parameters | 400 – 667 m | 667-992 m |
|---|---|---|---|
| 2 | Species richness | 33 | 28 |
| 3 | Species diversity (H’) | 2.6 | 2.8 |
| 4 | Mean diameter (dbh) | 23.7± 4.2 | 28.3± 4.9 |
| 5 | Stem density (stemsha$^{-1}$) | 318 ± 4 | 283 ± 4 |
| 6 | Basal area (m$^2$ha$^{-1}$) | 39.5±15.0 | 40.5±8.9 |
| 7 | Volume (m$^3$ha$^{-1}$) | 486.2±233.9 | 499.81±126.9 |
| 8 | Carbon in trees (tha$^{-1}$) | 180.6± 43.6 | 185.6± 23.6 |
| 9 | Carbon in soils (tha$^{-1}$) | 319.5± 47.6 | 137.1±42.6 |

### 4.4.3 Change in soil carbon stock with elevation

It was observed that there was no significant difference in soil carbon stock across elevation gradient. The trend showed that there was a slightly increase in carbon stock in from lower elevation to higher elevation (Fig. 16). In other studies Munishi (2001) found higher elevation contained relatively high soil organic carbon than lower elevation in the Eastern Arc Mountain. Similarly, Karhu *et al*. (2010) found that high elevation forest soils stored relatively large quantities of organic carbon in Austria and Spain. The high organic carbon in high altitude is attributed by low organic matter decomposition rate at high elevation because of low temperature resulting in high accumulation of organic matter in soils (Munishi, 2001; Karhu *et al*., 2010). On other hand, old growths at high altitude can account for the high accumulation of soil organic carbon at high elevation. According to Munishi (2001); Munishi and Shear (2004) old growth forest was likely to have relatively stable soil organic carbon pool in form of humic substances with long residence times. In Nilo Nature Reserve, high elevation contained old growth forests as there was no anthropogenic disturbance compared to mid and lower elevation forests parts.

# CHAPTER FIVE

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

Based on the results obtained from the present study, it can be concluded that:

**(a) Status of stand structure**

- Tree species such as: *Sensypallum msolo, Tabarnaemontana usambarensis, Macaranga capensis, Leptonychia usambarensis, Strombosia scheffleri, Newtonia buchananii, Cylicomorpha parviflora, Albizia zimmermannii, Albizia gummifera and Drypetes subdentata* are the most abundant and highly distributed in Nilo Nature Reserve.
- High tree species diversity in the Nilo Nature Reserve reflects high heterogeneity of tree species in the Nature Reserve. Heterogeneity in tree species in the forest is important for resilience of forests from adverse condition such as disease and climate change if occurs.
- High number of regenerants than big trees in the natural forest of Nilo Nature Reserve is an assurance of future recovering of the forest ecosystem from the anthropogenic disturbances.
- The mean stem density, basal area and volume were relatively high in Nilo Nature Reserve in comparison to forest of the same type.

**(b) Above ground and soil carbon storage**

- The forest has high quantity of carbon in both vegetation and soil which is evidence that its existence is important for carbon emission mitigation strategy.

**(c) Relationship between stand structure and carbon storage**

- Tree diameter size, basal area and volume are strongly positively related to carbon storage and hence are good prediction of the carbon stocks in forests.

**(d) Variation of stand structure and carbon stock across elevation**

- Average diameter, basal area, volume and above ground carbon stock were significantly at high elevation than the mid-elevation band.

## 5.2 Recommendations

Based on the objectives, results and discussion from this study, it recommended that:

a. Nilo Nature Reserve should be effectively protected from illegal logging because this practise leads to alteration of stand structure thus reducing carbon storage capacity of the forest.

b. Study on relationship of stand structure and carbon storage in natural forests in large scale in different vegetation types is recommended.

c. Nilo Nature Reserve can be a good site for REDD+ activities based on its carbon content in conjunction with other ecosystem services it provides.

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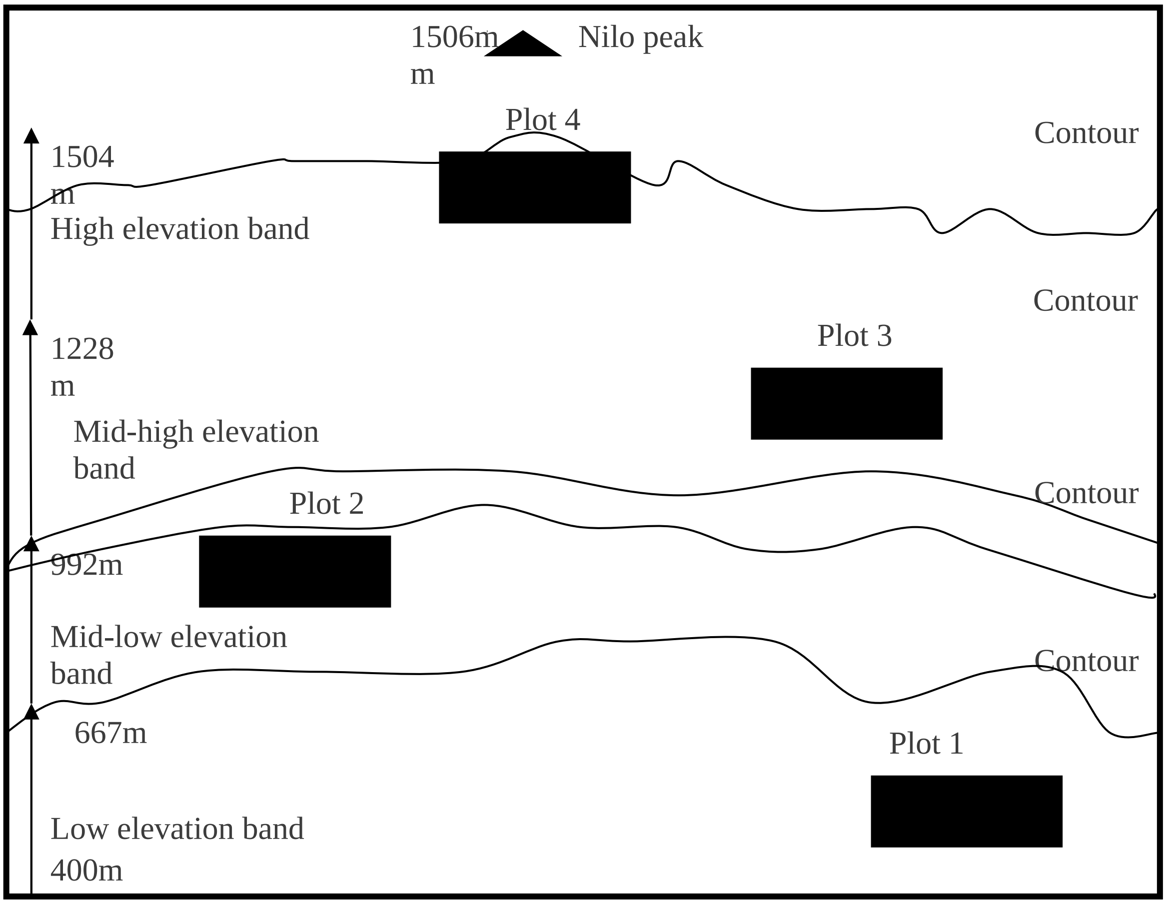
# APPENDICES

## Appendix 1: Sketch diagram of Sapling design in the Nilo Nature Reserve



**Appendix 2: Importance Value Index and carbon storage for each tree species in Nilo Nature Reserve**

| S/n | Species botanical name | RF | RDo | RD | IVI | C ($tha^{-1}$) |
|---|---|---|---|---|---|---|
| 1 | Sensypallum msolo | 6.04 | 11.64 | 7.15 | 30.44 | 21.89 |
| 2 | *Newtonia buchananii* | 3.13 | 6.58 | 2.81 | 15.96 | 13.83 |
| 3 | *Cylicomorpha* parviflora | 2.68 | 6.15 | 2.95 | 15.25 | 13.63 |
| 4 | *Strombosia scheffleri* | 4.25 | 6.54 | 4.07 | 17.15 | 12.07 |
| 5 | *Albizia gummifera* | 1.34 | 4.60 | 0.84 | 10.04 | 11.24 |
| 6 | *Albizia* zimmermannii | 1.34 | 4.91 | 0.98 | 10.79 | 10.35 |
| 7 | Tabarnaemontana usambarensis | 6.04 | 5.97 | 8.56 | 20.50 | 9.49 |
| 8 | Deinbollia kilimandischarica | 0.22 | 0.01 | 0.28 | 0.30 | 7.96 |
| 9 | *Leptonychia usambarensis* | 7.16 | 2.59 | 13.74 | 18.92 | 7.60 |
| 10 | Trichilia emetica | 1.12 | 2.55 | 0.84 | 5.94 | 5.85 |
| 11 | *Polyscias fulva* | 2.01 | 2.28 | 2.38 | 6.94 | 4.86 |
| 12 | *Syzygium guinensis* | 0.67 | 2.05 | 0.42 | 4.53 | 4.60 |
| 13 | *Zanha golungensis* | 0.22 | 1.89 | 0.14 | 3.92 | 4.47 |
| 14 | *Malanthes genemias* | 0.22 | 1.86 | 0.14 | 3.85 | 4.38 |
| 15 | *Cephalosphaera usambarensis* | 2.01 | 2.65 | 3.23 | 8.54 | 4.32 |
| 16 | Isoberlinia scheffleri | 1.5 | 1.43 | 1.82 | 4.68 | 4.31 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 7 | | | | |
| | | 5.3 | | | | |
| 17 | *Myrianthus holstii* | 7 | 2.79 | 3.79 | 9.37 | 4.07 |
| | | 2.4 | | | | |
| 18 | *Shirakiopsis elipticum* | 6 | 2.15 | 2.38 | 6.69 | 3.50 |
| | | 1.5 | | | | |
| 19 | Lansianthus kilimandischaricus | 7 | 0.14 | 1.26 | 1.54 | 3.05 |
| | | 1.3 | | | | |
| 20 | *Quassia undulata* | 4 | 1.74 | 1.12 | 4.61 | 2.95 |
| | | 0.4 | | | | |
| 21 | *Parinari excelsa* | 5 | 1.18 | 0.28 | 2.64 | 2.51 |

| **S/n** | **Species botanical name** | **RF** | **RDo** | **RD** | **IVI** | **C (tha$^{-1)}$** |
|---|---|---|---|---|---|---|
| | | 0.2 | | | | |
| 22 | Hoslundia opposita | 2 | 0.02 | 0.28 | 0.32 | 2.38 |
| | | 1.1 | | | | |
| 23 | Sensypallum cerasiferum | 1 | 1.28 | 0.7 | 3.25 | 2.22 |
| | | 0.2 | | | | |
| 24 | *Margaritaria discoidea* | 2 | 0.11 | 0.28 | 0.50 | 1.97 |
| | | 2.2 | | | | |
| 25 | *Drypetes gerrardii* | 4 | 3.79 | 1.96 | 9.54 | 1.93 |
| | | 2.2 | | | | |
| 26 | *Chrysophyllum gorungosanum* | 4 | 1.21 | 1.68 | 4.10 | 1.90 |
| | | 3.5 | | | | |
| 27 | *Sorindeia madagascariensis* | 8 | 1.18 | 2.24 | 4.60 | 1.79 |
| | | 1.3 | | | | |
| 28 | *Ficus valis-chao-dae* | 4 | 0.55 | 1.12 | 2.22 | 1.41 |
| | | 0.8 | | | | |
| 29 | *Mesogyne insignis* | 9 | 0.63 | 1.40 | 2.66 | 1.30 |
| | | 0.2 | | | | |
| 30 | *Casearia batiscombei* | 2 | 0.67 | 0.14 | 1.48 | 1.29 |
| | | 0.4 | | | | |
| 31 | *Cola grenwayii* | 5 | 0.72 | 0.70 | 2.13 | 1.13 |
| 32 | *Cola scheffleri* | 0.4 | 0.61 | 0.28 | 1.50 | 1.09 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 5<br>1.3 | | | | |
| 33 | Antiaris toxicaria | 4<br>0.6 | 0.61 | 0.98 | 2.20 | 1.07 |
| 34 | *Cleistanthus polystachyus* | 7<br>0.8 | 0.65 | 0.84 | 2.14 | 1.02 |
| 35 | Trilepsium madagascariensis | 9<br>2.0 | 0.58 | 0.56 | 1.72 | 0.92 |
| 36 | Allophyilus meliodorus | 1<br>1.1 | 0.65 | 1.40 | 2.69 | 0.89 |
| 37 | *Ficus sur* | 2<br>0.6 | 0.29 | 1.26 | 1.85 | 0.76 |
| 38 | Allanblackia stulhmanii | 7<br>0.6 | 0.33 | 0.42 | 1.09 | 0.55 |
| 39 | *Barringtonia racemosa* | 7<br>1.5 | 0.38 | 0.42 | 1.18 | 0.53 |
| 40 | Aulacocalyx toxit | 7<br>0.2 | 0.46 | 0.14 | 1.05 | 0.53 |
| 41 | *Garcinia volkensii* | 2<br>1.3 | 0.00 | 0.14 | 0.15 | 0.46 |
| 42 | *Ficus exasperata* | 4<br>0.6 | 0.13 | 0.84 | 1.10 | 0.37 |
| 43 | Celtis gomphophylla | 7<br>0.6 | 0.20 | 0.56 | 0.96 | 0.24 |
| 44 | *Zenkerella egregia* | 7<br>4.9 | 0.17 | 0.70 | 1.05 | 0.19 |
| 45 | *Macaranga capensis* | 2 | 7.54 | 5.33 | 20.40 | 0.18 |

| S/n | Species botanical name | RF | RDo | RD | IVI | C (tha$^{-1)}$ |
|---|---|---|---|---|---|---|
| 46 | *Maesa lanceolata* | 1.12 | 0.12 | 1.26 | 1.51 | 0.15 |
| 47 | Entandrophragma excelsum | 1.12 | 1.12 | 0.70 | 2.94 | 0.15 |
| 48 | *Trema orientalis* | 0.22 | 0.10 | 0.14 | 0.35 | 0.14 |
| 49 | Rothmannia manganjae | 0.67 | 0.12 | 0.42 | 0.67 | 0.14 |
| 50 | *Khaya anthotheca* | 0.45 | 1.84 | 0.28 | 3.96 | 0.13 |
| 51 | Croton macrostachyus, | 0.22 | 0.09 | 0.14 | 0.33 | 0.12 |
| 52 | *Celtis africana* | 0.89 | 0.11 | 0.56 | 0.78 | 0.12 |
| 53 | *Xymalos monospora* | 0.89 | 0.11 | 0.56 | 0.79 | 0.12 |
| 54 | Psychotria faucicola | 1.12 | 0.12 | 1.12 | 1.37 | 0.11 |
| 55 | *Breonadia salicium* | 0.22 | 0.06 | 0.14 | 0.26 | 0.07 |
| 56 | *Cussonia spicata* | 0.89 | 0.07 | 0.70 | 0.85 | 0.06 |
| 57 | Blighia unijugata | 0.67 | 0.05 | 0.42 | 0.53 | 0.06 |
| 58 | Alsodeiopsis schumannii | 1.12 | 0.07 | 1.12 | 1.26 | 0.06 |
| 59 | *Milletia oblata* | 0.22 | 0.04 | 0.14 | 0.22 | 0.05 |
| 60 | Rothmannia mepiliciformis | 0.67 | 0.02 | 0.70 | 0.75 | 0.03 |
| 61 | *Harungana madagascariensis* | 1.12 | 0.34 | 0.70 | 1.39 | 0.01 |
| 62 | Phyllanthus amarus | 0.45 | 0.01 | 0.28 | 0.31 | 0.01 |
| 63 | *Chytranthus obliquineries* | 0.22 | 0.01 | 0.14 | 0.16 | 0.01 |
| 64 | Calancoba welwitschii | 0.45 | 0.01 | 0.28 | 0.30 | 0.01 |
| 65 | Clerodendrum rotundifolium | 0.22 | 0.01 | 0.14 | 0.15 | 0.01 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 66 | Antidesma membranaceum | 0.2<br>2 | 0.01 | 1.82 | 1.84 | 0.01 |
| 67 | Cremaspora triflora | 0.2<br>2 | 0.01 | 0.14 | 0.15 | 0.01 |
| 68 | *Milicia exelsa* | 0.2<br>2 | 0.01 | 0.14 | 0.15 | 0.00 |
| 69 | *Milletia dura* | 0.2<br>2 | 0.01 | 0.14 | 0.15 | 0.00 |
| 70 | *Cussonia arborea* | 0.2<br>2 | 0.01 | 0.14 | 0.15 | 0.00 |
| 71 | Rytigynia schummanii | 0.2<br>2 | 0.01 | 0.14 | 0.15 | 0.00 |
| 72 | Tarrenna nigrescens | 0.2<br>2 | 0.00 | 0.14 | 0.15 | 0.00 |
| 73 | *Funtumia africana* | 3.5<br>8 | 1.06 | 3.23 | 5.34 | 0.00 |
| 74 | Vernonia colorata. | 0.2<br>2 | 0.00 | 0.14 | 0.15 | 0.00 |
| 75 | Oxyanthus speciosa | 0.2<br>2 | 0.00 | 0.14 | 0.15 | 0.00 |
| 76 | *Garcinia buchananii* | 0.2<br>2 | 0.00 | 0.14 | 0.15 | 0.00 |
| 77 | *Rinorea ferruginea* | 0.2<br>2 | 0.00 | 0.14 | 0.15 | 0.00 |
| | **Total** | **100** | **100** | **100** | **300** | **184.61** |

**Appendix 3: Dominant tree density in various blocks in the natural forests**

| Elevations | Dominant tree species | Wood density |
|---|---|---|
| 1228-1504 m | *Tabarnaemontana usambarensis* | 0.55 |
| 992-1228 m | *Macaranga capensis* | 0.50 |
| 667-992 m | *Sensypallum msolo* | 0.37 |
| 400-667 m | *Cephalosphaera usambarensis* | 0.58 |
| | **The average density** | **0.50** |

**Appendix 4: Average diameter, species diversity, stem density, basal area, and volume and carbon stock per plot in Nilo Nature Reserve**

| Plot No. | Stand structure parameter and carbon stock per plot | | | | | | Carbon ($tha^{-1}$) |
|---|---|---|---|---|---|---|---|
| | Species composition per plot | Diversity (H') | Mean diameter per plot | Stem density | Basal area ($m^2ha^{-1}$) | Volume ($m^3ha^{-1}$) | |
| 1 | 5 | 2.49 | 46.67 | 250 | 2810.93 | 2810.93 | 1043.78 |
| 2 | 2 | 2.49 | 30.33 | 100 | 193.35 | 193.35 | 71.80 |
| 3 | 3 | 2.49 | 38.68 | 150 | 401.47 | 401.47 | 149.08 |
| 4 | 4 | 2.49 | 39.02 | 200 | 414.63 | 414.63 | 153.96 |
| 5 | 5 | 2.49 | 34.54 | 250 | 329.79 | 329.79 | 122.46 |
| 6 | 8 | 2.49 | 24.97 | 450 | 447.03 | 447.03 | 165.99 |
| 7 | 11 | 2.49 | 30.99 | 550 | 2087.31 | 2087.31 | 775.08 |
| 8 | 7 | 2.49 | 13.58 | 300 | 132.12 | 132.12 | 49.06 |
| 9 | 5 | 2.49 | 21.05 | 250 | 280.36 | 280.36 | 104.11 |
| 10 | 10 | 2.49 | 22.41 | 500 | 499.36 | 499.36 | 185.43 |
| 11 | 4 | 2.49 | 24.32 | 250 | 380.05 | 380.05 | 141.12 |
| 12 | 4 | 1.56 | 21.25 | 200 | 251.74 | 251.74 | 93.48 |
| 13 | 6 | 0.91 | 22.24 | 300 | 270.91 | 270.91 | 100.60 |
| 14 | 6 | 1.97 | 10.71 | 300 | 41.84 | 41.84 | 15.53 |
| 15 | 8 | 1.76 | 17.56 | 400 | 392.97 | 392.97 | 145.90 |
| 16 | 5 | 2.25 | 38.82 | 250 | 835.55 | 835.55 | 310.27 |
| 17 | 3 | 1.61 | 31.13 | 200 | 310.62 | 310.62 | 115.34 |
| 18 | 2 | 1.39 | 19.28 | 150 | 55.24 | 55.24 | 20.51 |
| 19 | 2 | 1.00 | 62.35 | 100 | 656.79 | 656.79 | 243.89 |
| 20 | 2 | 0.69 | 79.53 | 100 | 1231.36 | 1231.36 | 457.24 |
| 21 | 8 | 2.17 | 32.46 | 400 | 965.65 | 965.65 | 358.57 |
| 22 | 5 | 1.79 | 10.52 | 300 | 19.16 | 19.16 | 7.11 |
| 23 | 6 | 1.97 | 31.36 | 300 | 1453.41 | 1453.41 | 539.70 |
| 24 | 5 | 1.99 | 19.83 | 300 | 248.66 | 248.66 | 92.33 |
| 25 | 5 | 1.39 | 15.29 | 200 | 80.69 | 80.69 | 29.96 |
| 26 | 10 | 2.66 | 15.41 | 500 | 189.56 | 189.56 | 70.39 |
| 27 | 6 | 1.99 | 20.67 | 300 | 280.62 | 280.62 | 104.20 |
| 28 | 7 | 1.93 | 16.94 | 500 | 161.04 | 161.04 | 59.80 |

| Plot No. | Stand structure parameter and carbon stock per plot | | | | | | Carbon (tha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| | Species composition per plot | Diversity (H') | Mean diameter per plot | Stem density | Basal area (m$^2$ha$^{-1}$) | Volume (m$^3$ha$^{-1}$) | |
| 29 | 3 | 0.55 | 8.83 | 500 | 7.67 | 7.67 | 2.85 |
| 30 | 8 | 1.73 | 28.59 | 250 | 457.90 | 457.90 | 170.03 |
| 31 | 5 | 1.39 | 8.02 | 200 | 7.30 | 7.30 | 2.71 |
| 32 | 9 | 2.19 | 11.63 | 400 | 59.33 | 59.33 | 22.03 |
| 33 | 3 | 1.10 | 58.80 | 150 | 534.09 | 534.09 | 198.32 |
| 34 | 13 | 2.56 | 17.53 | 650 | 419.43 | 419.43 | 155.75 |
| 35 | 2 | 0.69 | 9.45 | 250 | 4.59 | 4.59 | 1.71 |
| 36 | 3 | 0.97 | 13.33 | 250 | 24.12 | 24.12 | 8.96 |
| 37 | 7 | 2.15 | 27.70 | 350 | 1141.08 | 1141.08 | 423.72 |
| 38 | 7 | 2.11 | 22.84 | 350 | 956.89 | 956.89 | 355.32 |
| 39 | 5 | 1.65 | 16.84 | 250 | 79.37 | 79.37 | 29.47 |
| 40 | 5 | 1.65 | 29.32 | 250 | 233.38 | 233.38 | 86.66 |
| 41 | 7 | 2.19 | 16.93 | 350 | 234.01 | 234.01 | 86.89 |
| 42 | 5 | 2.11 | 23.47 | 350 | 448.08 | 448.08 | 166.39 |
| 43 | 6 | 1.76 | 22.32 | 300 | 309.68 | 309.68 | 114.99 |
| 44 | 6 | 1.81 | 31.53 | 300 | 680.26 | 680.26 | 252.60 |
| 45 | 6 | 1.91 | 34.13 | 300 | 613.16 | 613.16 | 227.69 |
| 46 | 7 | 2.11 | 32.37 | 350 | 670.22 | 670.22 | 248.87 |
| 47 | 4 | 1.39 | 42.02 | 200 | 416.63 | 416.63 | 154.71 |
| 48 | 6 | 1.39 | 42.57 | 200 | 923.67 | 923.67 | 342.99 |
| 49 | 6 | 1.47 | 13.28 | 250 | 71.04 | 71.04 | 26.38 |
| 50 | 7 | 2.07 | 25.20 | 350 | 520.76 | 520.76 | 193.38 |
| 51 | 5 | 1.64 | 26.65 | 250 | 948.56 | 948.56 | 352.23 |
| 52 | 2 | 0.35 | 21.50 | 100 | 92.63 | 92.63 | 34.40 |
| 53 | 10 | 2.64 | 19.16 | 500 | 424.69 | 424.69 | 157.70 |
| 54 | 5 | 1.65 | 20.53 | 250 | 193.23 | 193.23 | 71.75 |
| 55 | 2 | -1.04 | 58.08 | 100 | 863.89 | 863.89 | 320.79 |
| 56 | 5 | 1.70 | 34.61 | 250 | 807.30 | 807.30 | 299.77 |
| 57 | 8 | 2.17 | 18.96 | 400 | 230.49 | 230.49 | 85.59 |
| 58 | 6 | 1.86 | 19.31 | 300 | 148.39 | 148.39 | 55.10 |

| Plot No. | Stand structure parameter and carbon stock per plot | | | | | | Carbon (tha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| | Species composition per plot | Diversity (H') | Mean diameter per plot | Stem density | Basal area (m$^2$ha$^{-1}$) | Volume (m$^3$ha$^{-1}$) | |
| 59 | 7 | 2.11 | 26.04 | 350 | 648.84 | 648.84 | 240.94 |
| 60 | 4 | 1.39 | 37.63 | 200 | 750.71 | 750.71 | 278.76 |
| 61 | 9 | 2.47 | 20.33 | 450 | 365.74 | 365.74 | 135.81 |
| 62 | 8 | 2.25 | 33.25 | 400 | 720.62 | 720.62 | 267.59 |
| 63 | 4 | 1.04 | 24.38 | 200 | 356.65 | 356.65 | 58.16 |
| 64 | 5 | 1.70 | 28.90 | 250 | 268.80 | 268.80 | 174.09 |
| 65 | 5 | 1.56 | 17.80 | 250 | 171.28 | 171.28 | 63.60 |
| 66 | 6 | 1.84 | 53.13 | 300 | 2253.56 | 2253.56 | 836.81 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 67 | 6 | 1.93 | 35.73 | 300 | 1249.14 | 1249.14 | 463.84 |
| 68 | 5 | 1.83 | 24.49 | 300 | 321.12 | 321.12 | 119.24 |
| 69 | 5 | 1.79 | 11.23 | 300 | 29.31 | 29.31 | 10.88 |
| 70 | 3 | 0.91 | 18.20 | 150 | 105.59 | 105.59 | 39.21 |
| 71 | 5 | 2.07 | 21.16 | 350 | 319.56 | 319.56 | 118.66 |
| 72 | 4 | 0.06 | 19.36 | 200 | 328.05 | 328.05 | 121.82 |
| 73 | 6 | 1.83 | 13.84 | 300 | 101.06 | 101.06 | 37.53 |
| 74 | 4 | 1.26 | 26.50 | 200 | 238.50 | 238.50 | 88.56 |
| 75 | 9 | 2.60 | 26.66 | 500 | 749.75 | 749.75 | 278.41 |
| 76 | 10 | 2.75 | 25.19 | 500 | 756.37 | 756.37 | 280.86 |
| 77 | 7 | 1.43 | 25.55 | 350 | 882.95 | 882.95 | 327.86 |
| 78 | 7 | 1.64 | 12.99 | 350 | 122.98 | 122.98 | 45.67 |
| 79 | 6 | 1.86 | 19.07 | 300 | 118.71 | 118.71 | 44.08 |
| 80 | 9 | 2.34 | 16.97 | 400 | 265.02 | 265.02 | 98.41 |

**Appendix 5: Multiple comparisons for average diameter between elevation bands in Nilo Nature Reserve**

| (I) Elevation band | (J) Elevation band | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval Lower Bound | Upper Bound |
|---|---|---|---|---|---|---|
| HE | MHE | 10.70* | 3.95 | 0.01 | 2.84 | 18.56 |
| | MLE | 3.16 | 3.95 | 0.43 | -4.70 | 11.02 |
| | LE | 7.74 | 3.95 | 0.05 | -0.13 | 15.60 |
| MHE | HE | -10.70* | 3.95 | 0.01 | -18.56 | -2.84 |
| | MLE | -7.55 | 3.95 | 0.06 | -15.41 | 0.31 |
| | LE | -2.97 | 3.95 | 0.45 | -10.83 | 4.89 |
| MLE | HE | -3.16 | 3.95 | 0.43 | -11.02 | 4.70 |
| | MHE | 7.55 | 3.95 | 0.06 | -0.31 | 15.41 |
| | LE | 4.58 | 3.95 | 0.25 | -3.28 | 12.44 |
| LD | HE | -7.74 | 3.95 | 0.05 | -15.60 | 0.13 |
| | MHE | 2.97 | 3.95 | 0.45 | -4.89 | 10.83 |
| | MLE | -4.58 | 3.95 | 0.25 | -12.44 | 3.28 |

*The mean difference is significant at the 0.05 level

**Appendix 6: Multiple comparisons for basal area between elevation bands in Nilo Nature Reserve**

| (I) Elevation band | (J) Elevation band | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval Lower | Upper |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | Bound | Bound |
| HE | MHE | 540.10* | 237.47 | 0.026 | 67.13 | 1013.0693 |
| | MLE | 265.05 | 237.47 | 0.268 | -207.92 | 738.0193 |
| | LE | 474.60* | 237.47 | 0.049 | 1.63 | 947.5693 |
| MHE | HE | -540.10* | 237.47 | 0.026 | -1013.07 | -67.1307 |
| | MLE | -275.05 | 237.47 | 0.250 | -748.02 | 197.9193 |
| | LE | -65.50 | 237.47 | 0.783 | -538.47 | 407.4693 |
| MLE | HE | -265.05 | 237.47 | 0.268 | -738.02 | 207.9193 |
| | MHE | 275.05 | 237.47 | 0.250 | -197.92 | 748.0193 |
| | LE | 209.55 | 237.47 | 0.380 | -263.42 | 682.5193 |
| LE | HE | -474.60* | 237.47 | 0.049 | -947.57 | -1.6307 |
| | MHE | 65.50 | 237.47 | 0.783 | -407.47 | 538.4693 |
| | MLE | -209.55 | 237.47 | 0.380 | -682.52 | 263.4193 |

* The mean difference is significant at the 0.05 level

**Appendix 7: Multiple comparisons for volume between elevation bands in Nilo Nature Reserve**

| (I) Elevation band | (J) Elevation band | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| HE | MHE | 685873.90* | 322330.26 | 0.037 | 43897.54 | 1327850.26 |
| | MLE | 389508.59 | 322330.26 | 0.231 | -252467.77 | 1031484.94 |
| | LE | 635664.52 | 322330.26 | 0.052 | -6311.84 | 1277640.87 |
| MHE | HE | 685873.90* | 322330.26 | 0.037 | 1327850.26 | -43897.54 |
| | MLE | 296365.31 | 322330.26 | 0.361 | -938341.67 | 345611.04 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | LE | -50209.38 | 322330.26 | 0.877 | -692185.74 | 591766.97 |
| MLE | HE | -389508.59 | 322330.26 | 0.231 | 1031484.94 | 252467.77 |
| | MHE | 296365.31 | 322330.26 | 0.361 | 345611.04 | 938341.67 |
| | LE | 246155.93 | 322330.26 | 0.447 | -395820.43 | 888132.29 |
| LE | HE | -635664.52 | 322330.26 | 0.052 | 1277640.87 | 6311.84 |
| | MHE | 50209.38 | 322330.26 | 0.877 | -591766.97 | 692185.74 |
| | MLE | -246155.93 | 322330.26 | 0.447 | -888132.29 | 395820.43 |

* The mean difference is significant at the0 .05 level

**Appendix 8: Multiple comparisons for carbon stock between elevation bands in Nilo Nature Reserve**

| (I) elevation band | (J) Elevation band | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval Lower Bound | 95% Confidence Interval Upper Bound |
|---|---|---|---|---|---|---|
| HE | MHE | 12.74* | 5.98 | 0.037 | 0.81 | 24.65 |
| | MLE | 7.23 | 5.98 | 0.231 | -4.69 | 19.15 |
| | LE | 11.80 | 5.98 | 0.052 | -0.12 | 23.72 |
| MHE | HE | -12.74* | 5.98 | 0.037 | -24.65 | -0.82 |
| | MLE | -5.50 | 5.98 | 0.361 | -17.42 | 6.42 |
| | LE | -.93 | 5.98 | 0.877 | -12.85 | 10.99 |
| MLE | HE | -7.23 | 5.98 | 0.231 | -19.15 | 4.69 |
| | MHE | 5.50 | 5.98 | 0.361 | -6.42 | 17.42 |
| | LE | 4.57 | 5.98 | 0.447 | -7.35 | 16.49 |
| LE | HE | -11.80 | 5.98 | 0.052 | -23.72 | 0.1175 |
| | MHE | .933 | 5.98 | 0.877 | -10.99 | 12.85 |
| | MLE | -4.57 | 5.98 | 0.447 | -16.49 | 7.35 |

* The mean difference is significant at the 0.05 level.

**Appendix 9: Tree species and their families found in Nilo Nature Reserve**

| S/n | Species name | Family name | Growth form |
|---|---|---|---|
| 1 | *Sorindeia madagascariensis* | Anacardiaceae | Tree |
| 2 | *Funtumia africana* | Apocynaceae | Tree |
| 3 | *Tabarnaemontana usambarensis* | Apocynaceae | Tree |
| 4 | *Croton macrostachyus,* | Euphorbiaceae | Tree |
| 5 | *Cussonia arborea* | Araliaceae | Tree |
| 6 | *Polyscias fulva* | Araliaceae | Tree |
| 7 | *Isoberlinia scheffleri* | Caesalpiniaceae | Tree |
| 8 | *Zenkerella egregia* | Caesalpiniaceae | Tree |
| 9 | *Cussonia spicata* | Caricaceae | Tree |
| 10 | *Myrianthus holstii* | Cecropiaceae | Tree |
| 11 | *Maranthes polyandra* | Chrysobalanaceae | Tree |
| 12 | *Parinari excelsa* | Chrysobalanaceae | Tree |
| 13 | *Garcinia buchananii* | Clusiaceae | Tree |
| 14 | *Garcinia volkensii* | Clusiaceae | Tree |
| 15 | *Harungana madascariensis* | Clusiaceae | Tree |
| 16 | *Allanblackia stulhmanii* | Clusiaceae | Tree |
| 17 | *Vernonia colorata.* | Compositae/Asteraceae | Shrub |
| 18 | *Antidesma membranaceum* | Euphorbiaceae | Tree |
| 19 | *Chytranthus obliquineries* | Euphorbiaceae | Tree |
| 20 | *Cremaspora triflora* | Euphorbiaceae | Tree |
| 21 | *Drypetes gerradii* | Euphorbiaceae | Tree |
| 22 | *Macaranga capensis* | Euphorbiaceae | Tree |
| 23 | *Margaritaria discoidea* | Euphorbiaceae | Tree |
| 24 | *Phyllanthus amarus* | Euphorbiaceae | Shrub |
| 25 | *Casearia batiscombei* | Flacourtiaceae | Tree |
| 26 | *Cola scheffleri* | Flacourtiaceae | Tree |
| 27 | *Shirakiopsis elipticum* | Sterculiaceae | Tree |
| 28 | *Alsodeiopsis schumannii* | Icacinaceae | Tree |
| 29 | *Hoslundia opposita* | Lamiaceae | Shrub |
| 30 | *Barringtonia racemosa* | Lecythidaceae | Tree |

| S/n | ***Species name*** | **Family name** | **Growth form** |
|---|---|---|---|
| 31 | *Entandrophragma excelsum* | Meliaceae | Tree |
| 32 | *Khaya anthotheca* | Meliaceae | Tree |
| 33 | *Trichilia emetica* | Meliaceae | Tree |
| 34 | *Albizia gummifera* | Mimosaceae | Tree |
| 35 | *Albizia zimmermannii* | Mimosaceae | Tree |
| 36 | *Newtonia buchananii* | Mimosaceae | Tree |
| 37 | *Xymalos monospora* | Monimiaceae | Tree |
| 38 | *Antiaris toxicaria* | Moraceae | Tree |
| 39 | *Ficus exasperata* | Moraceae | Tree |
| 40 | *Ficus sur* | Moraceae | Tree |
| 41 | *Ficus valis-chao-dae* | Moraceae | Tree |
| 42 | *Milicia exelsa* | Moraceae | Tree |
| 43 | *Mesogyne insignis* | Moraceae | Tree |
| 44 | *Trilepsium madagascariensis* | Moraceae | Tree |
| 45 | *Cephalosphaera usambarensis* | Myristicaceae | Tree |
| 46 | *Maesa lanceolata* | Myristicaceae | Tree |
| 47 | *Syzygium guineense* | Myrtaceae | Tree |
| 48 | *Strombosia scheffleri* | Olacaceae | Tree |
| 49 | *Milletia dura* | Papilionaceae | Tree |
| 50 | *Milletia oblata* | Papilionaceae | Tree |
| 51 | *Aulacocalyx t* | Rubiaceae | Tree |
| 52 | *Breonadia salicina* | Rubiaceae | Tree |
| 53 | *Calancoba welwitschii* | Flacourtiaceae | Tree |
| 54 | *Lansianthus kilimandischaricus* | Rubiaceae | Tree |
| 55 | *Psychotria faucicola* | Rubiaceae | Tree |
| 56 | *Rinorea ferruginea* | Violaceae | Tree |
| 57 | *Rothmannia manganjae* | Rubiaceae | Tree |
| 58 | *Rothmannia mepiliciformis* | Rubiaceae | Tree |
| 59 | *Rytigynia schummanii* | Rubiaceae | Tree |
| 60 | *Tarrenna nigrescens* | Rubiaceae | Tree |
| 61 | *Allophyilus meliodorus* | Sapindaceae | Tree |

| S/n | *Species name* | Family name | Growth form |
|---|---|---|---|
| 62 | *Blighia unijugata* | Sapindaceae | Tree |
| 63 | *Deinbollia kilimandischarica* | Sapindaceae | Tree |
| 64 | *Sensypallum cerasiferum* | Sapindaceae | Tree |
| 65 | *Zanha golungensis* | Sapindaceae | Tree |
| 66 | *Chrysophyllum gorungosanum* | Sapotaceae | Tree |
| 67 | *Cylicomorpha parviflora* | Sapotaceae | Tree |
| 68 | *Sensypallum msolo* | Sapotaceae | Tree |
| 69 | *Quassia undulata* | Simaroubaceae | Tree |
| 70 | *Clerodendrum rotundifolium* | Lamiaceae | Shrub |
| 71 | *Cola greenwayii* | Sterculiaceae | Tree |
| 72 | *Leptonychia usambarensis* | Sterculiaceae | Tree |
| 73 | *Celtis africana* | Ulmaceae | Tree |
| 74 | *Celtis gomphophylla* | Ulmaceae | Tree |
| 75 | *Trema orientalis* | Ulmaceae | Tree |
| 76 | *Oxyanthus speciosa* | Rubiaceae | Tree |
| 77 | *Cleistanthus polystachyus* | Euphorbiaceae | Tree |