# EVALUATING FOREST SAMPLING SCHEMES FOR SELECTED NATURAL FOREST TYPES IN KENYA

By

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# DECLARATION

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## Declaration by Supervisors

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# DEDICATION

This thesis is graciously dedicated to my wife, children and parents, and to all friends of forest conservation.

# ABSTRACT

This study determined and compared relative efficiency of commonly used sampling designs, intensities and plot sizes in assessing tropical natural forests. Relative efficiencies of random and systematic sampling designs with four plot sizes (25, 50, 100 and 400 $m^2$) and varying intensities (5, 10, 20 and 30%) were investigated with reference to full-cover 1-ha inventory in selected forest types: tropical rain forest (TRF), moist lower montane forest (MMF) and dry woodland forest (DWF) in Kenya. We hypothesized an ecological gradient from dry woodland foresst through montane to tropical rain forests mirrored by biophysical characteristics; that different forest ecosystems require different sampling protocols; and that optimal sampling designs, intensities and plot sizes exist for different forest attributes. Fifty-six sampling schemes were generated for efficiency testing using computed statistics in R-software and actual field data. Sampling error and effort (time) were intergrated to measure efficiency of each sampling scheme in estimating selected attributes. The three forests formed a complexity gradient in composition, structure, diversity and slope. Different sampling schemes resulted in mixed outcome for tested attributes across the forest types. Efficient schemes for tree regeneration include SSH-10mx5m-5% with 80% efficiency in TRF, SSD-10mx10m-30% with 81% efficiency in MMF and SRS-10mx10m-30% with 90% efficiency in DWF. Schemes for forest density include SSV-20mx20m-20% with 98% efficiency in TRF, SSH-10mx10m-20% with 99% efficiency in MMF and SSV-10mx5m-30% with 92% efficiency in DWF. Quadratic mean diameter sampling schemes are SSH-20mx20m-20% with 94% efficiency in TRF, SRS-10mx10m-20% with 75% efficiency in MMF and SRS-10mx10m-20% with 90% efficiency in DWF. Basal area assessment requires 100% inventory of 1 ha plot, subdivided into 20 m x 20 m data compilation units. For species diversity assessment, most efficient sampling schemes include 30% SSH with any plot size between 5m x 5 m and 20 m x 20 m in TRF and 10% SSH with 10 m x 5 m or 10 m x 10 m plot sizes in DWF. In MMF, all sampling options underestimated actual number of species. Where low sampling intensities are efficient in capturing species richness per hectare, there is no need to spend money and time on higher intensities. To construct cumulative species-area curves, one hectare data recorded in 5 m x 5 m units were found enough across the three forest types. The 30% sampling intensity was significantly favorable for both TRF (SSH-5mx5m-30% and SSH-10mx5m-30%; $R^2>99\%$) and MMF (SSH-20mx20m-30%; $R^2=86\%$). Slope gradient influenced efficiency of sampling for regeneration and basal area in the montane forest. The suitability of tested sampling options varied among attributes and across forest types. As such, multiple resource inventories require integration of different sampling schemes to ensure efficiency.

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# ABBREVIATIONS AND ACRONYMS

## Abbreviations

| | |
|---|---|
| ALS | Airborne Laser Scanning |
| CBFP | The Congo Basin Forest Partenership |
| DAP | Digital Aerial Photogrammetry |
| DBH | Diameter at breast height |
| DWF | Dry Woodland Forest |
| GHGs | Green house gases |
| HSR | High Spatial Resolution |
| MMF | Moist Montane Forest |
| QMD | Quadratic mean diameter |
| REDD+ | Reducing Emissions from Deforestation and Degradation |
| SCBD | Secretariat of the Convention on Biological Diversity |
| SLEEK | System for Land-Based Emission Estimation in Kenya |
| SRS | Simple Random Sampling |
| SS | Systematic Sampling |
| SSD | Systematic sampling along diagonal transect |
| SSH | Systematic sampling along horizontal transect |
| SSV | Systematic sampling along vertical transect |
| TLS | Terrestrial Laser Scanning |
| TRF | Tropical Rain Forest |
| VHSROSI | Very High Spatial Resolution Optical Satellite Imagery |

# Acronyms

| | |
|---|---|
| CCI | Clinton Climate Initiative |
| CMGGR | Committee On Managing Global Genetic Resources |
| CSIRO | Commonwealth Scientific and Industrial Research Organization |
| DRSRS | Directorate of Resource Surveys and Remote Sensing |
| FAO | Food and Agriculture Organisation |
| IPCC | Intergovernmental Panel on Climate Change |
| KEFRI | Kenya Forestry Research Institute |
| KFS | Kenya Forests Service |
| MENR | Ministry of Environment and Natural Resources |
| RCMRD | Regional Centre for Mapping of Resources for Development |
| SOK | Survey of Kenya |
| UNO | United Nations Organisation |

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# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

Resource managers need accurate and timely quantitative resource information to make decisions wisely (Schreuder, Gregoire & Wood, 1993) at various levels: locally, nationally, regionally and internationally (Wong, Thornber & Baker, 2001). Given the scarcity of resources and the scale of the challenge, there is a need to maximize the efficiency of both sampling strategies and sampling units. Generally, there is substantial improvement in prediction accuracy from larger plots compared to smaller plots (Mauya, et al., 2015). Unfortunately, there is little information on the relative efficiency of different approaches to floristic assessment in tropical natural forests. In Kenya, for example, the need for accurate and comprehensive information on the national forest and tree resources is felt for implementation of the National Strategy for Reducing Emissions from Deforestation and Forest Degradation (REDD+).

The above REDD+ strategy focuses on protecting the remaining forest resources and enhancing forest carbon stocks to improve local livelihoods and biodiversity (Nduati et al., 2016). It requires a back up of environmentally and socially sustainable forest and land-use policies. A key limitation for successful implementation of the REDD+ strategy is lack of reliable methods for quantifying forest aboveground biomass (Herold & Skutsch, 2011; Shijo, Herold, Sunderlin & Verchot, 2013). In Kenya, a national technical guideline is being developed to act as framework of undertaking mapping of land use and land cover classification by use of remote sensing data. The guideline or manual will enable the country participate in monitoring and estimating land based GHG emissions by providing consistent, complete, and time-series land cover change information (Directorate of Resource Surveys and Remote Sensing [DRSRS] et al., 2019).

Globally, the loss of biodiversity on Earth is reported to be a major threat to ecosystems and human well-being (Groombridge & Jenkins, 2000; Millennium Ecosystem Assessment, 2005; Mulatu, Mora, Kooistra & Herold, 2017). While accurate and consistent information on forest area and forest area change are needed to halt the loss of biodiversity at global, continental and regional scales. Feld et al. *(*2009) noted that existing policies have not yet adequately stimulated the development of comprehensive indicator systems suited to detect and measure the state and trends in biodiversity and their implication on ecosystem service provision. To close the critical information gaps, there is a need for a comprehensive and standardised design for sampling and data generation to permit comparisons across different areas and ecosystems. There is also a need to develop common monitoring schemes within and across habitats (Feld et al., 2009). For example, abiotic surrogate measures derived from remote sensing and spatial analyses must be validated in their linkage to the biota by ground truthing (Feld et al., 2009; Nilson et al., 2003). The need to integrate remote sensing and field data from either existing national inventories or collected independently is widely acknowledged (e.g. Chave et al., 2019; Lackmann, 2011).

Increasing interests in forest resources, their sustainable use and management have ignited international and national debates; major themes being forest degradation, rehabilitation and restoration of forest landscapes, climate change (mitigation and adaptation), carbon sinks and sequestration processes (Öztürk, Palta & Gökyer, 2018). Concerns are also expressed over the shrinking and fragmentation of forest areas (Ganivet & Bloomberg, 2019) in relation to loss of biological divesrity, species endemism, socioeconomic and governance issues in forestry and environment (Hitimana et al., 2011; Mullah, Otuoma & Kigomo, 2013). Global environmental concerns extend to desertification, agroforestry and tree domestication, water catchments, as well as management of all other tree resources outside forests including non-wood forest products (Wong et al., 2001). In the light of the aforementioned issues, there is an uprising paradigm shift in management and conservation of forest resources, from traditional timber orientation to multiple use forest management (Food and Agriculture Organisation [FAO], 2010; Schreuder et al., 1993). Multiple resource data are indeed required to support the current shift in the management and governance of the forest resources and landscapes. As observed by Wong et al. (2001), there is need of biometrically sound studies which, do not just collect quantitative information but uphold statistical principles that cover objectivity in selecting sampling design, number of sampling units used and independence of observations.

Tropical natural forests and woodland formations are uniquely more complex in their ecological diversity, management and conservation requirements than temperate forest ecosystems that are realitively simple formations and sufficiently studied (Oldfield & Newton, 2012). The dichotomy of ecological complexity of tropical ecosystems from lowland and upland rain forests through dry and humid montane forests to arid and semi-arid woodlands justifies the paucity of quantitative methods relating to studying these ecosytems and present a dilemma in adopting assessment methods developed for less complex temperate forests and / or forest plantations (Aldrich & Hamrick, 1998; Oldfield & Newton, 2012). Whereas some methods such as remote sensing are more or less universal and are applied across the globe without modification, field methods are, by contrast, situation-specific (Arellano, et al., 2016; Burkhart & Tome, 2012; Schreuder et al., 1993) and target population characteristics (Gillison & Brewer, 1985; Greenwood, 1996; Myers & Patil, 1995; Philip, 1994; Wong et al., 2001). They ideally require calibration and validation for suitability before they are adopted (Pretzsch, 2009; Weiskittel, Hann, Kershaw Jr. & Vanclay, 2011).

At forest ecosystem level, and in the context of climate change and biodiversity conservation challenges, there is also need to know and understand resource conditions and quality including the capacity of a forest to store carbon, regulate climate and sustain rich biodiversity (Hicks et al., 2014; Öztürk, et al., 2018). The global interests in tree conservation empasize on conserving threatened species and other components of biodiversity with actual or potential value to mankind (Groombridge & Jenkins, 2000; Njunge & Mugo, 2011; Oldfield & Newton, 2012). These species and other associated ecosystem components must be identified and evaluated through well designed and cost-effective studies.

## 1.2 Research Problem

Tropical natural forests and woodlands are of diverse complex types with lesser known and understood species mix and stand structure (Girma, 2012; Mulatu et al., 2017). These mixed species ecosystems are difficult to analyze and understand in their pristine state (Grainger, 1993; Lanly, 1997; Singh, 1993) due to lack of established, reliable and widely accepted designs for the assessment of tropical forest systems (Arellano et al., 2016). The existing sampling techniques in use have been developed in the context of ecosystems in temperate region which far much structurally simpler and less diverse than the complex mixed tropical natural forests. Tropical natural forests and/or woodlands are highly variable in composition, diversity, physical and dynamic structures (Hemp, 2006; Talbot et al., 2014). There is need for research on accurate and efficient forest sampling schemes to be used in inventory and resource assessment to collect data and generate knowledge for the support of sustainable management and conservation of tropical mixed natural forest ecosystems. This study sought to evaluate and determine field sampling schemes suitable for use across the diverse tropical natural forest types to accurately capture, quantify and describe multiple forest attributes of ecological and management significance while ensuring cost efficiency. The anticipated impact is to enhance assessment of tropical natural forest resources across the complex ‘tropical rain forests, moist montane forests and dryland forests and woodlands’ dichotomy using a consistent method.

## 1.3 Justification of the Study

Information on changes in forest resources is needed for policy decisions and for the purpose of strategic planning of forest management, rehabilitation or restoration at regional, national or local levels. Local level planning requires more detailed information on the quantities and location of forest resources. Forest degradation is best appreciated through its consequences within the ecosystem such as change in floristic composition, species diversity, forest regeneration and soil fertility (Grainger, 1993; Hitimana, Kiyiapi & Njunge, 2004; Serna, 1986). The scarcity of crucial data on the resources leads to high risk of making non-informed decisions (Schreuder et al., 1993; Wong et al., 2001) that compromises the ability to plan and enhance their sustainable use and renewability (Bellefontaine, Petit, Pain-Orcet, Deleporte & Bertault, 2002). Diversity of species and their distribution are influenced by a several factors such as climate, altitude or edaphic differences (Gentry, 1988a; Merganič, Merganičová, Marušák & Audolenská, 2012). Species’ distributions and abundance are also fundamental to understanding patterns of communities and their relations to environmental conditions (Ludwig & Reynolds,1988; McCune & Grace, 2002). There is not much detailed knowledge and understanding about the natural forest systems, their component species and how they interact (Matthews, 1989). The role of forests and trees in tropical regions is rapidly expanding as sources of a diverse range of products and environmental services, which demand better management and conservation initiatives. With the declining forest cover in most tropical countries including eastern africa (FAO, 2003), people are progressively turning more and more to trees in woodlands and other landscapes outside forests for tree products. Therefore the study of closed canopy forests is as important as that of open canopy forests and woodlands in their various forms. There is a need for standardized and efficient sampling methods to enhaance assessment of diverse tropical forests and woodland formations.

## 1.4 Significance of the Study

Through well designed sampling studies, it is possible to measure, model and manipulate linkages between a forest resource and associated factors (biophysical, social and economical) that control its temporal and spatial variability. This study was designed to test and identify reliable sampling schemes for use in characterising the prevailing conditions and values of tropical natural forests and dry woodlands. The impact of this research process and output is to avail necessary sampling tools for objective assessment of forest regeneration, recruitment, horizontal and vertical structure, tree biodiversity, relative dominance and forest density in terms of standing stems and basal area. Understanding and appreciating complex forests, tree characteristics and human x forest/tree interactions are prerequisites to the development and implementation of sustainable multi-resource management and conservation plans at different ecosystem, landscape, national and international levels.

This study is significant for Kenya National Forest Monitoring System by addressing reliability of temporal field-based datasets which are often problematic to collect in the proposed strata of Western Rain forests, Montane forests and Dryland forests (DRSRS et al., 2019). Internationally, the study supports data on use of sampling designs for different forest vegetation types and provides information about factors to consider in selecting sampling designs, plot sizes and sampling intensities.

## 1.5 Objectives of the Study

### 1.5.1 General Objective

The general objective of this study was to explore overall applicability of various sampling designs, intensities and plot sizes over different forest ecosystems and tropical woodlands.

### 1.5.2 Specific Objectives

The specific objectives were:

1) To characterize and model on-per-hectare variation in forest structure, composition and tree species diversity in three selected tropical forest types (tropical rainforest, moist montane forest and dry woodland forest) in Kenya.
2) To determine relative efficiency of sampling schemes in capturing tree species diversity, forest regeneration, stem density, basal area and quadratic mean diameter on-per-hectare basis within and across three natural forest types in Kenya.
3) To determine optimum plot sizes, sampling intensities and reliable sampling designs suitable for estimation of forest structure, composition and diversity attributes across the mixed tropical natural forest types in Kenya

## 1.6 Hypotheses

1) An ecological gradient exists from dry woodland forests through montane to tropical rain forests mirrored by biophysical characteristics, structure and species composition.

2) Different forest ecosystems require different sampling protocols .

3) Optimal sampling designs, intensities and plot sizes exist for different forest ecosystems.

## 1.7 Thesis Overview

This thesis has six separate but related chapters. The introduction chapter sets the stage for the research background, justification, study objectives and hypotheses.

Chapter 2 presents the review of literature. Chapter 3 covers the study area and field methods. Chapter 4 presents the results starting with description of studied forest units of reference in terms of composition, diversity and structure; followed by evaluation of relative efficiency of different sampling schemes (combination of sampling designs, plot sizes and sampling intensities) in different forest types. Sampled forest attributes are: species diversity / richness measures, regeneration and stand density measures. Results are discussed in Chapter 5. Finally, conclusions, recommendations and suggested future research are presented in Chapter 6.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Scope

This chapter contains an in-depth review of literature on the complexity nature of natural forest ecosystems in the tropics and of the diverse needs for their assessments. It covers the evolution of forest resource assessments from timber oriented studies to multiple use contexts of the contemporary world. Literature on the evolution of sampling methods, approaches of studying forest ecosystems, as well as on commonly assessed forest attributes is reviewed. The chapter continues with the review of experiences and limitations of applications of sampling designs to tropical natural forest systems leading to the context of this particular study. It ends with a summary of identified knowledge gaps and related research questions.

## 2.2 Diversity of Tropical Natural Forest Ecosystems

Globally, forests occupy 4.03 billion hectares (about 30% of total land area), make 75% of terrestrial gross primary production and 80% of total plant biomass (Pan, Birdsey, Phillips & Jackson, 2013). The amount of carbon stored in forest soils and biomass exceeds the amount existing in the atmosphere (Sullivan et al., 2017). Forests are defined and classified in many contexts as resources and organized ecological systems (Pan et al., 2013) comprising of living organisms (plant, animals and others), interacting with their physical, chemical, biological and social environments (Bolkin & Talbot, 1992; Jahn, 1982; Kent & Coker, 1992; Sharma, 1992). A continuous canopy of large trees at least 10 m tall usually distinguishes forests from other types of plant communities (Beentje, 1994). According to Food and Agriculture Organisation (FAO, 2010), a forest is a community of trees, shrubs, herbs and associated plants and organisms covering a surface area of at least 0.5 ha, with a tree canopy cover of 10 % or above. Trees are the main elements that govern multiple functions of forests that are beneficial to mankind (Tomlinson, 1983; Committee On Managing Global Genetic Resources [CMGGR], 1991). Tropical forest formations comprise of tropical rainforests, montane forests, and woodlands (Malhi, Adu-Bredu, Asare, Lewis & Mayaux, 2013). The tropical rainforest biome has four main characteristics: very high annual rainfall, high average temperatures, nutrient-poor soil, and high levels of biodiversity; and has unique combination of ecological, climatic and human interactions, experiencing high human pressure (Morris, 2010). Montane forests form the catchments of many rivers and their vegetation varies with altitude and rainfall. Those forests in high potential areas are characterized by thick undergrowth, and are under constant pressure of being exploited for wood and non-wood products (Hitimana et al., 2004; Hitimana, Kiyiapi, Njunge & Bargerei, 2010) as well as being converted into agricultural land usage. They are also rich in biodiversity and are good habitats for wildlife.

Beside closed canopy forests, other treed natural vegetation types in Kenya include dry woodland forests in the Arid and Semi-arid climate, characterized by high temperatures, erratic precipitation and moisture deficit, all affecting the vegetation type and growth behaviour (Bryan, 1994; Dangasuk, 1999; Kiruki, van der Zanden, Gikuma-Njuru & Verburg, 2017). The dry zone forests in Kenya are found in the dry areas which include dense savanna acacia forests. The dry woodlands include trees measuring 5 - 15 m high, with dwarf understorey. The dry sub-forest type also covers the dry forests on the hilltops and semi-arid savanna dry forests that developed under harsh climatic conditions and support grazing and browsing livestock and/or wildlife (Ministry of Environment and Natural Resources [MENR], 2016).Woodlands are open stands of trees at least 8 m tall and with a canopy cover of at least 40% (Beentje, 1994). Woodland sub-categories include wooded grasslands or savanna, that is, land covered with grass and other herbaceous species, with scattered or grouped trees and shrubs that cover 10 to 40% of the ground; bushlands (vegetation types with some grass and dominant woody plants having 3 to 7 m height and a canopy cover of at least 40%); and bushed grasslands that are characterized by dominant woody plants less than 6 m high (Beentje, 1994).

Reviewed literature on tropical dry forest and woodland ecosystems (e.g. Mayaux, et al., 2005; Muturi, 2012; Omondi, 2016) indicates that they cover about 40 % of tropical ecosystems globally; approximately 54 % of the African land cover (Ribeiro et al., 2013), and about 87 % of Kenya (Muturi, 2012). Generally, these ecosystems are in four categories: hyper arid, arid, semi-arid and sub-humid (Pauw, Göbel & Adam, 2000). According to Kiruki et al. (2017) review, these ecosystems’ dynamics are poorly understood and their monitoring and modelling neglected (Gerhardt & Todd, 2009; Grainger, 1999) despite being central to the livelihoods of many millions of people in

Africa (Campbell, Costanza, Belt & Van Den, 2000; Kabubo-Mariara, 2013). They provide a range of ecosystem services including micro-climate regulation, soil conservation, flood control and carbon sequestration (Kalema, Witkowski, Erasmus & Mwavu, 2014; Syampungani, Chirwa, Akinnifesi, Sileshi & Ajayi, 2009).

Sustainable use, management and conservation of dry woodlands require knowledge and understanding of their composition, diversity, structure and regeneration (Kiruki et al., 2017; Mwavu & Witkowski, 2009; Worku, Teketay, Lemenih & Fetene, 2012) as well as threats they face such as fire, grazing and different forms of exploitation (Eshete, Sterck & Bongers, 2011). The dry forests and woodlands are found in regions receiving between 100-800 mm annual precipitations and experiencing dry seasons of about 4-7 months (Bullock, Mooney & Medina, 1995; Eshete et al., 2011). The area is severely affected by recurrent droughts, and erratic floods with serious rangeland deterioration, loss of livestock and forest degradation (Bryan, 1994; Chidumayo & Marunda, 2010).

In Kenya, the Land Cover Change Mapping Programme categorizes forest land into three categories, primarily based on remote sensing: Dense Forest (above 65% cover), Moderate Forest (40 % to < 65%) and Open Forest (15 % to < 40%). Under the National Forest Monitoring System [NFMS], the Intergovernmental Panel on Climate Change [IPCC] (2006) forestland land use class is used based on Kenya's definition of forests (MENR, 2016). Forestlands are areas occupied by forests and characterised by tree crown cover ≥ 15%, an area ≥ 0.5 ha and a tree height ≥ 2 m. It also includes areas managed for forestry where trees have not attained 2m height but with potential to do so, and areas that are temporarily destocked natural forests include mangrove forests, bamboo forests, dry land forests, montane forests and western rain forests.

Montane forests are those found in high altitude regions of Kenya (above 1,500 m); they include Mt Elgon blocks. They are the most extensive and are described as water towers due to their support to water catchments. These forests differ in species composition due to climate and altitude (Beentje, 1994). The western rain forests are those with characteristics of the Guineo-Congolean forests and include Kakamega forest. Trees are significantly taller and larger as compared to other forests of Kenya. The dryland forests are found in the arid and semi-arid regions of Kenya. The category also includes riverine forests in dry areas. Their carbon stocks may differ from that of other forests due to leaf shedding, elongated rooting systems and high specific wood density (DRSRS et al., 2019).

## 2.3 Forest Structural Complexity

Forests are documented to be the dominant terrestrial ecosystems on Earth and environmental factors control their structure and global distribution (e.g. Jucker et al. 2018). Natural forests and woodlands play major functions in supporting life (e.g. Hitimana et al., 2011). Natural forests are self-regulating system units (Brunig, 1983; CMGG, 1991; Bruenig, 1998), but their ideal structural model can be modified by localized environmental factors, biotic or abiotic, e.g., human activities, topography, soils and climate influence (Hett & Loucks, 1976; Brunig, 1983; Denslow, 1995). Generally, forests and tree resources are influenced by dynamic socio-economic and ecological contexts. Good knowledge of the structure, distribution and biomass of forests provides ecological insights and opportunities that guide sustainable forest management, enhanced forest conservation and provision of ecosystem services (Pan et al., 2013). Spatial distribution patterns of forests are increasingly discernible using new remote sensing systems, improved land-based forest inventory systems and global ecosystem modeling. Forest ecosystems are well known habitat to most species on Earth and source of diverse ecosystem goods and services for the well-being of humanity (SCBD, 2010). Globally, 17% of forests are in Africa with 95% being natural formations (Pan et al., 2013). Table 1 shows the extent and characterization of tropical natural forests climatic conditions and productivity.

## 2.4 Factors Controlling Forest Complexity

Factors influencing the complexity of patterns in forest associations and structure include adaptation of trees to aspects of geography, climate, climate change induced by anthropogenic greenhouse gases [GHGs] emmissions, topography, soil, environmental variation and disturbances (e.g., Holdridge, 1967; Whittaker 1975; IPCC 2007; Swanson et al., 2011; Walther, 2010). Complex mosaics of forest distribution and high landscape-scale diversity are created by varying types, scales, intensities and frequencies of disturbances. Global assessment results by FAO (2010) indicate that more than 60% of the world’s forests are recovering from a past disturbance and 3% are disturbed annually through logging, fire, pests, or weather.

Documented evidence reveals upward movements of tree species and tree lines along elevational gradients in response to increased Earth warming (e.g., Beckage et al., 2008; Colwell, Brehm, Cardelus, Gilman & Longino, 2008; Kullman & O¨berg, 2009; Malhi et al., 2010; Clark, Hurtado & Saatchi, 2015). Influence of climate change on forests may be through inducing high frequency and intensity of wildfires, windstorms or insect outbreaks, drought and heat stress increase in tree mortality, forest die-offs, decrease in forest productivity (Dale et al., 2001; Allen et al., 2010; Phillips et al., 2009). Understanding of the complexity of issues surrounding the health and sustainability of natural forests is critical for strategic interventions but it requires detailed field studies, guided by well-structured methods and procedures.

**Table 1: Climatic conditions, canopy height and biomass carbon of selected world’s tropical* forests and woodlands**

| Forest biomes | Mean temperature yr$^{-1}$ ($^{o}$C) | Total rainfall yr$^{-1}$ (mm) | Seasonality | Canopy height (m) | Total biomass carbon density (Mg C ha$^{-1}$) | Existing forest (M ha) |
|---|---|---|---|---|---|---|
| Tropical rainforest | ~20–25◦C | >1,500 | No dry season | 25–50 | 145 ± 53 | 1,354 |
| Tropical dry forest | >15◦C | 500–1,500 | 5-8 dry months | 5–20 | 53 ± 35 | 645 |
| Tropical shrub lands | >15◦C | 200–500 | 8–11 dry months | 3–15 | 71 ± 45 | 701 |
| Tropical mountain systems | <18◦C | 700–2,000 | 0–11 dry months | 3–35 | 124 ± 54 | 351 |

*Tropical zone : 23.5$^{o}$N–23.5$^{o}$S; all months without frost.

**(Extracted** from Table 1 in Pan et al., 2013**)**

Documented evidence shows upward movements of tree species and tree lines along elevational gradients in response to increased Earth warming (e.g., Beckage, Osborne, Gavin, Pucko, Siccama & Perkins, 2008; Colwell et al., 2008; Kullman & O¨berg, 2009; Malhi et al., 2010; Clark et al., 2015). Influence of climate change on forests may be through inducing high frequency and intensity of wildfires, windstorms or insect outbreaks, drought and heat stress increase in tree mortality, forest die-offs, decrease in forest productivity (Dale et al., 2001; Allen et al., 2010; Phillips et al., 2009). Understanding of the complexity of issues surrounding the health and sustainability of natural forests is critical for strategic interventions but it requires detailed field studies, guided by well-structured methods and procedures.

## 2.5 Complexity of  Tropical Natural Forest Resource Assessment

### 2.5.1 Diversity of Forest Management Contexts

Measurable elements of structural development and complexity of forests include stand ages, species diversity and variations in tree-size categories (Franklin et al., 2002). These attrbutes can be quantified using scores derived from multivariate analyses or remote sensing data to map forest structural complexity or interpret forest structural patterns within environmental contexts (McElhinny, Gibbons, Brack & Bauhus, 2005; Kane et al., 2011; Pasher & King 2011). Forest structure dynamics is a key to ecosystem stability and conservation; and should be analysed in relation to disturbances, primary production, mortality, biomass, and woody debris accumulation on spatial and temporal scales (Spies, 1998).

In the tropics, the diversity of data requirements for forest management is dictated by the existence of the many forest management options e.g intensive forest management with precision silviculture for timber production; management for non-wood products as the main focus; restoration of mining sites; forest management for environmental goods, services and values where multiple management strategies are integrated. Modelling for management of old-growth forest landscapes is also complicated (Bawa & Seidler, 1998). In tropical countries where natural forests are managed extensively for a range of goods and services including wood, recreation, biodiversity and other values or forests are managed on degraded land for only non-wood benefits such as environmental services including carbon sequestration, data collection for management model development require many variables. In multiple use forestry, profitability is optimized by supplementing intensive timber production with non-wood products and services. For example, consider the understorey as complementary rather than competing vegetation. The complementary products and services place different demands on data and models.

### 2.5.2 Traditional Timber Assessment Context

Forest inventory is the systematic collection of data on the forestry resources within a given area (Schreuder et al., 1993). It allows assessment of the current status of the forest resources and lays the ground for analysis and planning for sustainable forest management. Forest inventory must be clearly defined, the focus of the data collection must be well articulated and respond to information needs of the users. All inventory operations follow four key steps: (i) definition of the inventory objectives and information desired; (ii) development of sampling design and methods; (iii) data collection from field surveys, remote sensing data analysis and other sources; and (iv) data analysis and publication of the results (Schreuder et al., 1993). Forest assessment protocols should clearly report on sampling design with adequate details on how sampling units (e.g. plots) are located, plot dimension, plot numbers, and enumeration techniques, describing where and how each sampling unit was assessed (Wong et al., 2001). Sampling techniques are applied to minimize the cost and time constraints associated with forest inventories (Nassiuma, 2000). Sampling refers to the process of selecting an assumed representative part or subset of an entire population of individual materials or organisms so that inferential statistics can be applied (Schreuder et al., 1993). Forest sampling is the process of selecting a representative sample of trees and obtaining the required estimates. The ultimate aim of sampling is to arrive at unbiased true estimates of population parameters; that is, to make correct inferences about the population. Sampling units are non-overlapping, that is, independent collections of elements from the population that cover the entire population (Nassiuma, 2000). Forest sampling is widely applied in forest inventory for a variety of purposes such as collecting data for forest trees and stands growth and yield modeling (Weiskittel et al., 2011), including evaluating site quality (Burkhart & Tome, 2012), biodiversity dynamics and carbon sink estimations. According to FAO (Wong et al., 2011), yield is the amount of product available and useful for harvest at a given point in time; or as the total biological potential of a species; and its assessment is by measuring product availability or quantifying the amount of a product that can be harvested from an area of a forest.

## 2.6 Evolution of Sampling Methods and Efficiency in Forest Inventories

### 2.6.1 Puropose and Evolution of Sampling in Forestry

The main purpose of national forest inventory is to estimate the present state and the changing trends of the natural forest resources. Additional purposes of forest inventory include measurement of volume, biomass, carbon stocks and characteristics of trees and stands including forest land area. In order for a nation to efficiently manage and preserve its natural resources using scientific methods, the detailed state of the resources and any changes that occur must be surveyed and analyzed periodically (Park et al., 2016). Multiple methods exist for the estimation of tree density from point-based sampling including distance based and area based approaches (Levine et al., 2017). Sampling schemes of increasing intensity have been simulated to estimate sampling error for forest density estimates in surveys (Levine et al., 2017).

Statistical sampling or sample survey refers to the collection of data in a scientifically acceptable manner, that is, the selection of a representative sample (Schreuder et al., 1993). A representative sample is generally the probabilistic with every unit in the population having a positive probability of selection and these probabilities are known and independent of the person taking the sample. A representative sample provides information of interest to the manager and gives a measure of its reliability, i.e. precision of parameter estimate (Brown, 2007). Assessment of the reliability of information is often as important as information itself. Cost of attaining reliable estimates may be greater than the funds available. The ideal technique for collecting data in natural resource surveys is to map in a statistically valid manner, which is usually expensive, but yields the most complete information about a population – how much and where for each variable. Collecting data using aerial photography and digital remote sensing is attractive to many because much resource information can be mapped and measured accurately at low cost. Pioneers in sample surveys are Kiaer in Norway and Wriht in the USA (Seng, 1951) but it is

Bowley (1906) who argued about the value of sampling and the need to include an error estimate when sampling is used (Schreuder et al., 1993). Bowley (1926) and Student (1908) demonstrated that under a normal distribution assumption, useful probability statements can be made about the estimates. Student and other early statisticians recognized multistage sampling and stratified sampling as strategies to achieve “most efficient estimation” (Neyman, 1934; Smith, 1976; Tschuprow, 1923).

Scientific methods in forestry were introduced in Europe 200 to 300 years ago (Schreuder et al., 1993). Site specific experience tables were used for the estimation of wood production. These experience tables evolved over time to present day yield tables and growth models (Schreuder et al., 1993). Classification of stand mean height based on species and typical site was introduced in the early 19th century following the realization that stand mean height at a given age was a practical measure of site productivity (Schreuder et al., 1993). National Forest Inventory in the USA was established by the McSweeney-McNary act in 1928. Survey interval used in the country is 5 years, consistent with survey intervals used in Japan and China.

White et al., (2016) reviewed the suitability of five remote sensing technologies used in forestry (ALS, TLS, DAP, HSR and VSROSI). Emerging new technologies may enable accessibility of some census data rather than sample data, but not all. Two emerging technologies illustrate the possibilities to obtain vast range of forest measurements: advanced remote sensing technologies and machine-based data collection (White et al., 2016), which collectively offer the possibility to work with census data, that is, measurements on every individual in the population rather than with samples. However, McRoberts, Tomppo and Naesset (2010) observed that although remotely sensed data are increasingly used to enhance inventories, they cannot completely replace ground data. Expanding inventories to address emerging demand issues such as sustainability and biodiversity requires information on variables such as deadwood, species types that are beyond operational efficiency of remote sensing technologies. Remotely sensed data are not currently sufficient for producing species-level estimates, particularly in tropical countries that have high number of tree species in their forest ecosystems. There is high reliance on unbiased estimates of certain attributes obtained from plots for tree or stand models. Those attributes are often sensitive to both plot configuration and size. For example, it is reported that circular shape are useful and accurate for larger plot sizes (Curtis & Marshall, 2005) but the boundaries are difficult to demarcate. Rectangular plots are useful if oriented to reduce variation within plots. Regardless of plot configuration, all plots require adequate buffer surrounding the plot's measurement area.

### 2.6.2 Field-Based Inventory Methods and Experiences in Kenya

Over the last decades, studies of tree species diversity in tropical forests have been increasingly standardized in order to allow comparison among research groups (Condit, 1995; Condit et al., 2002; Malhi et al., 2002; Ganivet and Bloomberg, 2019). However, there is a wide variation in field-based inventory methods commonly used worldwide in terms of plot shapes and sample area (Table 2). The review demonstrated that standardisation of sampling methods, sampling units and minimum diameter sizes has not been achieved worldwide; and continuing research efforts are required in this context.

**Table 2: Summary of common field inventory methods used for tree species diversity and structure assessments in tropical forests**

| Method | Shape | Area covered (ha) | Area inventoried (ha) | DBH min (cm) | Permanent | Field effort (person-days) | References |
|---|---|---|---|---|---|---|---|
| i) Gentry plot | 2 x 50 m transects | 2 | 0.1 | 2.5 | No | 7 | Boyle, 1996, Phillips et al., 2003b,Phillips et al., 2003a) |
| ii) Whittaker plot | 20 x 50 m transects | 0.1 | 0.1 | 2.5 | No | 7 | Campbell et al., (2002) |
| iii) Modified gentry plot | 10 x 50 m transects | 2 | 0.5 | variable | No | 8 | Baraloto et al., (2011) |
| iv) 0.5 ha plot | 50 x 100 m | 0.5 | 0.5 | 2.5 | Yes | 15 | Baraloto et al. (2012) |
| v) 1 ha plot | 100 x 100 m | 1 | 1 | 10 | Yes | 25 | FAO (1981) |
| vi) Circular plot | 30 m radius | 0.28 | 0.28 | 10 | Yes | 5 | Asner et al. (2010) |
| vii) 20-50 ha plot | 500 x 500 m to 1000 x 500 m | up to 52 | up to 50 | 1 | Yes | ≥500 | Condit (1995) |
| viii) 0.1 ha plot | 20 x 50 m | 0.1 | 0.1 | 2.5 | No | 5-20 | Arellano et al. (2016) |

**Source:** Ganivet and Bloomberg (2019)**.**

Muchiri et al. (2016) provides a summarized review of forest inventories in Kenya and reveals a gap in harmonisation of sampling schemes applied and, though useful information was generated, it cannot be compared with known level of certainty. The current national estimates of forest areas and mean volumes are mainly based on forest inventories carried out at different times, between the start of the 1990’s during the compilation of Kenya Forestry Master Plan in 1994 (Wass, 1994) to the inventory of Mau Forest block in 2014 (Kinyanjui, Shisanya, Nyabuti, Waqo & Ojwala, 2014). According to Muchiri et al. (2016), past forest inventory work in Kenya include forest inventory and resource assessment projects accomplished during that period include Kenya Indigenous Forests Conservation project (KIFCON) in 1993, Mt Elgon Forest Mapping and Inventory in 1997, Forest inventory for indigenous forests in Arabuko Sokoke Forest reserve in 2001, Indigenous trees inventory and vegetation survey in Mt Elgon Reserve in 2001, Trees Inventory and Vegetation Survey in Mukogodo Landscape in 2005, Tree resources inventory of South Nandi forest reserve in 2005, Kenya forest plantations inventory in 2010 – 2012 and Kakamega Forest Mapping by Biota project in 2005. In all these projects, the applied sampling designs varied, revealing the need to conduct inventories based on a harmonized sound sampling design and data analysis. Harmonised inventory schemes will provide reliable and comparable information about Kenya’s forest resources. Inaccuracy of information on forest resources in Kenya has also been reported in many reports (e.g., Cox et al., 1988). For biophysical forest resources assessment in Kenya, Muchiri et al. (2016) propose the use of double stratified two-phase systematic cluster sampling in which Kenya is stratified into four strata based on the county boundaries and the agro-ecological zones. The choice of the design was based on experiences of earlier practices from Kenya and elsewhere, and a pilot forest inventory done in five forest types in Kenya. However, the piloting adopted and used concentric sample plot sizes with no much knowledge about the suitability and precision level of the same sampling units.

### 2.6.3 Uncertainty, Bias and Sampling Efficiency

Precision (i.e. measure of how tightly sample estimates are clustered) and accuracy (i.e. measure of level of closeness of the estimates to the true population value) of inventory results are computed and some confidence put in the results (Wong et al., 2001; Jayaraman, 2000). Conventionally, precision of the results is measured by the sampling error or % uncertaitly according to Lackmann (2011). The precision is high when errors are small, and accuracy is high when the estimated average value is close to that of the whole population (Wong et al., 2001). Ideally, estimates from assessments should be both precise and accurate. Uncertainty is the lack of knowledge of the true value of a variable and is computed as a probabiliity density function characterizing the range and likelihood of possible values (Equation 1; Lackmann, 2011):

$$\text{\% Uncertainty} = \text{Sampling Error \%} = \frac{{}^{1}\!/_{2}\ (\text{95\%Confidence interval width})}{\mu} \text{x100}$$

………..... (Equation 1)

Where μ is the mean of the distribution. Sampling error (SE %) is the 95 percent confidence interval expressed as a percentage of the mean.

Quantitative measures of the uncertainty include random errors and bias. Bias is a systematic error and indicates lack of accuracy Random error describes a random variation below or above a mean value; it is inversely proportional to precision and. According to Morais and Schreuber (1997), sampling inventories should provide the statistical precision of estimated quantities within accepted limit. Often, inventories are designed to deliver a specific sampling error, typically 10 -20% and thus it is important to know how many sampling units to use e.g. number of plots. Large numbers of sampling units reduce the sampling error (Wong et al., 2001). In complex forests, precision levels of estimates of carbon stocks and carbon stock changes fall within ±10 % of the mean at 95 % confidence and at a modest cost (Lackmann, 2011).

Uncertainty of the average, rather than the entire range of variability, is of most interest in forest inventories. However, variability is an inherent property of the system of nature and not of the analyst, and can only be reduced by sampling entire populations or by stratifying the area (Lackmann, 2011). Unbiased estimator of a parameter is efficient if its variance attains the Rao–Cramer lower bound (Hogg, McKean & Craig, 2012). The efficiency of an estimator is thus defined as the ratio of the Rao–Cramer lower bound to the actual variance of the unbiased estimator of the parameter (Strimbu, 2014).

Cielo-Filho, Gneri and Martins (2009) investigated sampling effort and factors influencing the precision of estimates of tree species abundance in a tropical forest stand of a semi-deciduous Atlantic forest in Brazil by adopting maximum allowed sampling error of 20% at 95% confidence level to estimate density, frequency, dominance, and importance value index for species with five or more adult individuals. Morais and Scheuber (1997) define density as the number of trees per unit area, measured by a count of stems in a plot. Density measurement is most useful in evaluating the need for future density control in a stand for yield optimisation or to maintain forest structural stability.

Phillips et al. (2003a) compared relative efficiency of two inventory protocols in the Amazon landscapes on the diversity, composition and structure of forests. The standard method involved a one-time census of all stems ≥ 10 cm diameter in an area of 1 ha (the 1 ha-method). The second method involved sampling all stems ≥ 2.5 cm diameter in ten 2 ×50 m (the 0.1-ha method). The 0.1-ha method sampled a larger part of the flora, because of the lower size cut-off. This method has been applied mostly in the Neotropics although ecological analyses have successfully used such data to model forest structure, diversity and composition at pantropical and global scales (Enquist & Niklas 2001; Gentry, 1993). A review by Phillips et al. (2003a) revealed that the main application of 0.1-ha samples (over 90%) and of 1-ha samples (over 50%) in forest inventories is about eco-floristic assessment. The applied crude inventory efficiency measure was the number of species recorded divided by the person-days in the field. Though 1-ha method captured more species, 0.1-ha inventories were substantially more efficient in terms of floristic data gained per effort invested. The crude inventory efficiency of 0.1-ha samples was three to four times that of 1-ha samples in some sites. Ethonobotany studies often rely on single 1-ha plot. Originally, this size was arrived at using species-area curves but is now an accepted standard (Wong et al., 2001) to capture most of the flora of a region. However, these plots should be objectively established across the forest and in sufficient number to ensure they are of value for management purposes. Sub-sampling the 1-ha forest unit chosing appropriate sampling scheme would have advantage of carrying out detailed measurements and achieve statistically sound information, useful for extrapolations and predictions (modelling) in multistage and multiphase sampling schemes. Relatively complex protocols are required for sampling and assessment of multi-species and multipurpose inventories, typical for natural forests. Optimizing sampling designs in natural forest inventories poses methodological challenges. A sampling protocol covers plot size, plot shape, number of plots and spatial or temporal arrangement, i.e., sampling design (Wong et al., 2001).

Burkhart and Tome (2012) used model errors as a measure of precision or model bias in evaluating modelling efficiency or model performance. Bias refers to the deviation of the average model errors from zero and precision is the size of the model errors. The average model error (mean prediction error) is commonly applied to assess model bias while the mean squared error is used to assess model precision (Mauya et al., 2015). The relative root mean square error (RMSE %) is a good measure of how accurately the model predicts the response and is the most important criterion for fit if the main purpose of the model is prediction (Yoo, Im & Wagner, 2012).

Plots of observed versus predicted values have often been used to characterize bias and precision. Mean bias is the average difference between predicted and observed values. According to Husch, Beers and Kershaw (2003), sampling error is generally reduced by selecting an adequate sample size, sufficiently defining the population of interest and using appropriate sampling technique. According to Wong et al. (2001), deciding on how many plots are needed for an inventory is required. The sample size is critical for the management of sampling errors; the greater the size, the smaller the sampling error, and the more precise and potentially accurate the results will be. Generally, for forest inventory, the target error is taken as 10 – 20 percent of the mean. However, there is a non-linear relationship between the number of plots and the sampling error. The gains in precision reduce as the number of plots increase, following the law of diminishing returns (Nassiuma, 2000; Shiver & Borders, 1996; Sullivan et al., 2018; Wong et al., 2001). This relationship can be used to estimate the required sample size to achieve a specified sampling error. The cost of assessing elements in a plot is also needed where cost-efficiency is a concern.

### 2.6.4 Selecting Efficient Sampling Scheme

As reviewed by Grusu et al. (2016) about optimum plot and sample sizes for carbon stock and biodiversity estimation in tropical forests, sampling designs aiming to assess stand attributes must consider attribute variability (Kral et al., 2010). For example, there are considerable uncertainties about carbon stock estimation in tropical forests, mainly due to the scarce knowledge of the quantity and spatial distribution of forest biomass at the landscape level (Laumonier, Edin, Kannien & Munadar, 2010). When time and financial resources are limited, the precision of such surveys depends on the trade-off between using larger plots which have a lower per-plot variance and using a larger amount of smaller plots which tend to reduce the standard error of the mean (Evans & Viengkham, 2001). The choice of plot size and number of replicated plots deserves attention (Picard, Magnussen, Banak, Namkosserena & Yalibanda, 2010) in establishing a network of permanent sample plots (Alder & Synnott, 1992). It was found that using a 1-ha permanent sample plot network is not cost-efficient. On the contrary, sampling smaller plots is more efficient, as variability decreases faster at smaller plot sizes. Also, the total area sampled to achieve a given precision in the estimation of the parameters is smaller at smaller plot sizes, despite the larger number of samples required. However, a lower number of bigger plots might be more cost-efficient due to reduced travel cost (Evans & Viengkham, 2001). The sample size determines the uncertainty in forest inventory (Student, 1908) as well as the cost of the estimate of the population. The number of sample plots depends on the desired level of precision in the results. For example, it was established that more variance in carbon stocks required more sample plots to achieve low uncertainty (Lackmann, 2011). According to Lackmann, forest stratification and cluster sampling also reduce the variability between plots, the required sampling size and the cost for a desired sampling error.

There is need to explore the efficacy of sub-sampling a large plot area, say the standard 1 ha, using smaller plots in order to reduce inventory cost, while also increasing accuracy and precision of parameter estimates resulting from relatively high concentration on measurements and observations within smaller plots (Freese, 1989; Jayaraman, 2000; Schreuder, Gregoire & Wood, 1993).

### 2.6.5 Plot Size

In forest inventory and modelling, the ideal plot size should normally be large enough to be representative of a stand and its inherent variability, but small enough to ensure high-quality measurements and the capability to be replicated across the landscapes (Weiskittel et al., 2011). Quantitatively, ideal plot size (in ha) ranges from 0.01 times the dominant height in metres to 1.0 ha. Larger plot sizes are required in naturally-regenerated, mixed species and uneven-aged stands due to their higher inherent variability (typical of tropical natural forests) as compared to planted, pure and even-aged stands (Weiskittel et al., 2011). Important considerations in selecting plot size for developing a growth model include the degree of plot permanence, whether modelling response to forest management is of interest and consistency.

Consistent plot size is preferred to minimise potential confounding effects of variable plot sizes. For example, growth model predictions are sensitive to plot size; and larger plot should be used if multiple measurements are intended (e.g. Permanent Sample Plots). Smaller plots are useful when a single measurement exercise is planned through use of temporal sample plots. Plot size should be based on the size of trees at the final and not at the initial measurement. For example, a plot size required to capture 50 trees in a plot ranges from 0.05 to nearly 0.45 ha as the quadratic mean diameter increased from 15 cm to 60 cm (Curtis & Marshall, 2005). Hernández-Stefanoni et al. (2018) studied effects of sample plot size (80, 400 and 1000 $m^2$) and GPS location errors on aboveground biomass estimates from LiDAR in tropical dry forests. Accurate estimates of above ground biomass are required for monitoring carbon in tropical forests. Larger plots were found less affected by GPS location error and vegetation conditions, highlighting the importance of selecting an appropriate plot size for field forest inventories used to estimate biomass and /or stored carbon. Mauya et al. (2015) arrived at similar conclusion after studying effects of field plot size on accuracy of aboveground biomass in airborne laser scanning-assisted inventories in tropical rain forests of Tanzania. The prediction accuracy of the model improved as the plot size increased, from 200 to 3000 $m^2$.

A 1-ha plot size has been adopted as a standard forest unit in several studies, mostly permanent sample plot to monitor forest dynamic structure, disturbances and/or growth (Holmes et al., 2002; Wong et al., 2001). Phillips et al. (2003a) described the “1 ha-method” and elaborated that one hectare inventories are used routinely and extensively by botanists. Collected quantitative floristic data are regularly used to infer major ecological pattern and process at local, regional and continental scales (Gentry 1988a;

Gentry 1988b; Pitman, Terborgh, Silman & Nunez, 1999; Ter Steege et al., 2000; Terborgh & Andresen, 1998). These samples are sometimes converted into long-term plots to monitor forest processes but this requires significant extra investment (Alder & Synnott, 1992).The plot size needs to be decided before calculating the required number of plots. As reported by Lackmann (2011), plot size is related to the number of trees, tree diameter and variance of carbon stocks among plots. For example, the plot size would usually vary between 100 $m^2$ for densely stocked stands with 1000 trees $ha^{-1}$ and 1000 $m^2$ for sparsely stocked stands. Table 3 shows recommended plot sizes for different tree sizes.

**Table 3: Commonly applied plot sizes in forest assessment studies**

| Diameter | Circular plot radius | Square plot |
|---|---|---|
| < 5 cm dbh | 1 m | 2 m x 2 m |
| 5 – 20 cm dbh | 4 m | 7 m x 7 m |
| 20 – 50 cm dbh | 14 m | 25 m x 25 m |
| ≥50 cm dbh | 20 m | 35 m x 35 m |

**Source**: Lackmann (2011).

Commonly applied plot sizes in dry woodlands include those that were adopted by Kiruki et al. (2017) in Kitui drylands of Kenya. They applied 2 m x 5 m (10 $m^2$) for regeneration count and 20 m x 50 m (1000 $m^2$) for large trees and coppices in the Somalia-Masai Acacia-Commiphora deciduous bushland and thicket. The plot sizes were described as robust enough to capture essential information on woody plants. However, no evidence of robustness claim was provided. Regeneration was defined as individuals with diameter ≤ 3cm at 30cm off the ground (i.e. stump diameter). Seedlings were woody plant less than 1.4m in height and stump diameter less than 3cm. For field-based inventories, Ganivet and Bloomberg (2019) recommended the use of small plots (e.g. 20 m × 50 m) for assessment of trees sized 10 cm DBH and above. The gap now remains for smaller individuals that represent the future conditions of a forest in terms of regeneration and recruitment.

By increasing the sample plot area, variation among plots can be reduced; permitting the use of small sample size at the same precision level (Freese, 1989; Lackmann, 2011; Grussu et al., 2016). However, Brown and Williams (2016) cautioned consumers of research ouputs that the single-plot sampling of plant species richness at a site may not provide any indication of variability across the site. Without multiple plots, it is impossible to determine the mean and variance of index values among plots, to examine whether the sample data are actually representative or not, and to characterize site variation in plant communities accurately (Magurran, 1988; Bourdaghs, Johnston, and Regal, 2006). However, Krebs (1989), Matthews, Tessene, Wiesbrook and Zercher (2005), and Bourdaghs et al. (2006) argued that increasing the area sampled has its own pitfalls. Strategies should be found to create multiple plots without increasing the sampled area. For example, one hectare single plot can be transformed into multiple sample plots by adopting 10 plots of 0.1 ha each. Some forest attributes such as species composition and richness are area-dependent. Increasing the size of the sampling area increases species richness estimates and other measures related to it e.g. mean coefficient of conservatism and floristic quality index. Species richness index is a measure of variety (Jayaraman, 2000), computed as shown in Equation 2. According to Schulz, Bechtold and Zarnoch (2009), there is need to balance between number and size of plots in vegetation inventories where the objectives combine estimates of abundance and species composition. Pilot studies are often used to optimize the plot configuration and sample size (Kenkel & Podani, 1991).

$$\text{Species richness index} = \frac{S}{\sqrt{N}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \text{(Equation 2)}$$

where S = Number of species in a collection N = Number of individuals collected

The increase in the number of species in relation to the area covered (or to the number of individuals) can be expressed graphically by a species accumulation curve (Jayaraman, 2000). The relationship between number of species (S) and the area (A) covered can also be represented mathematically as shown in Equation 3.

$S = aA^b$, …………………………………. (Equation 3)

with a and b being parameters to be estimated empirically using linear regression techniques, the data on area covered and the corresponding number of species recorded.

According to McCune and Grace (2002), the “many and small plots” scheme will yield accurate estimates of abundance for the most common species, but incomplete species lists. The “few and large plots” scheme results in a more complete species list but overestimates the abundance of rarer species. A sample design based on cluster plots (groups of subplots) is a tradeoff between the two approaches (Schulz et al., 2009).

### 2.6.6 Plot Allocation

Plots can be spatially distributed randomly or systematically. However systematic sampling is the most practiced in forestry due to logistical advantages despite some statistical weaknesses (Avery & Burkhart, 2015; Freese, 1989; Schreuder et al., 1993). Subjective choice of plot locations can be avoided by locating plots or clusters of plots randomly over the study area. Plots are systematically located in a regular pattern (e.g. Figure 1b-c) to ensure plots are evenly distributed over the area. It is advised to randomize the starting point of in the grid as well as the direction of the grid. Thereafter, sample plots are either located aligned (Figure 1b) or randomly placed unaligned within each cell of the grid (e.g. Figure 1c). In the systematic sampling method, plots may be organized into clusters (e.g. Figure 1d.) such that a cluster of plots is located in each distinct stratum.

**Figure 1: Illustration of plot allocation patterns for simple random sampling (a), aligned systematic sampling (b), unaligned systematic sampling (c), and systematic cluster sampling (d). (Source: Lackmann, 2011).**

Cluster sampling is cost-efficient due to overall reduction of travel distance between sample plots. Generally, with the same budget, more units are assessed through clusters than independent units, and this process may increase accuracy of the estimates. However, information gain from measuring a new unit in a cluster may be less than applying independent units as a result of high inter-units correlation within a cluster. To minimise such correlation, the distance between units in a cluster must be large enough, e.g., at least 250 – 300 m, depending on the stratum size.

### 2.6.7 Multipurpose Forest Assessment

While in the past forest inventories were primarily aimed at assessing timber availability, in recent years the forest is recognized as a complex ecosystem with several interactions among its elements or components including humans. A forest inventory is now commonly conceived as a multipurpose forest inventory with the contribution of expertise from different fields such as sampling theory, surveying, information technology, remote sensing, social science, mensuration and modelling to assess the multiple functions of forests and trees (Ohmann, Gregory & Roberts, 2014). The main purpose of a forest inventory is to determine the value (volume, quantity) of resources in an area as accurately as available time and money will permit. Reliable estimate of the forest area (maps, air photos, GIS databases), measurements of unbiased sample of the resources and otherwise determine the characteristics of the resource in question. In terms of scale, a wide range of needs, and therefore approaches, are possible. Global forest inventories are aimed at determining the extent and status of forest resources at the global level (i.e. FAO’s Forest Resources Assessment being carried out since 1946 which also serves as mechanism for facilitating the harmonization of terminologies and definitions). Smaller areas inventories are usually driven by specific goals, often for forest planning and operations. They include regional inventories (portions of the country area); reconnaissance inventories (rough insights of forest resources in a limited area); diagnostic sampling to orient silviculture and forest management; exploitation surveys (focused at assessing harvestable timber availability and planning of harvest and logging operations); post-harvest inventories (to assess regrowth and damage caused by logging operations); forest health monitoring (often linked to salvage cuts operations) (Avery & Burkhart, 2015; Ohmann et al., 2012).

### 2.6.8 Integrated Forest Inventory

According to Schreuder et al. (1993), advantages of sampling include cost effectiveness (saving of resources: funds, time, manpower); it is cheaper and faster, more timely, than complete enumeration. There is reduced workload during data processing, leading to more precise and accurate estimates or measurements. According to Hyvönen et al. (2016), collecting data for developing tree volume and biomass models is very time consuming and expensive, and requires a lot of precise measurements; sampling operations up to along a tree provides a solution to this challenge. A general principle is to determine a sample of trees that is representative with respect to the entire population. Dealing with few individuals under the limitations of time and resources allow higher concentration in comparison with complete census. Savings resulting from sampling could also be used to buy better instruments and employ or train higher caliber personnel. Sampling is also used as a technique of quality control of field data collection. In some instances, complete measurement or enumeration may be impossible or not feasible due to the characteristics of the population such as infinite population or very large population size. The sampling may target one, few or all tree species and a pre-determined number of trees by the selected species is obtained by the end of field data collection (e.g. Hyvönen et al., 2016). Sample trees for each species are obtained from varying climatic conditions and different agro-ecological zones. The characteristics used in selecting sampling of trees to ensure data are collected from a representative sample of the whole population are: Agro-ecological zone, Vegetation type, Forest stand characteristics: diameter distribution, age, density, species composition and management regime.

Askari, Saei and Rezaei (2013) also emphasized the imperative need of collecting appropriate qualitative and quantitative data necessary for proper management and planning and using reliable inventory methods. They evaluated various distance-based sampling methods to study of shrub density and spatial patterns of the shrubs over 53 hectare of forest reserve in Iran. The study revealed differences among distance sampling methods (nearest individual, nearest neighbor, second nearest neighbor, T-Square and compound in the 150×100 meter net). Student t-test analysis showed that two nearest neighbor and compound sampling methods were not different from the perfect inventory (real quantity).

Sist, Mazzei, Blanc and Rutishauser (2014) used one-ha-permanent sample plots as adequate unit of forest study to investigate the long term effect of reduced-impact logging on above-ground live biomass dynamics in the Eastern Amazon rainforest. According to Ganivet and Bloomberg (2019), there is a need for developing assessment tools to monitor fragmentation of tropical forests in order to conserve tree species diversity adequately. Several methods, including field-based and remote-sensing approaches are potentially useful to achieve this goal rapidly and cost-effectively. Combined use of field-based and remotely-sensed methods is becoming the ideal strategy whereby remotely sensed data are used to predict and map tree species diversity, stand structure, forest biomass and function at meso and large scales while ground-based field inventories provide accurate information at local scales for validating and calibrating data from remote sensing (Gonçalves, 2018; Pan et al., 2013; Seidel, Fleck, Leuschner & Hammett, 2011). Field measurements constraints of sampling and studying a small fraction of the global domain, and remote sensing limitations from varying sensor angles, atmospheric properties, physical constraints and technological changes (Pan et al., 2013) are best overcome by integrating both approaches. The positives of remote sensing, such as uniform measurements across the full domain, are combined with the strengths of field measurements in providing detailed measurements of tree biomass, species diversity, growth and mortality over time (Morales, 2012). For example, recent studies focusing on landscape scale and large-area estimates of forest biomass have succeeded in integrating LiDAR with field validation plots through allometric modelling of height-biomass relationships (e.g., Asner et al., 2012; Saatchi et al., 2011). Allometric relations exist between characteristics of two different plant organs, whereby, the first parameter is measurable and the second is the non-measurable (or difficult to measure) parameter of interest (Seidel et al., 2011). Plot based sampling studies are relevant in the context of enhancing the integrated strategy of forest inventory.

## 2.7 Assessing Components of a Natural Forest Ecosystem

The study of forest dynamics deals with the changes in forest structure and composition over time; including the response to anthropogenic and natural disturbances (Pretzsch, 2009). In analyzing and describing forest ecosystems, both the structure and composition are analysed. Typically, every forest stand is characterized by its tree species mixture and structure. Forest structure looks at forest organisation with trees being principal determinants of vertical and horizontal arrangements of the components of forest ecosystem (Bourgeron, 1983). Forest structure is both a product and driver of ecosystem processes and biological diversity. Important components of forest structure include live-tree sizes, vertical foliage distribution, and horizontal variation in canopy density and coarse woody debris. Examination of forest structure in terms of basal area and tree height heterogeneity revealed that forest productivity did not increase with diversity; instead, forest structure emerged as the key variable of productivity (Bohn & Huth, 2017). The optimal species distribution and forest structure indices explained obtained productivity values, with coefficient of determination between 70% and 95%. The study used small-scale forest stands of 400 $m^2$ wherein trees compete for light.

Forest vertical structure is the characteristic differentiation into distinct vegetation height layers (Bourgeron 1983, Whittaker, 1975). Canopy height distributions are commonly used in vertical structure analysis of forests. Stand canopy heights rather than individual tree heights are best indicators of the forest height profile. Shannon-Wiener's index of diversity is a quantitative measure of habitat diversity (Brower Zar & Von Ende,1990; McManus & Pauly, 1990). The vertical habitat diversity has an application in biodiversity measurements and conservation. For example, vertical habitat diversity level and foliage density correlated positively with bird species diversity in forest ecosystems. Forest screening efficiency, which is the percentage of concealed skylight through the forest foliage, is reported to be inversely related to light intensity reaching undergrowth through forest canopy (Lowman, 1986). This is critical in shaping the nature and magnitude of understorey vegetation including forest regeneration. Screening efficiency is an indicator of the level of conopy cover and foliage density but not of the exact physical amount of light reaching the floor. The ecological significance of light screening includes its influence on the regeneration of suppressed seedlings (Connell, Tracey & Web, 1984). The frequency of gaps in terms of percentage of empty plots is often included in vertical forest structure as a measure of continuity of the distinct vegetation layers (Hitimana et al., 2004). Other forest attributes include forest horizontal structure as defined by the diameter size distribution of trees individually or as a community (Avery & Burkhart, 2015; Burkhart & Tome, 2012; Hitimana et al., 2004), the crowding of trees measured in numbers or basal area per unit area, and spatial distribution patterns of trees (Brower et al. 1990; Krebs, 1989). Tree diameter size distributions are often represented by stand curves as indicator of rates of recruitment, growth and mortality in the forest over time (Churski, 2006; Wang et al., 2009). Generally, the logarithm of the number of trees over diameter class becomes a straight line for regular recruitment and sufficient regeneration; and this characteristic implies a trend of decrease in number of individuals with increasing diameter size (Devis & Johnson, 1987). Fluctuating trend line indicates good but discontinuous regeneration over time which results in a wave-like recruitment of small individuals into the larger size classes (Poorter, Bongers, van Rompaey & de Klerk, 1996).

Forest stand curves for different forests or sites may differ in inclination as measured by the line slope towards larger size classes (Rollet, 1974). Forest structure and dynamics studies use a diversity of models, including Meyer (1952)'s negative exponential model (e.g. Devis & Johnson, 1987; Marimon & Felfili, 1997; Mushove, 1997; Shackleton, 1993), negative power function (e.g. Kigomo, Savill & Woodell, 1990), as well as United Nations Organisation [UNO] (1994) model of balanced forests in East African natural forests (e.g. Hitimana et al., 2004; Ronoh, Sirmah, Hitimana & Mullah, 2018); all the above models are based on the concept of reverse –J curve (Devis & Johnson, 1987). Diameter size is used as an indicator of age, with larger trees assumed to be older in age than smaller ones (Devis & Johnson, 1987; Hitimana et al., 2004) though this relationship may not be true in some cases (Harper, 1977). None of the above models is defacto superior to the other; the suitability of a particular model depending on the unique characteristics of a given forest ecosytem. Spatial distribution patterns and distribution of trees across diameter classes for individual species reveal how well the forest growing stock is utilizing the forestland (Krebs, 1989). In phytosociological studies, the species inventory is fundamental to characterize both α diversity (species richness of a particular community considered homogeneous) and β diversity (degree of variability or replacement in the composition of species among different communities of an environment (Whittaker, 1962). To study the composition and structure of a plant community, the following fundamentals are considered: the choice of sampling method (e.g. random or systematic), location, size, shape, and number of sample units (Barbour, Burk, Pitts, Gilliam & Schwartz, 1998; Concenço et al., 2017). Based on field measurement on species composition, importance value (SIV) and biodiversity indices (Barbour et al., 1998; Concenço et al., 2017) are computed.

Plant species composition is recognized as an important attribute of habitat for many wildlife species (Cade, 1997) and is fundamental for describing vegetation changes associated with plant succession (Mueller-Dombois & Ellenberg, 1974). The study of forest composition refers to identification of taxonomic groups making the forest as well as their relative importance based on abundance data (density and/or basal area) and frequency of occurrence. Species composition of a forest influences the products and services derivable from the same ecosystem, notably woody biomass for carbon storage, biodiversity conservation value and structural stability. Species - area curves are useful in comparing species richness between forests or sites. Arellano et al. (2016) found that systematic placement of plots contiguously was accurate and had added advantage of being relatively time- and cost-effective in species diversity assessment as compared to spread samples. Using basal as an estimate of tree cover may be advantageous when the resources important to wildlife species of interest are directly linked to tree biomass (Cade, 1997). With respect to forest composition studies, the species importance value (SIV) combines measures of relative frequency, relative density and relative basal area (relative dominance) to come up with the crude index of ecological dominance (Brower et al., 1990; Clarke et al., 1986; Concenço et al., 2017; Morais & Scheuber, 1997). Ecologically, dominant species or group of species contribute over 50% of the total forest basal area or density and have over 80% frequency of occurrence (Richards, 1981) and influence the management and conservation strategies of natural forests.

### ***Diversity indices***

The study of species composition enables one to appreciate species diversity through computing diversity indices such as Shannon-Wiener (Kent & Coker, 1992), Simpson (Hawksworth, 1995; Pielou, 1977) and Kinaro (1993). These diversity indices encompass both species richness and evenness (Kent & Coker, 1992; Krebs, 1989). Calculation of diversity indices, α (alpha), β (beta), and γ (gamma), allows the comparative analysis of homogeneous or heterogeneous plant formations; they measure, respectively, the species richness of a community, the degree of change or replacement in species composition among different communities, and their richness in the set of communities (Concenço et al., 2017; Merganič et al., 2012).

Most widely used diversity indices include Margalef (α), Menhinick (Dm), Simpson (D), and modified Shannon–Weiner (*H'*), besides species density itself (Gurevitch, Scheiner & Fox, 2009; Merganič et al., 2012). The Margalef index (Margalef, 1958) is used to estimate the biodiversity of a community based on the numerical distribution of the individuals of the different species according to the number of individuals in the sample being analysed, and is computed by Equation (4). This method compares species richness among samples collected from different habitats. The

Menhinick index, Dm, is equivalent to species richness index (Equation 2). It is based on the relationship between the number of species and the total number of individuals observed (Equation 5), which increases together with sample size (Whittaker, 1962). The Simpson index (Barbour et al., 1998) is obtained by Equation (6). Its calculation is strongly influenced by the importance of the most dominant species. Since its value is inverse to equity, diversity by Simpson is usually calculated by Equation (7), which indicates that closer to the value of 1, the greater the equity. Simpson's D gives very little weight to rare species and is more sensitive to abundant species.

$$\alpha = \frac{(S-1)}{lnN} \quad \text{…………………………………………..…. (Equation 4)}$$

where α = Margalef index, S = number of species, and N = total number of individuals.

$$Dm = \frac{S}{\sqrt{N}} \quad \text{……………………………………………………... (Equation 5)}$$

where Dm = Menhinick index, S = species collected, and N = total number of individuals from all the species, S.

$$\lambda = \sum P_i^2 \quad \text{………………………………………………….…..… (Equation 6)}$$

$$D = 1 - \sum P_i^2 \text{……………………………………………………..…. (Equation 7)}$$

where λ = Simpson index, Pi = proportion of individuals of species “i” divided by the total number of individuals in the sample, and D = diversity of Simpson.

The Shannon–Weiner diversity index ($H'$) is commonly used to characterize species diversity in a community and is more sensitive to rare species (McManus & Pauly, 1990); therefore sampling errors may be high (Barbour et al., 1998; Moore & Chapman, 1986; Pandeya, Puri & Singh, 1968). It is computed as in Equation 8 and ranges from 0 to the Natural logarithm of S (Barbour et al., 1998).

$$H' = -\sum[P_i \times \ln(P_i)] \qquad \text{(Equation 8)}$$

where $H'$ = Shannon–Weiner diversity index, $P_i$ = proportion of individuals of species “i” divided by the total number of individuals in the sample.

### Species-accumulation curves

Species-accumulation curves, also knowm as species - area curves, are used as tools to evaluate consequences of disturbance on species diversity (Denslow, 1995). Species -area curves are important in examining sampling effectiveness for species richness within different forest sites; and species richness falls within the scope of biodiversity measures (Schwarz, Thor & Elsner, 1976). Species accumulation curves are used to estimate the rate of species accumulation along a transect (Gillison & Brewer, 1985). Species - area curves are also used to examine sampling effectiveness for species richness and determine optimum unit sample area within different forests or sites (Brower et al., 1990; Hitimana, 2000).

### Measuring β-diversity

Similarity indices also exist that are used to compare different communities or forest sites. They include Jaccard index, Sorensen index among others (Concenço et al., 2017; Kent & Coker, 1992; Spellerberg, 1991). The methods for quantifying β- diversity are divided into two classes: similarity-dissimilarity and exchange/replacement of species. The different indices are applied depending on the nature of the data, whether qualitative or quantitative, and what the relationship between the samples is, what it implies, how samples are organized, and how they were obtained. Thus, the similarity or dissimilarity expresses the degree of comparability in species composition and its abundances between two communities.

The Jaccard (J) and Sorensen (So) index values (Equations 9-10) should be interpreted on an absolute scale from 0 to 1 [or 0 to 100%] ; with 0 indicating total dissimilarity and 1 [or 100%] absolute similarity. Sorensen’s index, puts more weight on the co-occurrence of species, compared to Jaccard’s index. Sorensen relates the number of shared species with the arithmetic mean of the species in both compared sites, while

Jaccard relates the number of shared species with the total number of exclusive species (Kent & Coker, 1992). Sorensen index above 50% indicates high similarity, and the threshold is 25%  for Jaccard index (Concenço et al., 2017).

$$J = \frac{c}{a+b+c} \quad \text{……………………….…………………………… (Equation 9)}$$

$$So = \frac{2c}{(2c+a+b)} \quad \text{……………………………………………..…… (Equation 10)}$$

where J = Jaccard's similarity index; So = Sorensen's similarity index; $a$ = total number of species in area $a$; $b$ = total number of species in area $b$; and $c$ = number of species common to areas $a$ and $b$.

According to Spellerberg (1991), sample size and diversity do affect similarity indices and the choice of a given index should be based on comparative advantages and the objectives of the study.

## 2.8 Common Forest Parameters of Interest in Tropical Natural Forest Assessments

Phytosocio-ecological studies in tropical forests include tree species composition across different development stages, tree species diversity and dominance indices, and abundance of each species in the forest (Concenço et al., 2017; Girma, 2012). It was found taxa-based inventory may provide the optimal instrument for biological survey and conservation planning (Higgins & Ruokolainen, 2004). Tree species richness and evenness are components of species diversity used in assessing forest biodiversity value.

In sampling forest elements to construct and characterize forest structure, both vertical and horizontal structural elements may vary with local microenvironment. Species are the fundamental units of biological organisation, and any small changes in the species diversity may alter to some extent ecosystem functions and services (Hitimana et al., 2004; You, Vasseur, Régnière & Zheng, 2009). As reviewed by Girma (2012), species diversity, species richness and biodiversity are widely used terms, sometimes interchangeably, in ecology and natural resource management. Species diversity is a fundamentally multidimensional concept that includes species richness, abundance and evenness (Hitimana et al., 2004; Kent & Coker, 1992; Merganič et al., 2012; Purvis & Hector, 2000).

The ideal structural models can be modified at various spatial scales by localized environmental factors including the biotic and / or abiotic e.g. topography, soils (Brunig, 1983; Denslow, 1995; Hett & Loucks, 1976). Vertical structure parameters include stand height and foliage dispersion or density and screening efficiency (Brower et al., 1990; Brunig 1983). The model horizontal structure of a mixed uneven-aged tropical rain forest is characterized by trees in all diameter sizes; decreasing basal area and diameter size distribution of the forest community (Brunig, 1983; Devis & Johnson, 1987; Philip, 1994).

In carrying out analytical measurements of horizontal forest structure, tree diameter size distribution and/or basal area (Hitimana et al., 2004) are represented by stand curves as indicator of rates of recruitment, growth and mortality in the forest over time. Tree diameter size pattern is an indicator of forest stability, regeneration history and impact of past disturbances. Generally, the logarithm of the number of trees over diameter class becomes a straight line for regular recruitment and sufficient regeneration (Poore & Sayer, 1991). McWilliams et al. (2015) described a regeneration indicator for forest inventory and analysis including sampling and estimations. Options of measurements of regeneration may be done in sample plots, in subplots or in microplots. Variables include counts, heights and root collar diameter. The number of tree seedlings is used as a measure of regeneration potential of a forest.

Stand density depicts the degree to which a given site is being utilized by the growing trees. Its measures include the number of trees per unit area, basal area per unit area, quadratic mean diameter and relative spacing (Burkhart & Tomé, 2012; Hitimana et al., 2004; Philip, 1994).

Stand basal area is the sum of the basal areas of all living trees in a forest stand, and larger than a specified minimum diameter. It is expressed on a horizontal area basis and is used as reference variable for quantitative description of forest stands. Stand basal area typically ranges from 0 - 60 $m^2ha^{-1}$ depending on the forest type and site quality. Basal area attribute is assessed in all ground-based forest resource inventory because estimates of timber volume and / or biomass are derived from it. In ecological studies, basal area is a measure of both the degree of crowding of trees in a forest stand and the level of space utilization attained (Schreuder et al., 1993). Basal area per unit area is also described as the cumulative cross-sectional areas at breast height of all trees over that unit area. The major advantage of basal area as a measure of density is that it incorporates both number of trees and tree sizes (Pretzsch, 2009). A stand with many small trees can have a large basal area as one with fewer but larger trees. Basal area per unit area and number of trees per unit area combined specify the average tree size. Both measures are sometimes combined to obtain improved quantification of average stand density for input into planning silviculture treatments and projecting stand growth and yield.

Quadratic mean diameter (QMD) is a stand parameter used in appreciating average tree diameter sizes for different woody vegetation types. Being the diameter of the tree of average basal area (Burkhart & Tome, 2012), QMD is a surrogate measure of stand density. It gives weight to larger trees and is more directly related to stand volume; thus becomes a superior size parameter of trees in comparison with the arithmetic mean DBH (Schreuder et al., 1993).

Relative spacing is a stand parameter which assume that stands with desirable stocking share similar ratios of average distance between trees to average dominant height. Average top canopy height is also an important factor in modeling stand biomass production and in describing stand site quality. Saud, Lynch, Anup and Guldin (2016) applied quadratic mean diameter and relative spacing index to improve predictive capacity in tree height–diameter and crown ratio modeling. Their application in natural forests is however not common.

According to Zeide (2005), the number of trees per unit area is the true measure of stand density, but not a sufficient index of competition. Basal area is a more effective measure because it integrates both the number and diameter sizes of the trees in a stand (Zeide, 2005). However, basal area is not also a true measure of species competition unless it is combined with some measure of stand development. Otherwise, basal area treats all species as equal contributors to competition and there are multiple pathways to the same basal area value: few large trees or many small trees. Zeide (2005) observed that basal area is only an effective index of competition when it is compared to basal area derived from a normal yield table. It varies with species, site and age, making it a relative density measure. Likewise, quadratic mean diameter is not a true measure of competition but it is widely used to describe stand structure; preferring it over the simple arithmetic mean. Combining number of trees, basal area and quadratic mean diameter leads to construction of alternative measures of stand density which describe competition but primarily in even-aged stands.

Quantification of site occupancy in terms of stand density is central to developing reliable models for predicting forest growth and yield. Stand density is a quantitative term describing the degree of stem crowding within a stocked area. The extent of competition in a stand is determined by the number of trees per unit area, their respective sizes and spatial distribution. The number of trees per unit area is a simple, easy to measure expression for average stand density. Description and analysis of stand structures include use of natural stocking density index (SDI) which is the ratio of observed basal area in a stand to the maximum observed basal area (Burkhart & Tome, 2012; Pretzsch, 2009). Stand density rule which is based on the relationship between quadratic mean diameter and stem numbers per hectare in a fully stocked, unmanaged, pure even-aged stand, is expressed by Equation (11).

$$N = aQ^b \text{ ……………………………………………...…………….(Equation 11)}$$

where $\ln N = \ln a + b \ln Q$ is the double logarithmic coordinate system; N is the total number of individuals; Q is quadratic mean diameter; a and b are parameters to be estimated.

All measures of stand density are dynamic; they change over time and in space due to fluctuations in the environment. Stand density itself influences forest productivity and is used as an input variable for stand volume or yield models, together with stand age and site index. Age of trees in natural forests being difficult to measure, the density remains the most indispensible predictor to rely on. However, the use of density in stand volume equations works better for even-aged than uneven-aged stands. Finally, we note that tree growth and disturbances also characterize forest dynamics, which are equally influenced by available resources, e.g., radiation, water and nutrients, and prevailing environmental conditions such as temperature, soil acidity and air pollution (Burkhart & Tome, 2012; Öztürk et al., 2018; Pretzsch, 2009).

## 2.9 Experiences and Limitations of Application of Sampling in Natural Forests

Field studies through sampling are combined with most commonly used remote sensing technologies to accelerate assessment of forest resources (Lackmann, 2011; Morales, 2012; Nilson et al., 2003), in particular for large scale inventories or for integrated assessment of forest ecosystems such as ecological studies at ecosystem level (Hitimana et al., 2004; Hitimana et al., 2009; Asthana & Asthana, 1998). Remote sensing technologies are also used in forest or tree canopy cover assessments and research in this field to refine methods for improved accuracy is active e.g. Ucar et al., (2016) compared point-based sampling with plot (grid) sampling approaches for assessing the urban forest canopy cover from aerial photography. Based on the standard error of the mean, they found the second approach superior to the more commonly applied point-based sampling approach. The development of an accurate estimate of tree canopy cover can be a critical aspect of assessments of the carbon sequestration potential (Nowak et al., 2008).

Commonly used field sampling techniques in tropical forest ecosytsems include walk trails, transects and plots to determine tree species diversity, vegetation types, wildlife richness, forest structure and regeneration (Hitimana et al., 2009; Mutiso, Cheboiwo, Kiyiapi, Sang & Hitimana, 2016) as well as allometric relationships for modelling forest growth and yield including evaluating site quality (Burkhart & Tome, 2012; Morales, 2012; Weiskittel et al., 2011). Sampling strategies in tropical forests are dictated by such factors as ragged terrain, abundant wildlife, expansiveness and scarcity of baseline data e.g. checklists of indigenous species. Past field studies have integrated stratified sampling designs, nested plots characterised by purposively mixing use of different plot sizes and sampling intensities (e.g. Hitimana, 2000; Hitimana et al., 2009; Mutiso et al., 2016; Ronoh, 2016), indigenous knowledge, satellite images and geographic information system, all to overcome existing technical and scientific challenges for many situations in tropical forests.

Different researchers in Kenya have used varying plot sizes, e.g. 20 m x 10 m (Hitimana et al., 2009; Warinwa, Mwaura, Kiringe & Ndubi, 2016), 10 m x 10 m (Ronoh, 2016), at predetermined distances along georeferenced line transects to capture trees and forest physical habitat. In addition, sub-sampling through nested smaller plots within the large units are often used to assess forest regeneration (Hitimana et al., 2004; Kiruki et al., 2017; Ronoh et al., 2018). Sapling and seedling individuals are counted from smaller but different sub-plot sizes e.g. 40 $m^2$ and 20 $m^2$, respectively. The above sampling approach enabled the collection of useful information on a diversity of attributes from mixed tropical forests and within a relatively short term. The collected primary data enabled the understanding of actual forest regeneration, recruitment, density, structure, diversity as well as other realities about studied ecosystems such as wildlife and water resources, types and extent of anthropogenic activities (Bulafu, Mucunguzi & Kakudidi, 2007; Clausnitzer, Churchfield & Hutterer, 2003; Hitimana et al., 2009; Hitimana et al., 2010; Hitimana et al., 2011; Kiringe, Mwaura & Warinwa , 2016). Plot data also enable objective documentation and analysis of effects of grazing and cultivation on forest plant communities (e.g. Hitimana et al., 2009; Reed & Cokie, 2000). Integrating use of aerial photographs and field sample plots along altitudinal changes provided data for the description of vegetation in montane forests (e.g., Hamilton & Perrott, 1981).

The review of literature revealed that a mix of different plot shapes, plot sizes and sampling intensities have been applied in different studies and inventories at the will of different reseachers and with no justification nor indication of any possible impact such mix would have on the reliability (accuracy and precision) of the findings.

## 2.10 Demand for Quality Data in Forest Inventories

Ecological and socioeconomic factors such as biodiversity, protection and recreational functions are becoming increasingly important in addition to tree and forest biophysical attributes (Pretzsch, 2009). Integrated knowledge of a stand about stand level or at landscape level is more relevant for ecosystem management rather than fragmented details about trees, stands and ecosystem functioning. System management requires integration and a holistic view of the system in question. There is a link between models and inventories; from deductive to inductive approaches. Two features of modern forest inventories that contribute considerably to bridging the gap between scientific and practical relevance. According to Vanclay (2003), there are emerging new demands for pertinent information for forest management which dictate the need to develop tools to collect and analyze the data efficiently. Special challenges to modeller of tropical moist forests include high species diversity up to 100 tree species per hectare and a range of lifeforms and stem sizes (Vanclay, 1995).

Model development involves exploring data to provide new insights into the forest dynamics and reveal gaps in present knowledge. Quality data are therefore an imperative to achieve this important goal of modelling. The quality of growth models and their predictions depend on many factors, chief of them being the quality of calibration data; they must be reliable. According to Kiruki et al. (2017), the management and conservation of dry woodlands need knowledge about composition diversity, structure and regeneration of plant species. We need a healthy, stable population of woodland species which recruits regularly overtime. The impact of human land use on vegetation structure is normally complex (Nacoulma et al., 2011) and often influenced by land ownership (Kiruki et al., 2017); resource ownership to a greater extent determines accessibility and utilization.

Pretzsch (2009) extensively reviewed the use of quadratic mean diameter in forest dynamics, growth and yield studies. The critical role of inventory data in modeling forest dynamics, growth and yield was stressed and demonstrated. Inventory data are used in the inductive approach as start values for simulation runs and for the derivation of site-growth relations. The current (1st time or baseline inventories) need to be used as model input to provide the start or initial variables for simulation runs. These inventories are expected to provide detailed information about standing volume, diameter distribution and spatially explicit information about stand structure e.g. stem coordinates. Successive inventories on fixed permanent plots provide information about stand and tree growth for empirical models development (Morales, 2012; Pretzsch, 2009). There is therefore need for consistent, standardized and harmonised use of inventory schemes.

Repeated surveys of the forest state, increment, environmental conditions and resource supply make it possible to initialise growth models. Stand dynamics are closely related to the initial stand structure. Use of the detail information can raise the accuracy and precision. Diverse demands on the forest complicate planning process and decision making. Tools and methods of forest and tree assessment are neither specific nor new;

what is more original is the way they are combined and implemented (Bellefontaine et al., 2002). Large scale aerial photographs are good for describing the spatial distribution of tree and forest formations. Satelllite data are used to stratify a region on the basis of ecological and land use criteria. For ground measurements, sampling arrangements designed for forests are diverse. More essential to planners and managers is the ability to assess patterns of change over time and/or space, and to identify suitable methods to produce the needed data.

## 2.11 Summary of Knowledge Gaps

Different plot sizes, sampling intensities, sampling techniques have been applied in mixed tropical forests with no indication of the efficiency or quality of methods used. Multistage sampling techniques are known to increase efficiency in forest inventories especially in the mixed tropical forests that are notably heterogeneous at the local scale such that variance increases as plot size decreases (Alder & Synnott, 1992). Experience suggests that a plot size of one hectare is a suitable compromise for sampling purposes. According to Synnott (1979), a square 100mx100m-plot is adequate for sampling purposes in tropical forests. The plot is convenient for subdivision into quadrats of 20 m x 20 m or 10 m x 10 m in terms of cost effectiveness and accuracy of information during field work. A study in Nandi forests by Girma (2012) used 20mx20m-plots to collected vegetation information. The plots were distributed along transects that ranged from 1 km to 1.6 km and were laid parallel to the slope. It is widely accepted that the distribution of biota, stand structure and floristic composition are strongly influenced by physical environmental gradients (Lee et al., 2002). However, there has been no serious discussion of the statistical implications of purposive sampling along such gradients. Advantages of purposive sampling along gradient-oriented transects over sampling along non-gradient-oriented transects have not also been established.

Girma laid five small plots of size 3 m x 3 m within each main quadrats; four at the corners and one at the center to record herbaceous plants and seedlings of all woody plants. Large plots were used to record all woody plants which were ≥ 2 cm DBH and height > 1 m as well as lianas (Gerwing et al, 2006; Girma, 2012). Fewer but larger plots are preferred to many but small plots. There is always need to strike a balance between the cost and precision or accuracy when fixing required sampling intensity. Subdividing any forest estate into 1 ha inventory units is therefore a common and agreeable practice. Is there any opportunity to subsample this standard unit and reduce the cost of inventory and at the same time achieve statistically similar or higher accuracy of estimates on per hectare basis?

Some important points can be drawn from the reviewed literature:

- Forest assessment studies are complex in the context of tropical mixed natural forests and in the wake of changing roles of forests and tree resources due to dynamic socio-ecological and economic situations.
- There are many research initiatives undertaken in forest resources assessment. However, studies on efficiency and harmonization of sampling methodologies in forestry are rare.
- Natural forests and woodlands are today recognized as a critical asset for livelihoods, biodiversity conservation, economic development and climate moderation for which quality information-guided strategic planning is mandatory. Unfortunately, there is serious lack of scientifically tested and locally adapted tools to be used in generating the much needed knowledge.
- Based on the existing knowledge in forest sampling techniques, on past practices in forest assessments as well as the availability of computer technologies, research on efficiency (accuracy and cost effectiveness) of sampling schemes is achievable.
- Variation in forest species data may arise due to sampling designs and not necessarily from the difference in forest vegetation characteristics per se.
- There is need to harmonise sampling designs in forestry to allow comparability of data from different researchers in the context of National Forest Management System.

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Introduction

In view of the existing methodological constraints with respect to inventory systems in natural tropical forests, this study sought to circumvent such challenges by designing, testing and evaluating 48 sampling schemes based on three sampling designs, four plot sizes and four sampling intensities to study forest structure, composition and species diversity attributes using known, original empirical data from field-based inventories in selected tropical natural forests in Kenya. The efficiency by which different sampling models captured studied forest parameters were determined and compared based on known field populations and computer-based simulated samples. The research used scientific analytical tools to discern, ascertain and recommend the most effective schemes in terms of accuracy, precision and effort by which observed or measured population parameters were estimated. The selected three natural forest types in Kenya were: Kakamega mixed tropical rainforest (TRF), Mt Elgon moist lower montane forest (MMF) and Loruk dry woodland forest (DWF), respectively representing dense western rain forests, dense montane forests and open dryland forests strata proposed under the National Forest Monitoring System in Kenya (DRSRS et al., 2019).. Simple random sampling (SRS) and systematic sampling designs along horizontal, East-West oriented transects (SSH) and along vertical, North-South oriented transects (SSV), four plot sizes (25, 50, 100 and 400 m$^2$) and four sampling intensities (5, 10, 20 and 30 %) were screened for suitability in estimating biophysical forest attributes commonly used in comprehensive description of natural forest ecosystems. The evaluated attributes in each of the three forests are: tree species composition, diversity, top canopy height structure, regeneration, recruitment, diameter size structure and forest density measures (stems per hectare, basal area per hectare) and average forest tree diameter size.

Complete inventory provided population parameter values for each of the attributes. Each forest was represented by a well demarcated 100 m by 100 m square-shaped forest unit of reference. The population parameters values served as a control against which we gauged the relative *efficiency* of the different sampling *schemes*. Before sampling, each one of the forest units of reference was described. Drawing of samples, data organisation and analysis were based on conventional quadrat methods using R-programming software (version 3.3.1) tools such as selection of plot samples, averages, descrptive statististics, dispersion box plots, analysis of variance and multiple comparison tests. Tables were created and graphs drawn using MS Excel 2013 spreadsheet tools. Editing and grouping of graphs or photos as presented in the document were done using print screen and PowerPoint 2013 functions.

## 3.2 Study Area

Figure 2 shows forest map of Kenya, the location of the three studied forests (Kakamega rainforest, Mt Elgon moist montane forest and Loruk dry woodland) and the specific study sites. The selected forest types represent three main geographical formations in Kenya. Mt Elgon forest represents High Mountain and high range forests, Kakamega rainforest represents forests on the Western plateau, and Loruk woodland/forest represent forests in dry low altitude woodlands.

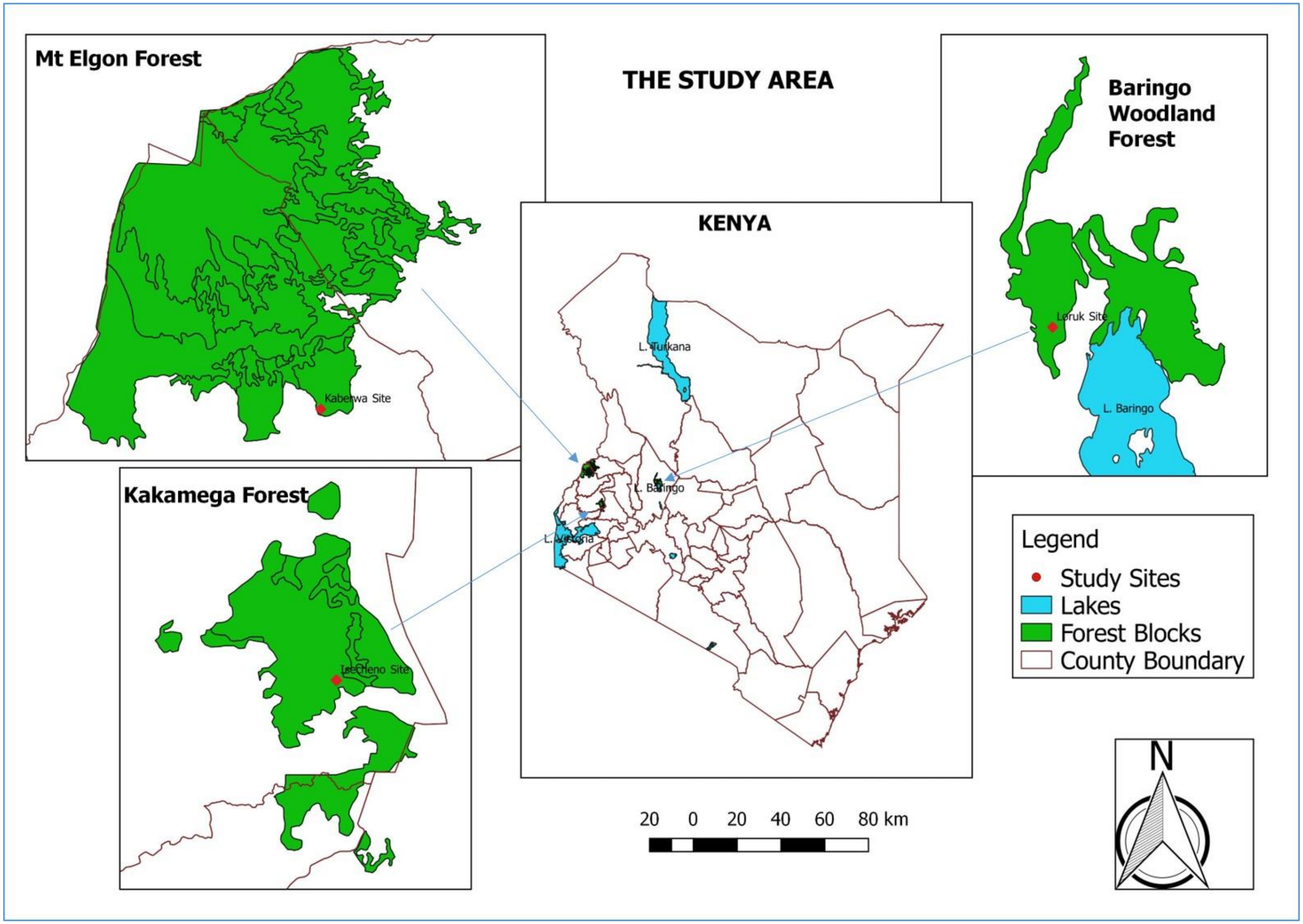


**Figure 2: Location of Study Sites in Kenya (Author, 2019)**

## 3.3. Study Sites

The geo-ecological locations of the three forest types represent western rain forests (Kakamega site), montane forests (Mt Elgon site) and dryland forests (Loruk site) (DRSRS et al., 2019). Geo-referenced coordinates, climatic regimes and Agro-Ecological Zones (Jaetzold & Schmidt, 1983) are provided in Appendix I. The general floristic characteristics of the studied forest ecosystems are described in subsequent sections. Kakamega forest zone (AEZ UM0) has shallow soils but tropical rain forest nutrient cycling process ensures a flourishing vegetation and above-ground tree biomass. Mt Elgon forest zone (AEZ UH0) has moderate to high fertility. The Loruk zone (AEZ LM5) has shallow soils with variable fertility level (Jaetzold & Schmidt, 1983).

### 3.3.1 Kakamega Rainforest

The sampled Kakamega forest (Figure 3) is the only tropical rainforest in Kenya of the Guineo–Congolian type (Kumelachew 2008, Megevand et al., 2013; Miao 2008) but has a cooler and less humid climate (Kokwaro, 1988). The current Kakamega forest is a fragment of past Nandi-Kakamega single block of forest. Fregmentation of this large forest block gave rise to different forests: including Kakamega gazetted forest reserve, Kisere forest, Malaba forest, Bunyala forest, North Nandi and South Nandi forests (Girma, 2012; Kokwaro, 1988).

Megevand et al., (2013) documented salient features of the Congo Basin forest that are similar to those in Kakamega tropical rainforest. The Congo Basin forests harbor thousands of endemic plants in both low altitude and montane forests. These forests are also habitat to a range of wildlife e.g. African elephants, buffalo and many endemic animal species such as antelope, birds and gorillas (CBFP, 2006; Ervin et al., 2010). Dense forests represent the largest portion of land cover; about 46 % of them classified as dense humid forests. The distribution of forest types in the Congo Basin correlates strongly with annual rainfall. Kakamega forest falls within the category submontane forests of the Congo Basin forest which fall with an elevation range of 900 – 1500 m.

Kakamega rainforest consists of a large block and six fragments (Peters, Fischer, Schaab & Draemer, 2009). The study site was located in the central main forest block, which covers 8245 ha. The site is at 0° 19' N, 34° 52' E; elevation 1580 m and 40 km north-west of Lake Victoria (Fashing, Forrestel, Scully & Cords, 2003; Mutiso, Hitimana, Kiyiapi, Sang & Eboh, 2013).

Generally, this part of the forest was subjected to selective logging in the1940s (Fashing et al., 2003) and to other anthropogenic activities (Momanyi 2007). Currently, man-made trails are the main disturbance affecting Kakamega forest ecosystem (Mutiso et al., 2013). It is dominated by thick undergrowth beneath large and tall trees (Figure 3) which are influenced by high rainfall regime and constant temperatures. Despite past disturbances, the forest is on the recovery path and near climax development stage (Mutiso et al., 2013) with high tree species diversity (Kokwaro, 1988).

At this site, average annual temperature is 20.4 °C with 21.3 °C for the hottest month and 19.3 °C for the coldest month. Average annual rainfall is 1971 mm with average rainfall of 61 mm for the driest month and 273 mm for the wettest month. The data is within the range found in other publications as reviewed by Mutiso et al. (2013).

**Figure 3: Tropical rain forest top most canopy layer (A) and lowest canopy layer with typicaly thick undergrowth (B) and buttressed huge tree stems (C) sizes, Kakamega forest structure, Kenya (Source: Author, 2019)**

### 3.3.2 Mt Elgon Montane Forest

Mt. Elgon forest ecosystem description is documented in Hitimana et al. (2004). The study site was located in the diversity-rich tropical moist lower montane forest side, on the steep slopes of the extinct volcano Mt. Elgon (height of 4321 m a.s.l.) in Kenya (Figures 2 & 4). Elevation is between 2000 and 2100 m a.s.l, higher than in Kakamega forest. Entire forest is confined between 0°49'–1°13'N and 34°05'–34°47'E, and covers 78025 ha (Hitimana et al., 2004). Annual mean temperature at the study site is documented to be 15.2–18.0 °C, with a bimodal annual rainfall: 1460 mm (May) and 1622 mm (August); the driest month (January) has an average annual rainfall of 41 mm (Hitimana, 2000; Jaetzold & Schmidt, 1983). The forest area is reported to be under-stocked tropical mixed rain forest, affected by historic logging activities, with a good overall forest regeneration but which does not mirror the regeneration status of some individual tree species (Hitimana et al., 2004). Selective logging affected the population structure of some affected species (Hitimana et al., 2010). The ecosystem is a habitat to a rich diversity of tree species and globally threatened faunal species (MENR, 2016). Mt Elgon moist lower montane forest is in the building phase, with its canopy cover intersected by some forest gaps (Hitimana et al., 2004). Thick and continuous undergrowth developed beneath scattered canopy trees (Figure 4). The Mt Elgon ecosystem is a critical catchment for the Lake Victoria drainage system and the Nile River system at large.

**Figure 4: Mt Elgon forest undergrowth and canopy characteristics in disturbed area, Kenya (Source: Author, 2019)**

### 3.3.3 Loruk Dry Woodland

The sampling schemes were evaluated at Loruk site in the larger Baringo woodlands (Figure 2), representing dry woodland forests. In Kenya, tropical dryland forests and woodlands occupy expansive area and support many people and over 75% of livestock. Lake Baringo woodland ecosystem falls within the Arid and Semi-Arid Lands (Omondi, 2016; Pauw et al., 2000). Figure 5 shows the typical Loruk dryland forest, with short trees and poorly developed undergrowth. Loruk site is classified as a ranching zone in North-West of Lake Baringo and characterized by erratic rainfall and high temperatures (Jaetzold & Schmidt, 1983). The average annual rainfall is 629 mm, with 21 mm average rainfall for the driest month and 92 mm for the wettest month. The average annual temperature is 23.7 °C, with the warmest month recording 24.8°C and the coldest month registering 22.5 °C.

## 3.4 Field Methods

### 3.4.1 Forest Unit of Reference

A one-hectare forest unit of reference was demarcated in each forest type, at least 500 m inside the typical vegetation type of the forest in order to get a good representation of the local vegetation type and avoid edge effect. The designated area of one hectare constitutes a forest unit of reference that contains “test populations” for all sampled variables and a benchmark or “control” against which relative efficiency of each of the candidate sampling schemes was compared and evaluated. Complete census (that is, 100 % sampling intensity) over each one ha forest unit also provided information that is used to describe each forest type of reference in detail.

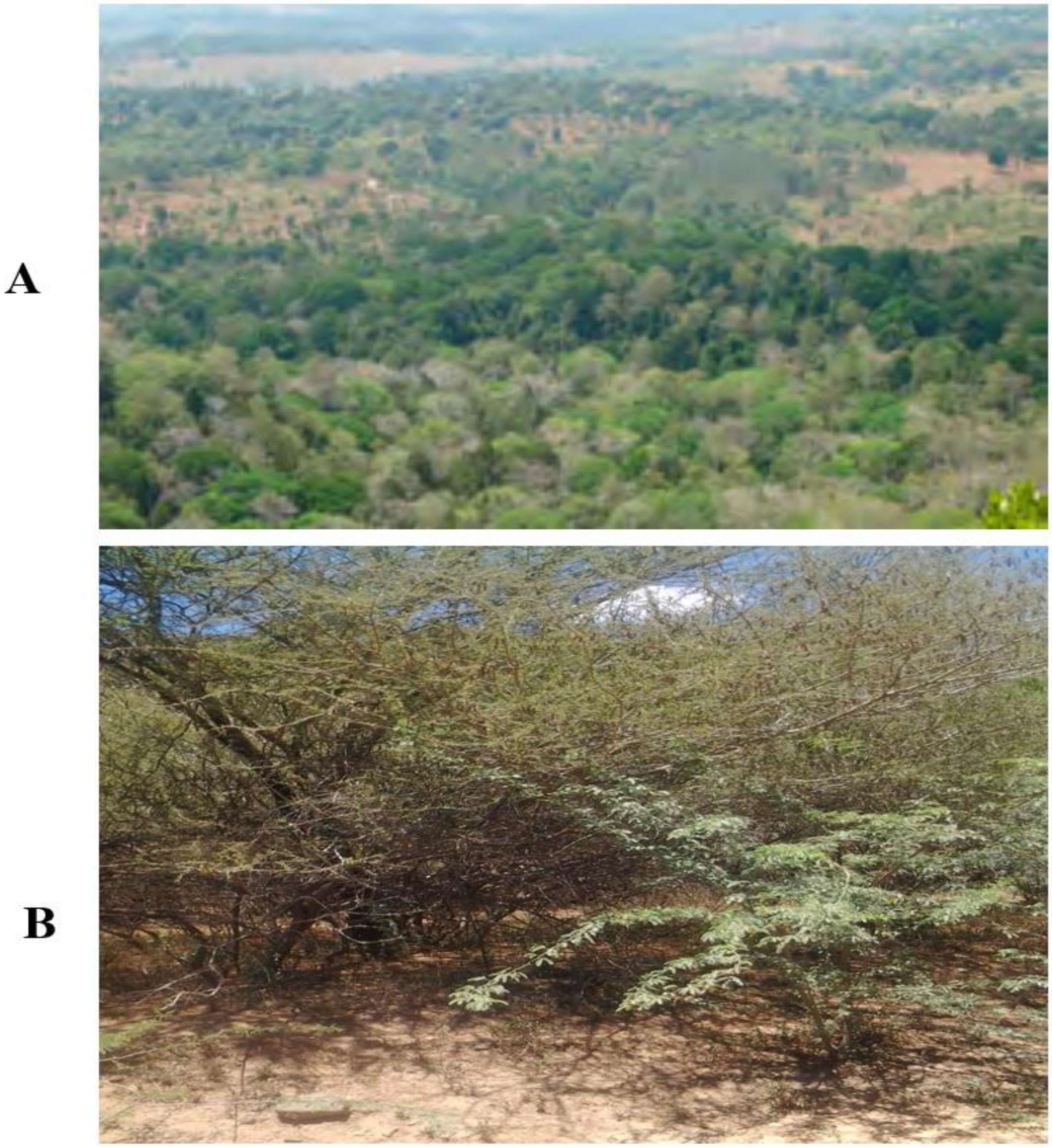


**Figure 5: Loruk Woodland Forest site (open low canopy vegetation with 65-40% cover) with a typical tropical dryland forest physiognomy (A) and Tropical dry woodland forest canopy structure in Loruk area (B), Baringo, Kenya**
(Source: Author, 2019)

One-hectare forest plot is widely used in tropical natural forest inventories and as permanent sample plots to study forest dynamics over time (e.g. Alder & Synnott, 1992; FAO, 1981; Ganivet & Bloomberg, 2019; Martinez & Phillips, 2000; Stropp, Ter Steege & Malhi, 2009). However, some studies have indicated that 1-ha plot size may not be most appropriate to measure species diversity (e.g. Phillips et al., 2003a), and smaller plot size e.g. 0.5 ha-plot is recommended for diversity studies (Baraloto et al., 2012) and contiguous 20mx50m-plots are used as standard protocol for woody plant inventories and soil characterisation in tropical forests (Arellano et al., 2016).

### 3.4.2. Field Work Organisation

Efficient planning of field work reduces labour costs, prevents safety risks and ensures accurate estimates (Lackmann, 2011). Data collection over 1-ha forest unit of reference was done in the field to determine “true” values of forest attributes. The demarcated one-hectare forest unit was subdivided into smaller units, up to 400 smallest 25m$^2$-plots. The subdivision exercise in the field started by progressively establishing temporal 10mx10m-field plots (Figure 6) and dividing each plot into four 5mx5m-subplots (Figure 7) to ensure accurate field observations of forest vegetation attributes from seedling stage were made and recorded. Complete enumeration of forest attributes was carefully and systematically done in 5mx5m-plots which was the smallest unit of data compilation. To enhance accuracy of observations on small sized individuals such as seedlings, thorough search and counting was done within 1mx1m-subplots, one after the other. Pre-prepared field data collection sheets were used and filled manually by trained field assistants. Measurements and observations on trees were later transferred into MS Excel spreadsheets. The four hundred 5mx5m-plots in each forest unit of reference were well labelled for easy identification and retrieval. The 20mx20m-plot was the largest.

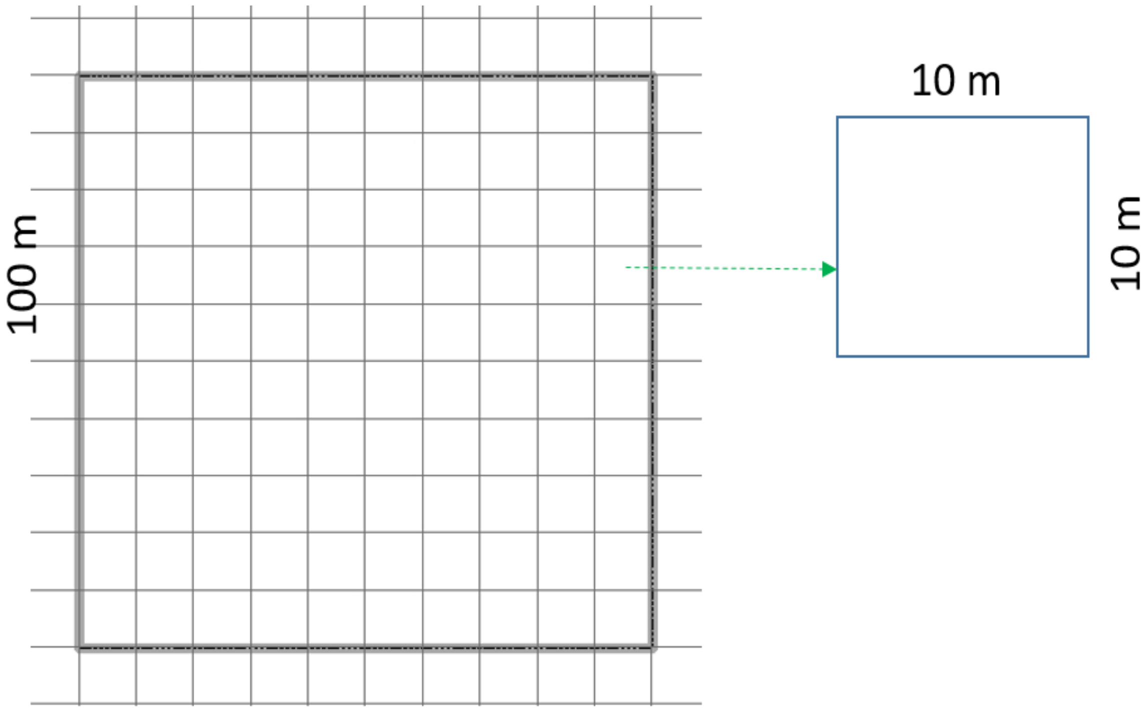
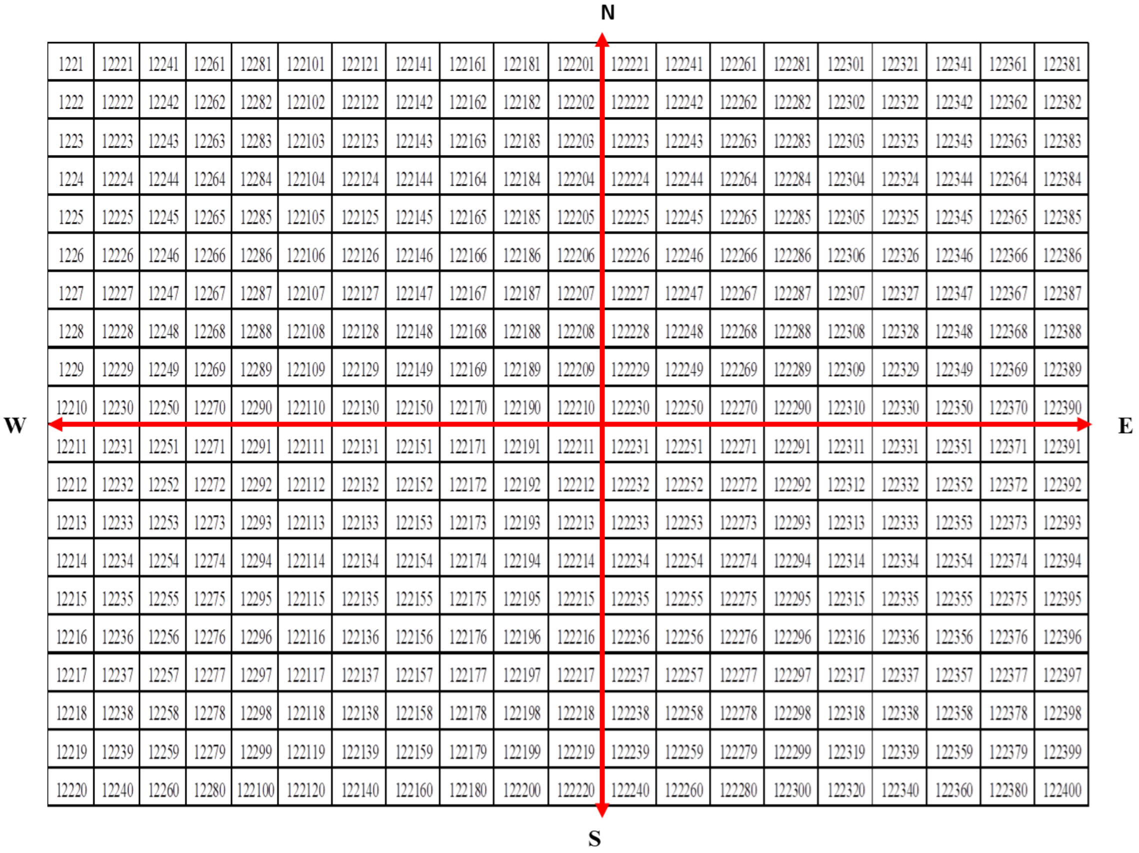


**Figure 6: Illustration of 100m x 100m forest unit of reference subdivided into 10 m x 10 m sampling plot units**



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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1221 | 12221 | 12241 | 12261 | 12281 | 122101 | 122121 | 122141 | 122161 | 122181 | 122201 | 122221 | 122241 | 122261 | 122281 | 122301 | 122321 | 122341 | 122361 | 122381 |
| 1222 | 12222 | 12242 | 12262 | 12282 | 122102 | 122122 | 122142 | 122162 | 122182 | 122202 | 122222 | 122242 | 122262 | 122282 | 122302 | 122322 | 122342 | 122362 | 122382 |
| 1223 | 12223 | 12243 | 12263 | 12283 | 122103 | 122123 | 122143 | 122163 | 122183 | 122203 | 122223 | 122243 | 122263 | 122283 | 122303 | 122323 | 122343 | 122363 | 122383 |
| 1224 | 12224 | 12244 | 12264 | 12284 | 122104 | 122124 | 122144 | 122164 | 122184 | 122204 | 122224 | 122244 | 122264 | 122284 | 122304 | 122324 | 122344 | 122364 | 122384 |
| 1225 | 12225 | 12245 | 12265 | 12285 | 122105 | 122125 | 122145 | 122165 | 122185 | 122205 | 122225 | 122245 | 122265 | 122285 | 122305 | 122325 | 122345 | 122365 | 122385 |
| 1226 | 12226 | 12246 | 12266 | 12286 | 122106 | 122126 | 122146 | 122166 | 122186 | 122206 | 122226 | 122246 | 122266 | 122286 | 122306 | 122326 | 122346 | 122366 | 122386 |
| 1227 | 12227 | 12247 | 12267 | 12287 | 122107 | 122127 | 122147 | 122167 | 122187 | 122207 | 122227 | 122247 | 122267 | 122287 | 122307 | 122327 | 122347 | 122367 | 122387 |
| 1228 | 12228 | 12248 | 12268 | 12288 | 122108 | 122128 | 122148 | 122168 | 122188 | 122208 | 122228 | 122248 | 122268 | 122288 | 122308 | 122328 | 122348 | 122368 | 122388 |
| 1229 | 12229 | 12249 | 12269 | 12289 | 122109 | 122129 | 122149 | 122169 | 122189 | 122209 | 122229 | 122249 | 122269 | 122289 | 122309 | 122329 | 122349 | 122369 | 122389 |
| 12210 | 12230 | 12250 | 12270 | 12290 | 122110 | 122130 | 122150 | 122170 | 122190 | 122210 | 122230 | 122250 | 122270 | 122290 | 122310 | 122330 | 122350 | 122370 | 122390 |
| 12211 | 12231 | 12251 | 12271 | 12291 | 122111 | 122131 | 122151 | 122171 | 122191 | 122211 | 122231 | 122251 | 122271 | 122291 | 122311 | 122331 | 122351 | 122371 | 122391 |
| 12212 | 12232 | 12252 | 12272 | 12292 | 122112 | 122132 | 122152 | 122172 | 122192 | 122212 | 122232 | 122252 | 122272 | 122292 | 122312 | 122332 | 122352 | 122372 | 122392 |
| 12213 | 12233 | 12253 | 12273 | 12293 | 122113 | 122133 | 122153 | 122173 | 122193 | 122213 | 122233 | 122253 | 122273 | 122293 | 122313 | 122333 | 122353 | 122373 | 122393 |
| 12214 | 12234 | 12254 | 12274 | 12294 | 122114 | 122134 | 122154 | 122174 | 122194 | 122214 | 122234 | 122254 | 122274 | 122294 | 122314 | 122334 | 122354 | 122374 | 122394 |
| 12215 | 12235 | 12255 | 12275 | 12295 | 122115 | 122135 | 122155 | 122175 | 122195 | 122215 | 122235 | 122255 | 122275 | 122295 | 122315 | 122335 | 122355 | 122375 | 122395 |
| 12216 | 12236 | 12256 | 12276 | 12296 | 122116 | 122136 | 122156 | 122176 | 122196 | 122216 | 122236 | 122256 | 122276 | 122296 | 122316 | 122336 | 122356 | 122376 | 122396 |
| 12217 | 12237 | 12257 | 12277 | 12297 | 122117 | 122137 | 122157 | 122177 | 122197 | 122217 | 122237 | 122257 | 122277 | 122297 | 122317 | 122337 | 122357 | 122377 | 122397 |
| 12218 | 12238 | 12258 | 12278 | 12298 | 122118 | 122138 | 122158 | 122178 | 122198 | 122218 | 122238 | 122258 | 122278 | 122298 | 122318 | 122338 | 122358 | 122378 | 122398 |
| 12219 | 12239 | 12259 | 12279 | 12299 | 122119 | 122139 | 122159 | 122179 | 122199 | 122219 | 122239 | 122259 | 122279 | 122299 | 122319 | 122339 | 122359 | 122379 | 122399 |
| 12220 | 12240 | 12260 | 12280 | 122100 | 122120 | 122140 | 122160 | 122180 | 122200 | 122220 | 122240 | 122260 | 122280 | 122300 | 122320 | 122340 | 122360 | 122380 | 122400 |

**Figure 7: Example of field arrangement for four hundred 5 m by 5 m subplots in the forest (Horizontal: E-W; Vertical: N-S).**

Each cell with a number represents a coded 5mx5m-plot for easy data set identification, entry, storage, retrieval and use in sampling activity. First three digits denote the forest site (122-Kakamega site; 111- Mt Elgon site; 131- Loruk site). The subsequent digits represent serial plot number within the 100 m x 100 m frame (see Appendix III for codes in all sampling frames used).

The field team was composed of three people: the researcher and two field assistants. The team was trained in the use of equipment and filling of data collection forms. The following instruments and materials were used: compass for orientation and geographic direction; fiberglass meter tapes for horizontal ground distance measurement, global positioning system [GPS] spatial coordinates to demarcate each 100 m x 100 m forest unit of reference, and wooden pegs used to mark corners of plots and subplots.

### 3.4.3 Sampling Frames

In this study, sampling schemes are combinations of sampling designs, plot sizes and intensities in capturing forest attributes of interest. Picking of random or systematic sample data for specified sampling intensities for each of the standard plot size considered was accurately achieved through programming with R Software. Each data entry was linked to a uniquely coded plot (e.g., Figure 7). Sampling frame varied as the plot sizes changed (Appendix II & Appendix III). Large plot sizes [10 m x 5 m, 10 m x 10 m, 20 m x 20 m] were derived from 5 m x 5 m cells using confounding technique in R-programming software. Codes used to merge plots are shown in Appendix II. The following sampling frames were formed: four hundred 5mx5m-plots ha$^{-1}$, two hundred 10mx5m-plots, one hundred 10mx10m-plots and twenty five 20mx20m-plots. Appendix III contains sampling frames for different plot sizes, using Mt Elgon forest site as an example. Merging of smaller plots was associated with automatic collation of records they contained. Calculations on plot data were done for all plot sizes, separately, using specialized functions in the R software.

### 3.4.4 Sampling

Two sampling methods, simple random sampling and systematic sampling, were tested. However, three designs that were evaluated for efficiency in each forest type were simple random sampling [SRS], systematic sampling along vertical transect (N – S direction) [SSV], systematic sampling along horizontal transect (E – W direction) [SSH]. Sampling process in R is described in Appendices IV-V. In addition, systematic sampling along slope gradient (diagonal transect) [SSD] was evaluated in the montane forest. The three directional sampling options: horizontal, vertical and diagonal are illustrated in Figure 8. The diagonal sampling direction is often applied along gradients such as slope or altitude in mountainous forest landscapes to strike a balance between variations influenced by vertical and horizontal directional factors. Sorting and arranging plots [and their corresponding data] along a progressively increasing slope factor was done [in R] based on plot characteristics at the Mt Elgon site. Serial plot numbers and percent slope measurements enabled actualizing the slope gradient. Sampling trials were then tested along this transect line using three plot sizes [10 m x 5 m; 10 m x 10 m; 20 m x 20 m] and three sampling intensities [10%, 20% and 30%]. Evaluated sampling schemes were composed of sampling designs, plot sizes and sampling intensities (Table 4).

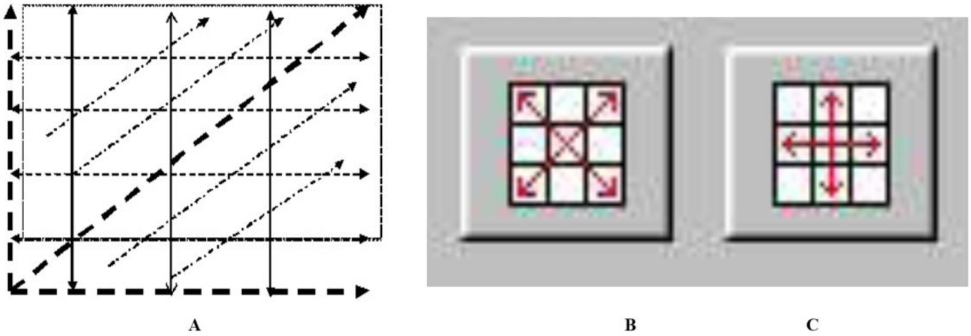


**Figure 8: Illustrated three directional sampling options within a forest unit of reference (horizontal, vertical and diagonal).**

On a slopping terrain such as in montane forests, vertical direction faced up slope (North-South) and horizontal direction is perpendicular to the slope (East-West) direction, and diagonal direction facing gradual change in slope (e.g South-East to North-West or South-West to North-East direction tangent to steepness). Only those plots traversed by transects in B and C have a chance to be selected and form samples in systematic sampling schemes. On flat terrain, only vertical and horizontal directions were considered.

**Table 4: Sampling frames (N) for different plot sizes and respective sample sizes for varying sampling intensities**

| Plot sizes (m x m) | → | 5x5 | 10x5 | 10x10 | 20x20 |
|---|---|---|---|---|---|
| Sampling frame (N = all plots $ha^{-1}$) | → | 400 | 200 | 100 | 25 |
| **Sampling specifications** | | | | | |
| Sampling intensity $(I)^1$ | | Sample sizes (n) | | | |
| 5% | No. sample plots → | 20 | 10 | 5 | 1 |
| | Actual sampled area ($m^2$) | 500 | 500 | 500 | 400 |
| 10% | No. sample plots | 40 | 20 | 10 | 2 |
| | Actual sampled area ($m^2$) | 1,000 | 1,000 | 1,000 | 800 |
| 20% | No. sample plots | 80 | 40 | 20 | 5 |
| | Actual sampled area ($m^2$) | 2,000 | 2,000 | 2,000 | 2,000 |
| 30% | No. sample plots | 120 | 60 | 30 | 7 |
| | Actual sampled area ($m^2$) | 3,000 | 3,000 | 3,000 | 2,800 |

[1] $[\mathrm{I} = \frac{\mathrm{n}}{\mathrm{N}} \times 100]$

A sampling scheme refers to a combination of three elements: a specified sampling design (D), a specified sampling intensity (I) and a specified plot size (S).

### 3.4.5 Designing and Actualization of Sampling Schemes

Data were collected on each of the three forest types independently but applying similar designs. Simple random sampling (abbreviated as SRS) was performed using randomisation function in R. Various samples drawn from each forest type using simple random sampling (SRS) and systematic sampling (SSH and SSV) are shown for different sampling intensities in Appendix VI, Appendix VII and Appendix VIII. In the case of systematic sampling, we applied belt transect technique with constant length of 100m; the width varied with sampling intensity. Vertical transects faced north – south to support the vertical systematic sampling design, shortened as SSV. Horizontal transects faced east – west to support the horizontal systematic sampling design, shortened as SSH. Sampling along the diagonal direction was only applied at Mt Elgon forest where the slope gradient is prominent and could influence forest attributes of interest.

In this study, 48 distinct sampling schemes were generated by combining three designs, four plot sizes and four sampling intensities (Table 4 and Table 5). The number of sampling units (sample size, n) for each sampling scheme are shown. Each sampling scheme was applied across the three natural forest types and evaluated for efficiency (accuracy and cost-effectiveness) in each forest type as an independent block. Mapping of actual distribution of sampling units for each sampling scheme was done using R programming software, Excel spreadsheet and MS Word.

### 3.4.6 Assessed Forest Variables

Sampling was performed on each test pupulation using different schemes which combined three sampling components: method, plot size and sampling intensity. Key Forest attributes of interest were assessed for use to describe and understand overall structure and floristic composition of each ecosystem based on the one-hectare forest unit of reference subdivided into the 5m x 5m plot size as the smallest basic units for data collation. Broadly the data was about tree species composition, species diversity (richness and evenness), top canopy height, diameter size distribution and basal area distribution patterns. These attributes were selected due to their high ecological, silvicultural and conservation significance in forest resource conservation and management. Despite its multiple dimensions, biodiversity is usually equated with species richness only (Feld et al., 2009; Merganič et al., 2012). This study adopted species richness concept by Hamilton (2005), which is the number of species in a habitat or sample without considering the number of individuals in each species. Measurement techniques and applications of measured variables are summarized in Table 6. Forest top canopy height was measured within each 5 m x 5 m basic plot unit using suunto hypsometer. The maximum slope inclination was recorded in percentage using suunto clinometer. Light screening efficiency of the canopy was dermined using a transparent frame with 100 square grid, at the plot centre (Brower et al., 1990). Time taken to complete work within the plot (duration) was recorded in minutes using a watch chronometer.

**Table 5: Sample sizes for different candidate sampling schemes**

| Sampling Design | Sampling intensity (n /N %)[1] | Plot sizes | | | |
|---|---|---|---|---|---|
| | | 5 m x 5 m ($25\ m^2$) | 10 m x 5 m ($50\ m^2$) | 10 m x10 m ($100\ m^2$) | 20 m x 20 m ($400\ m^2$) |
| SRS | 5 | 20 | 10 | 5 | 1 |
| | 10 | 40 | 20 | 10 | 2 |
| | 20 | 80 | 40 | 20 | 5 |
| | 30 | 120 | 60 | 30 | 7 |
| SSH | 5 | 20 | 10 | 5 | 1 |
| | 10 | 40 | 20 | 10 | 2 |
| | 20 | 80 | 40 | 20 | 5 |
| | 30 | 120 | 60 | 30 | 7 |
| SSV | 5 | 20 | 10 | 5 | 1 |
| | 10 | 40 | 20 | 10 | 2 |
| | 20 | 80 | 40 | 20 | 5 |
| | 30 | 120 | 60 | 30 | 7 |
| SSD | 10 | 40 | 20 | 10 | |
| | 20 | 80 | 40 | 20 | |
| | 30 | 120 | 60 | 30 | |

SRS = Simple random sampling; SSH = Systematic sampling along horizontal transect;
SSV = Systematic sampling along vertical transect; SSD = Systematic sampling along diagonal transect
[1] n = sample size (no. of sample plots selected from on- hectare forest ecosystem);
N = population size (total number of plots in a one- hectare forest)

**Table 6: Checklist of variables assessed for overall forest characterization**

| Variables | Measurement | Application |
|---|---|---|
| i) Top tree canopy height | Haga hypsometer for each 5mx5m-plot | Vertical forest structure |
| ii) Tree diameter (≥ 1 cm at 1.3 m from ground level i.e. dbh) | Calipers: veneer caliper for small sizes e.g. saplings and large calipers for larger diameters | Diameter size distribution; derive basal area and quadratic mean diameter |
| iii) Maximum slope inclination | Suunto clinometers (percent scale) for steepness | Evaluate influence of slope on accuracy of inventory sampling method |
| iv) Canopy screening efficiency (100% - % skylight) | Transparent grid (polythene sheet) fixed on a wooden frame and divided into 100 squares | Measure concealed skylight reaching forest floor and perhaps influence regeneration quality and quantity |
| v) Canopy Brokaw gaps | Visual observation of empty plots | Deep canopy gap % [from ground level] and their possible influence on sampling scheme |
| vi) Name of tree species | Dendrology and plant taxonomy reference books | Species composition, tree diversity |

Counting of the number of tree seedlings within each 5mx5m-plot was done systematically and tallied in progressive 1mx1m-subplots. Diameter at breast height (DBH) for trees was measured at 1.3 m above higher ground level using a diameter tape. Trees were identified to species level using local parataxonmists, standard dendrology text books e.g. Beentje (1994) and herbarium specimens. Other field records include signs of forest disturbance, Geographic Positionning System coordinates for the 100 m x 100 m forest unit corners captured using Garmin GPS Unit.

### 3.4.7 Descriptive Analysis of the Forest Types Structure and Composition

***Simulated factorial experimental design and treatments***

For easy data organisation and statistical analysis, three factors (sampling designs, plot size and sampling intensity) were combined in a factorial fashion. The levels of each factor when combined produced 48 factorial treatments (sampling schemes) to be administered in each of the three forest types. A treatment is described and documented as a triplet “D-S-I”. To illustrate this, we take an example of a sampling scheme “simple random sampling with plot size of 5 m x 5 m or 25 $m^2$ and sampling intensity of 10%”. The scheme is identified by short names “SRS-25-10” or “SRS-5mx5m-10%”. Precision, accuracy, cost and relative efficiency of each scheme were computed.

### *Tree composition and diversity*

The trend in forest composition is described in terms of tree species from seedling stage to mature trees. Species compostion was evaluated and compared between forest types by grouping individuals according to species they belong to. Bar graphs were then displayed showing the level of representation of each species within the forest unit of reference and in relation to other species. After individual trees were organized into species, further classification was done for genera and families. The number of species, genera and families were compared among the different forest types and which families dominate within each forest. Similarities of the forest types in terms of families and species were also displayed.

Shannon diversity index (Merganič et al., 2012) was used to measure the level of species diversity in each forest and compared between the forests. Shannon species diversity index values were derived from species composition: the number of species and the relative abundance of each species. Species evenness ($E'$) was calculated from the ratio of observed diversity to maximum diversity (Magurran, 1988) using the following equation (12) below.

$$E' = \frac{H'}{H_{max}} = \frac{H'}{\ln(S)} \text{ ……………………….. (Equation 12).}$$

where $H_{max}$ is the maximum level of diversity possible within a given population, that is, the natural logarithm of the total number of species. $E$ ' value normally ranges from 0 to 1; where 1 is attained where all the species are abundant equally.

### *Forest vertical structure*

Comparison of forest vertical structure among the three forest types that form an ecological gradient of some sort was done based on the characteristics of canopy in the units of reference. The components of physical vertical structure of the 1 ha-forest units (reconstituting a sample of the entire forest) include top forest canopy height, screening efficiency, canopy gaps (Brokaw) percent, which gave insight into the relative complexity of the various forest types in terms of canopy structure as captured from 5mx5m-plot units. Brokaw (1982) defines a gap as a “hole in the forest canopy extending through all levels down to an average height of two meters above the ground”. Plotting forest canopy height was done for the three forest types in a comparative manner. The graph depicts height profiles for each forest type showing canopy layers for the tree component. The effect of plot size in capturing true picture of forest canopy height was evaluated by combining information from contagious smallest plot sizes ( 5 m x 5 m) and summarizing them in the largest plot size (20 m x 20 m).

### *Forest horizontal structure*

Sampling to analyze forest horizontal structure are common and critical in forest ecosystem analysis (Hitimana et al., 2004; Hitimana et al., 2011) for management, conservation and accounting for carbon sequestration. The forest horizontal structure covers the demographic trends from regeneration density (no. seedlings per ha) to tree density (stems per ha), and the trends in tree density, basal area, quadratic mean diameter relationships and what such relationships reflect in terms of forest structure and population dynamics across the different forest types. The transition of individual trees from one development stage to another indicates tree recruitment patterns (Girma, 2012) within the selected forest formations: tropical rainforest, moist montane forest and dry woodland. Standing basal area distribution was assessed as a positive indicator of volume, biomass and carbon sequestration in trees and was compared among studied forest ecosystems. Sampling schemes were also evaluated for same attributes in the three forest types. The horizontal analysis also includes tree diameter size structure and basal area structure.

Tree diameter size distribution patterns as we move from one forest type to the other was assessed as indicator of overall stability for the studied forest types. All data from plots were standardised by converting them on per-hectare basis. The reverse-J curve model of diameter size distribution (mathematical negative power function model) was fitted for each forest type using Hett and Loucks (1976)’s model (Equation 13). Least squares fit of this model was performed for all species combined after linearization through natural log transformation (Hitimana et al., 2004). The power model describes well diameter-size structure for populations with survival pattern characterised by a changing (rather than a constant) mortality rate over time (Hett & Loucks, 1976).

$$\mathrm{Y} = \mathrm{Y}_0\mathrm{X}^{-\mathrm{b}}$$ ………………………………………………………….….(Equation 13)

where Y is the number of individuals in any diameter class X, $\mathrm{Y}_0$ is the initial input into the population at time zero, i.e., the number of trees at the smallest dbh recognized in the data (1 cm for this particular study) and b is the mortality or depletion rate with time.

Relative stand density based on the number of trees in site were computed as shown in Equation 14.The use of density in stand volume equations works better for even-aged stands than for uneven-aged stands.

.

$$\text{Relative stand density for a site} = \left(\frac{\text{Density of the Site}}{\text{Sum of densities for all sites combined}}\right)\times 100$$

……………………….… (Equation 14)

Quadratic mean diameter, QMD, was computed (Equation 15) and used as a more stable stand parameter than basal area (Saud et al., 2016). It is derived from the diameter of a tree with mean basal area (Equation 16).

$$\mathrm{QMD} = \sqrt{\frac{\sum d_i^2}{N}} = \sqrt{\frac{4\times\overline{BA}}{\pi}}$$ ……………………………………...…. (Equation 15);

$$\text{With BA/ha} = \sum\frac{\pi d_i^2}{40000} = \frac{N\pi}{40{,}000} * \frac{\sum d_i^2}{N}$$ ……………………….……. (Equation 16);

where BA = basal area, N = number of stems per hectare, d is diameter at breast height

Relative basal area (BA) was computed based on diameter data in each site (Equation 17). It indicates relative dominance of each species within the ecosystem.

$$\text{Relative stand BA for a site} = \left(\frac{\text{Basal area value of the Site}}{\text{Sum of basal area values for all sites combined}}\right)\times 100$$

… (Equation 17)

Relative spacing (RS) is a stand parameter (Equations 18 and 19). It assumes that stands with desirable stocking share similar ratios of average distance between trees to average dominant height.

$$RS = \frac{\text{Average distance between trees}}{\text{average height of dominant canopy}}$$ ………………………. (Equation 18)

On per hectare basis,

$$RS = \frac{\sqrt{\frac{10{,}000}{N}}}{\overline{H}}$$ ……………………………………………… (Equation 19)

Where N is the number of trees per hectare and $\overline{H}$ is average dominant height (top canopy height).

### 3.4.8 Evaluation Tests for Sampling Efficiency

After creating plots of various sizes in R (Appendix II), sampling frames for each plot size were created defined and their grids displayed for Mt. Elgon as an example (Appendix III). The lists of all samples according to specified plot sizes, sampling intensities, sampling designs and forest types are shown in Appendices VI-IX. Statistical analyses were undertaken to establish suitability of various sampling schemes in terms of efficiency. Sample statistics values were compared against the corresponding values from complete inventory (population parameters). For each sampling scheme being evaluated, plot records were standardized by blowing them up to per hectare-basis. The sample statistics per hectare basis were compared with true population values for the variables of focus. Measures of precision and accuracy were also done on per hectare basis. Two broad approaches were applied in evaluating the efficiency of sampling intensities, plot sizes, designs that define sampling schemes for the selected variables: (i) exploratory approach based on indices and visual aids; and (ii) confirmatory statistical analyses.

***Evaluating sampling designs for tree species richness and diversity***

The study explored to what extent comparing the different forest types (along the tropical rain forests- moist lower montane forests- dry forests continuum) can be adequately achieved using simplest index of species richness (no. of species) instead of computing Shannon index ($H'$) of diversity. Species diversity is one of the measures of forest biodiversity. The relationship between species diversity index and species richness was established across studied forest types using regression analysis (SPSS version 21).
Preliminary exploratory analysis of the data indicated a positive correlation between the two and defined a predictive regression equation for the same where the number of species predicts almost perfectly species diversity measured by Shanon –Wiener index. The percentage richness (Equation 20) captured by different sampling schemes in relation to true richness (actual number of species recorded from 1 ha forest unit) was used to rank different schemes's suitability. This was done for the three different sampling designs: SRS, SSH and SSV.

$$\text{Percentage richness} = \left(\frac{\text{Number of species in the sample}}{\text{Total number of species in the population}}\right)\times 100$$

…………..…. (Equation 20)

Data from systematic sampling designs along transects were used to construct cumulative species – area curves as a relative measure of species richness across different forest types. We used contiguous plots of various sizes established along transects (belt transect method). The curves were models of rates of change in number of species with progressively increasing plot sizes (translated into sampling effort). Species-area curves were produced in MS Excel. Progressive species richness capture as we increase sampling intensity from 5%, 10%, 20% to 30% was interpreted and compared in each forest type between vertical and horizontal systematic sampling. The comparison was also made between different plot sizes.

Testing of sampling schemes' efficiency in capturing species richness based on species – area curves was done along vertical and horizontal transects. "Sample curves" relied on 5 %, 10 %, 20 % and 30 % sample intensities data to develop a predictive curve that would estimate maximum number of species to be found in a 1-ha forest area. Curves were drawn using the cumulative number of species (on vertical y axis) recorded from different sample area sizes (as represented by different sampling intensities) against the same sampling intensities (on the horizontal x axis). Projectory curves constructed from 30% of 1 ha were compared with predictive regression models which were constructed using all records from 1 ha including the actual number of tree species found in forest unit of study. They represent "true species –area curves" on per hectare basis against which efficiency of different sample plot sizes was determined and compared.

### *Evaluating efficiency of sampling schemes for forest structure assessment*

In this section, we used crude indices to evaluate effectiveness of different combinations of plot size, sampling intensity and sampling designs to determine regeneration density per hectare, tree density per hectare, basal area per hectare and quadratic mean diameter in different natural forest types. Plots data were standardized on per hectare basis and were analysed in a simulated factorial experimental design, in which a combination of sampling design type, plot size and sampling intensity form a treatment. This treatment is in effect a sampling scheme. Two stages of analysis were used: screening 48 candidate sampling schemes to pre-select those that were further evaluated by analysing deviations from the complete enumeration.

### *Screening sampling schemes*

The aim is identify sampling schemes that reduce sampling error and enhance great accuracy (Klauberg, Vidal, Silva, de M. Bentes & Hudak, 2016). The use of such schemes provides better direction for sustainable forest management and conservation. Accuracy of different sampling approaches were computed and compared for estimation of key forest paramters during inventories or ecological studies or other forest resource assessment programmes. Screening used simulations based on field data. A checklist of best sampling options based on efficiency index values is provided for each forest attribute of focus, accompanied by the plotting of deviations (errors) from reference values from complete enumeration after detailed descriptive analysis. Efficiency of each sampling scheme in estimating stand parameters of interest was descriptively and statistically evaluated.

### *Tests for Efficiency of the sampling schemes*

This evaluation was performed on four attributes: seedlings per hectare, trees per hectare, basal area per hectare and quadratic mean diameter. Statistical tests of significance between sampling errors emanating from different sampling schemes were performed and measures of relative efficiency used to rank suitable schemes computed following procedures in Strimbu (2014), Klauberg et al (2016) and Zar (1999). Bar graphs were used to display final outputs of statistical analysis. Reference population parameters were used for benchmarking accuracy levels of different sampling schemes. The following steps were followed to determine relative efficiency of sampling options:

- Computation of population variance based on 100 % intensity for each plot size and choosing the smallest variance for each of the four variables (seedlings per ha, density of trees per ha, basal area per ha and quadratic mean) per forest type.
- Calculating sample variance and standard error of mean for each sampling intensity (5%, 10%, 20% and 30%) with each of the specified plot sizes and sampling methods (SRS, SSH, SSV).
- Computing standardised cost per hectare associated with each standard error (sampling effort) and obtain Student’s t value for each sample size from t-table with α=5%. The cost of inventory for the sample was measured in terms of duration in minutes taken to take field records in a plot.
    - Applying the methods by Pálico-Netto and Brena (1997) (as cited in Klauberg et al., 2016) to compute sampling scheme precision (sampling error as a % of mean also known as uncertainty %) (Morais & Scheuber, 1997; Wong et al., 2001; Lackmann, 2011) (Equation 21) for each combination of plot size and intensity.

$$\text{Sampling error \%} = \frac{SE \times t}{\bar{X}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 21)}$$

The smaller the error, the more precise is the sampling scheme.

- In the preliminary screening, we set desired precision level (maximum allowable error as a percentage of the mean; Error %) to be ≤ 25%. Sampling schemes with higher error level were eliminated from the list as unsuitable. This level of acceptable error is adequate for inventories targeting multiple attributes in one survey from the highly variable tropical forests. Forest inventories in commercial plantation set a 10% error (Cavalcanti, Machado, Osokawa & Cunha, 2011), diagnostic inventory focusing on two forest species adopted 20 % and sampling for one species adopted 15% error (Klauberg et al., 2016).
- For the retained sampling schemes (error ≤ 25 % of the mean), tests of significance were done to determine those that differed statistically from reference values. One-way ANOVA and Tukey's test were applied (Zar, 1999) in R.
- Further, we determined the levels of relative efficiency (efficiency %; Equation 22) for each of the retained sampling schemes to zero-in on the most suitable schemes for each forest attributes and forest type. This efficiency measure was computed following the procedure recommended in Klauberg et al. (2016). The applied reference treament was the one with 100% intensity that produced smallest population mean variance,$\frac{\sigma^2}{N}$, regardless of forest type, plot size and sampling design (Table 7 ).
- For each sampling intensity 5%, 10%, 20%and 30% (per plot size category) and per design, variance, standard error of mean, the sampling effort i.e. standardised cost (area inventoried per hour) associated with each standard error per hectare was computed (Appendix XVI). In testing a rapid biodiversity assessment protocol for sampling termite assemblages in tropical forests, Jones and Eggleton (2000) defined sampling efficiency as the number of species collected per unit effort; where effort was measured as the number of days required for one trained person to collect, sort and identify the samples over a standard area.

**Table 7: Reference treatment based on mean population variance of 100 % intensity**

| Forest attribute | Forest | Smallest $\sigma^2/_N$ | Inventory cost (ha $h^{-1}$) | Basic unit of data compilation |
|---|---|---:|---:|---:|
| Seedlings $ha^{-1}$ | TRF | 1,726,559.16 | 0.02 | 5x5 |
| | MMF | 223,003.91 | 0.02 | 5x5 |
| | DWF | 3,033.49 | 0.04 | 5x5 |
| Stand density ha-1 | TRF | 5,239.46 | 0.02 | 5x5 |
| | MMF | 2,848.56 | 0.02 | 5x5 |
| | DWF | 2,427.01 | 0.04 | 5x5 |
| Basal area / ha | TRF | 46.967955 | 0.08 | 10x10 |
| | MMF | 7.148552 | 0.41 | 20x20 |
| | DWF | 0.050566 | 0.04 | 5x5 |
| Quadratic mean diameter | TRF | 0.000057 | 0.04 | 10x5 |
| | MMF | 0.000059 | 0.10 | 10x10 |
| | DWF | 0.000004 | 0.18 | 10x10 |

Comparable sampling efforts were recorded in a pilot inventory study in mixed natural forest (Aberdares site) as well as in the dry woodlands (Marigat Site) in Kenya (Nduati et al., 2016): 25.4 h $ha^{-1}$ equivalent to 0.04 ha $h^{-1}$ and 13.6 h $ha^{-1}$ equivalent to 0.07 ha $h^{-1}$, respectively.

In this study, the mean variance multiplied by actual sampling effort [cost] was used to calculate relative efficiency (Husch, Miller & Beers, 1972) (Equation 22)

$$\text{Efficiency \%} = \frac{\sigma_1^2 \times \frac{C_t}{N_1}}{S_1^2 \times C_1/_{n_1}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Equation 22)}$$

Where $S_1^2$ = sample variance for the sampling scheme; $n_1$ = sample size (i.e. number of plots based on the sampling intensity of the scheme); $C_1$= time (in hours) spent on measuring variables in the sample standardized per hectare (ie sampling effort or cost); $\sigma_1^2$ = population variance for reference (reference treatment) for the variable; $C_t$ = actual total cost of measuring variables in one-hectare forest unit of reference with the selected plot size; $N_1$ the population size (number of plots per ha, varying with plot size).

Relative efficiency introduced element of cost (sampling effort) measured in terms of time duration spent in each plot during field sampling activity. The average duration per ha (and hectare per hour) was computed based on the number of plots making the sample size and and total time spent on the sample. If relative efficiency is 100 %, then the tested scheme is 100 % efficient compared to the reference inventory (i.e. benchmark). Ideally, both effort and methods should be optimized so that overall sampling efficiency is not compromised (Gaspar, Cardoso, Borges & Gaston, 2014). At this stage, the most effective sampling schemes are those with highest efficiency and were selected based on the value of efficiency above 50 % (Klauberg et al., 2016). They were graphically displayed using bar graphs.

# CHAPTER FOUR

# RESULTS

## 4.1 Introduction

Description of studied forest types is covered before the sampling schemes for components are evaluated and reported. The tropical rain forest – moist lower montane forest – dry woodland forest gradient is described by floristic composition and similarities (Figures 9a–c; 10a-b; 11a-c), species richness, evenness and diversity (Table 8), vertical structure characteristics (Figures 12; 13a-d), diameter size distribution patterns (Figures 14 & 15), forest density (Figures 16) and **tree** recruitment trends (Figures 17a-b & 18). Results on sampling efficiency and optimum sampling schemes are presented in section 4.3. for species richness (Figures 19a-d; 20a-c and Table 9), for regeneration (Figures 21 & 22; Tables 10-12), for forest density measures (Figures 23-27;Tables 13-21). Finally, efficiency of sampling schemes along a slope gradient in montane forests is presented (Table 22; Figure 28 for regeneration; Figure 29 for density and Figure 30 fo basal area).

## 4.2. Characterisation of Studied Forest Types

### 4.2.1 Tree Species Composition, Relative Dominance and Similarity among the Forests

The data presented in this section were generated from complete enumeration of each of the three one-hectare-forest units. A total of 50 tree species from tropical rainforest, 36 from moist lower montane forest and 12 from dry woodland forest were recorded and their relative dominance across the three forest types is shown in Figures 9a-c. Recorded trees belonged to a mix of taxonomic groups across the three forest types (Figures10a-b; Appendix X). Overall, 81 different species belonging to 59 different genera and 36 different families were recorded in the three hectares we studied. However, each forest type contained some unique species, genera and families (Figure 10b). Respective lists of species, genera and families endemic to each forest type or shared among the three forest types are shown in Appendices X.4-6. Moraceae, Rutaceae, Euphorbiaceae and Bignoniaceae are the most species-rich families in TRF, those in MMF were Flacourtiaceae, Rutaceae and Ulmaceae. Mimosaceae was the only species-rich family in the dry woodland forest site; others being monospecific and monogeneric. Overall, Kakamega rainforest was the most diverse in species and genera unlike at family level where MMF diversity was as high as that in TRF (Figure 10b). Endemism of tree species and genera was found in the three forests. Tropical rain forest was the most species diverse and dry woodland forest the least diverse.

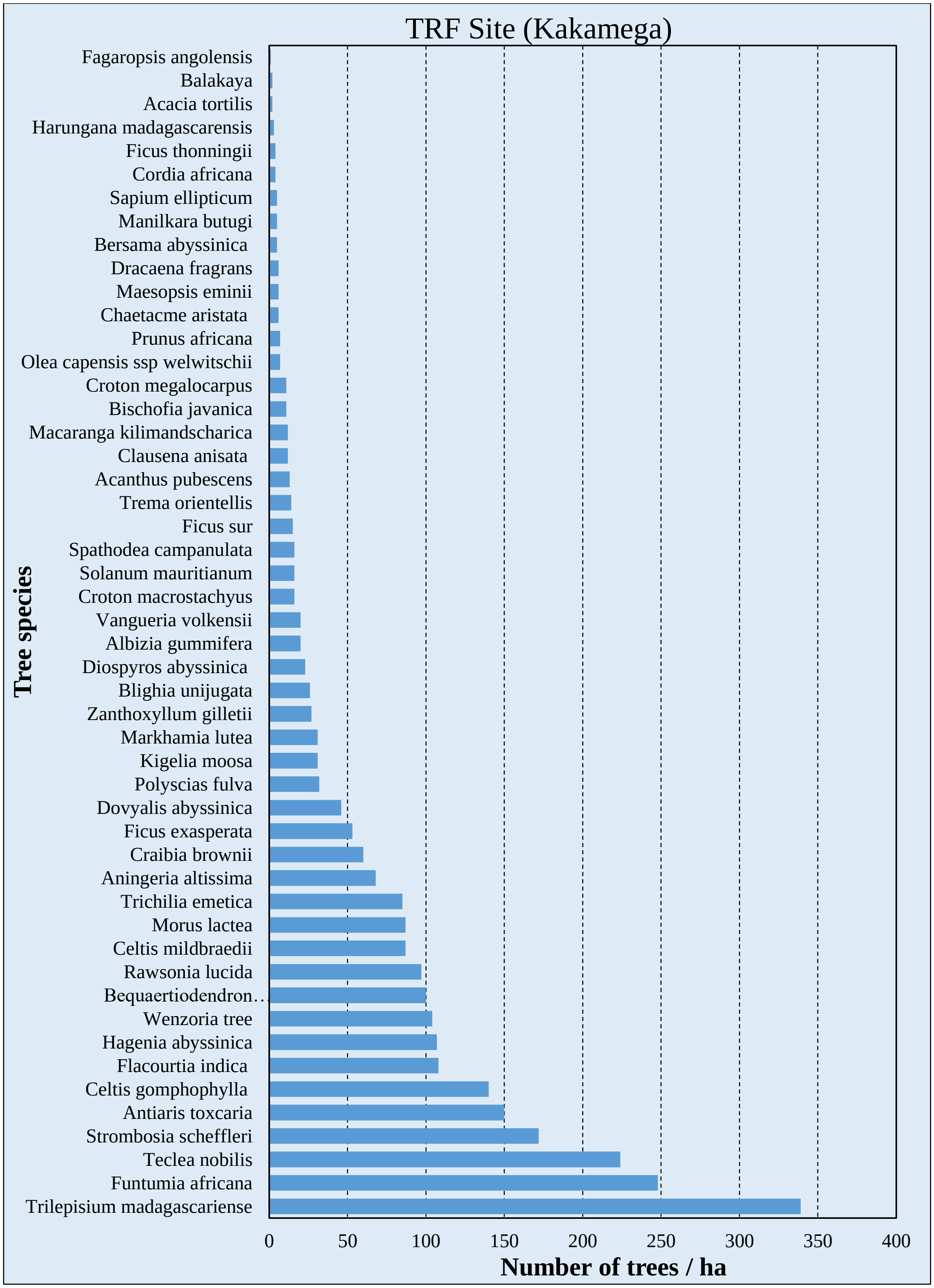


**Figure 9a: Forest tree species composition and dominance in the studied one hectare –block in Kakamega Rainforest, Kenya.**

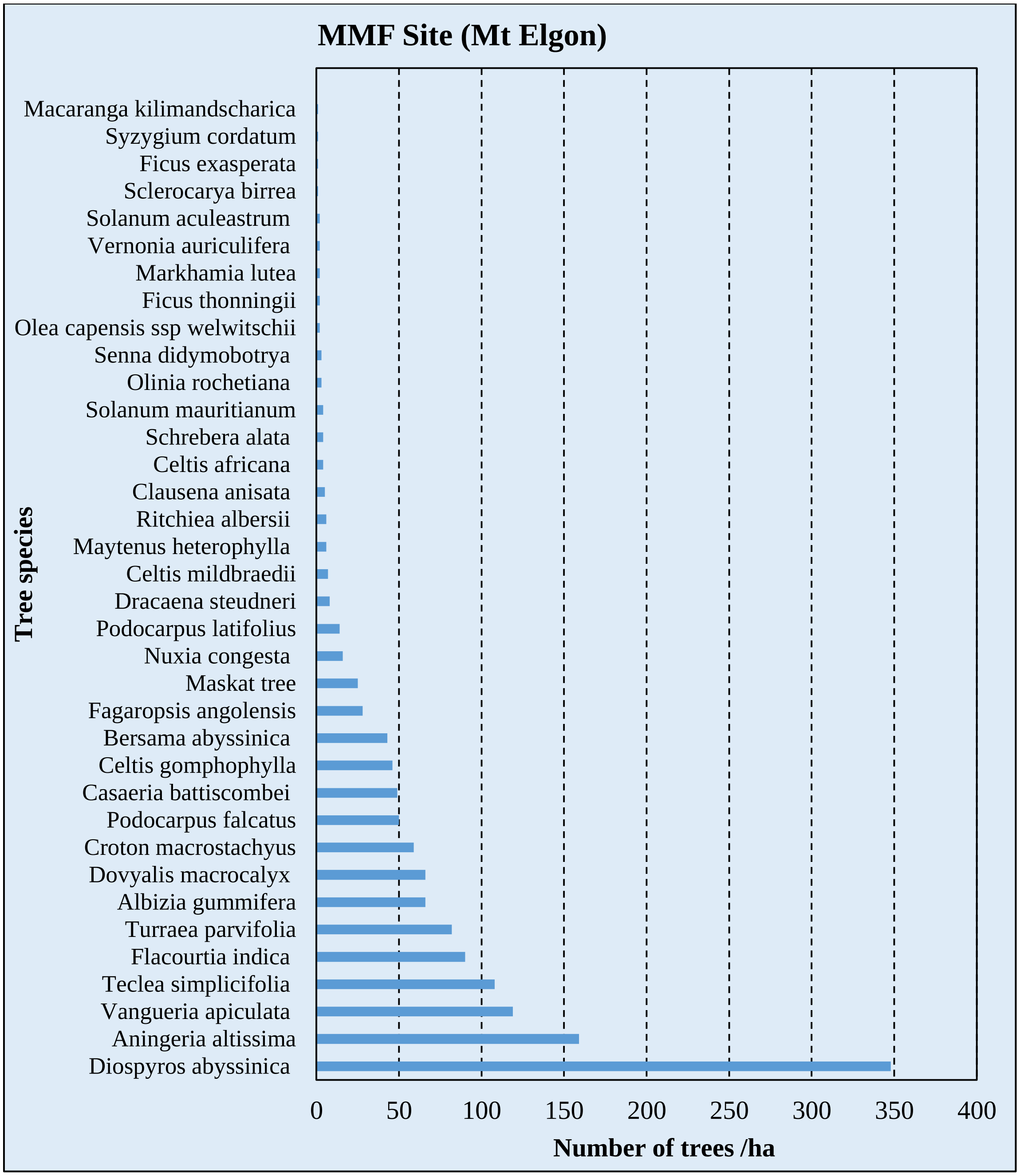


**Figure 9b: Forest tree species composition and dominance in the studied one hectare –block in Mt Elgon Moist montane forest, Kenya.**

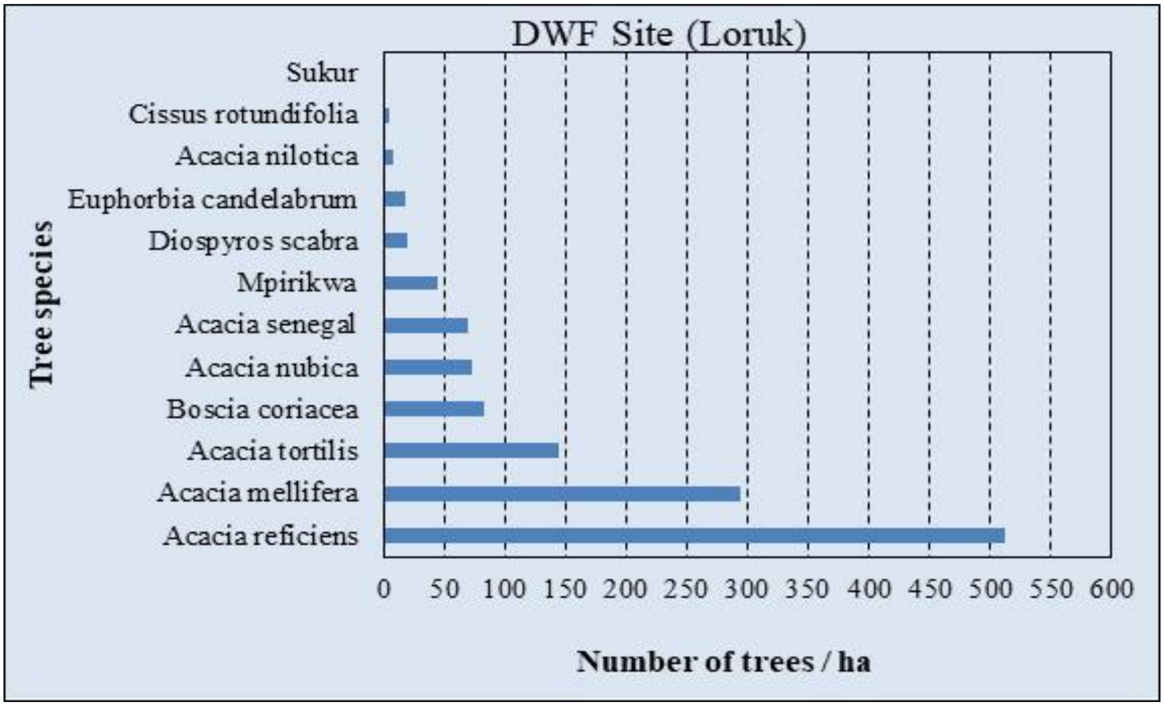


**Figure 9c: Forest tree species composition and dominance in the studied one hectare –block in Loruk dry woodland forest, Kenya.**

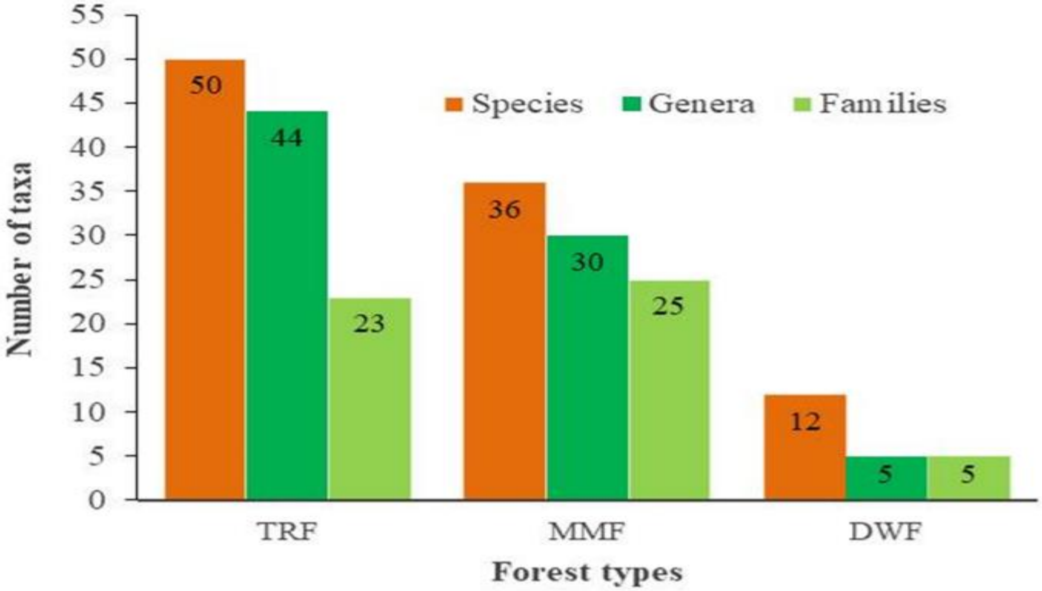
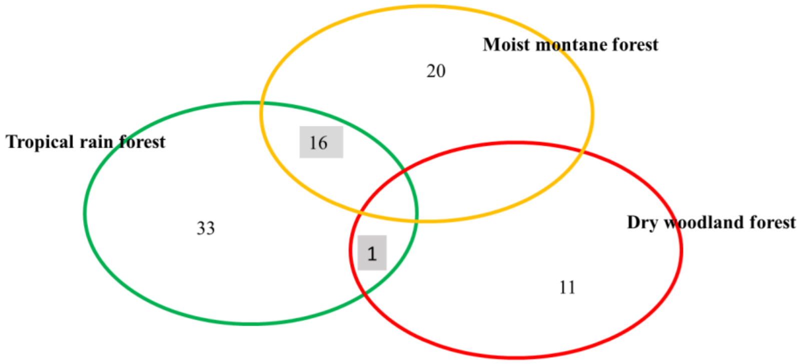
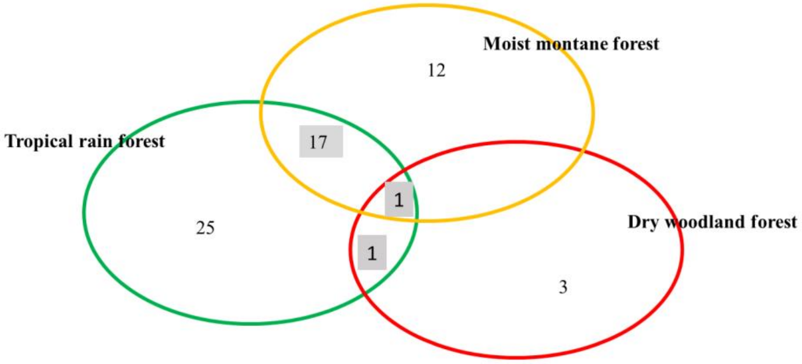


**Figure 10a: Total number of families, genera and species per hectare in Kakamega tropical rainforest, Mt Elgon moist montane forest and Loruk dry woodland forest, Kenya.**

(A) Distribution of the 81 tree species among the forest types



(B) Distribution of the 59 tree genera among the forest types



(C) Distribution of the 36 tree families among the forest types

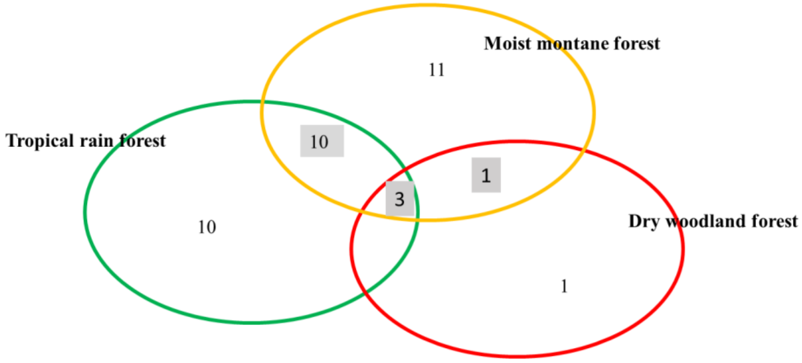


**Figure 10b: Similarity in composition among forest types in terms of tree species (A), tree genera (B) and tree families (C), Kenya.**

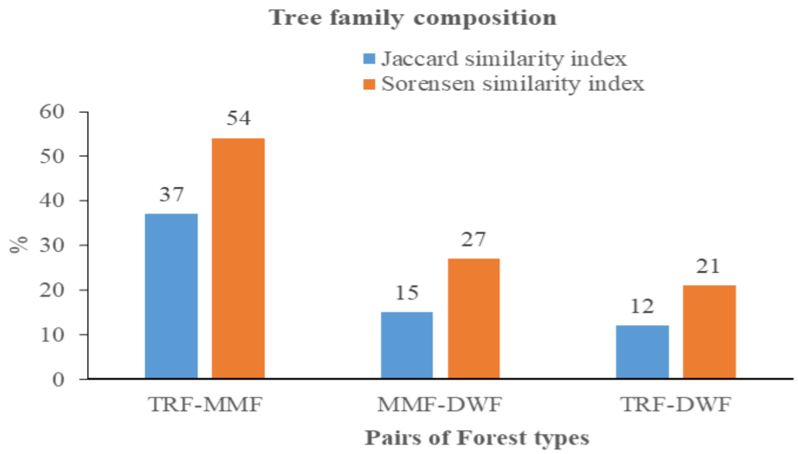


**Figure 11a: Percent (%) Jaccard and Sorensen similarity indices indicating similarity levels between different forest types [in terms of family composition], Kenya.**

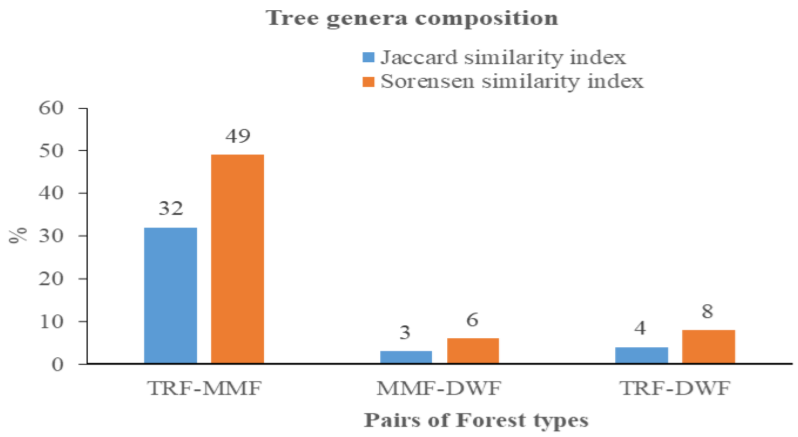


**Figure 11b: Percent (%) Jaccard and Sorensen similarity indices indicating similarity levels between different forest types [in terms of genera composition], Kenya.**

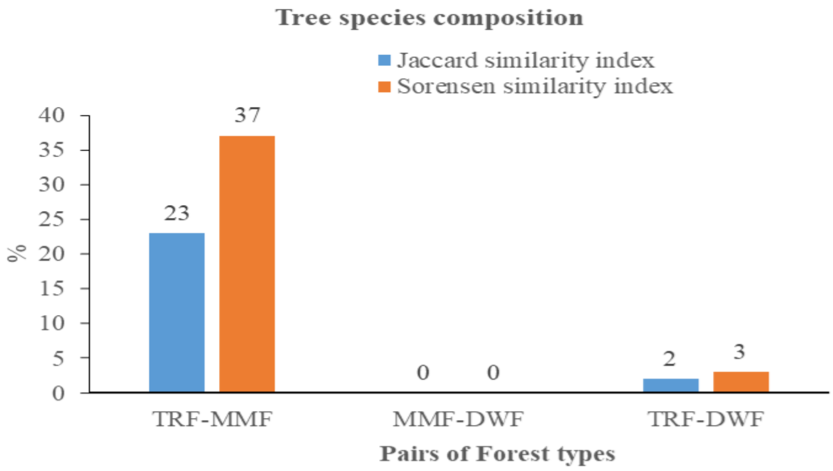


**Figure 11c: Percent (%) Jaccard and Sorensen similarity indices indicating similarity levels between different forest types [in terms of species composition], Kenya.**

### 4.2.2 Species Dominance and Diversity in Studied Forest Types

Species relative dominance structure was much similar across the forest types: 15 over 50 species (30 %) make 76 % of the stems in TRF, 10 over 36 (28%) make 77 % of the stems in MMF and 3 over 12 species (25 %) contribute 75% of the stems (Figure 9 & Appendix X). Shared tree species, genera and families among the forest types are shown in Appendices XI-XIII. Species diversity trends were analysed based on Shannon diversity index and evenness index. Species evenness was high for each of the three forest types (0.82 for TRF, 0.75 for MMF and 0.71 for DWF). Evenness of 1 represents a situation in which all the species are equally abundant (Magurran, 1988). The species diversity level is therefore more influenced by the number of species than evenness (Table 8); Shannon index of diversity being highest in TRF (3.25), lowest in dry woodland forest (1.76) and intermediate in montane forest (2.69). The value of Shannon diversity index is normally between 1.5 and 3.5 (and rarely surpasses 4.5) (Magurran, 1988). The three forests majorly differred in number of species, types of species but were much similar in species evenness and species relative dominance. The study established the extent to which tree species richness estimates species diversity along the gradient formed by the three different forest types. Rainforest was the most diverse and densely populated.

**Table 8: Species richness, evenness and diversity coefficients in the three forest types**

| Forest attributes | Rain forest | Moist montane forest | Dry woodland forest |
|---|---|---|---|
| N | 2684 | 1432 | 1275 |
| S | 50 | 36 | 12 |
| Dm | 0.97 | 0.95 | 0.34 |
| $H'^{1}$ | $3.24^{a}$ | $2.69^{b}$ | $1.76^{c}$ |
| Hmax=lnS | 3.91 | 3.58 | 2.48 |
| $E'$ | 0.83 | 0.75 | 0.71 |
| varH | 0.0037 | 0.0030 | 0.0026 |

[1] Shannon diversity index values followed by same letter in a row are not significantly different ($\alpha$=0.05). N = population size (number of individuals ≥ 1cm dbh); S = Number of tree species (= measure of richness); Dm = Menhinick species diversity index = species richness index; $H'$= Shannon Wiener species diversity index; $H_{max}$ = Maximum expected diversity index value; $E'$ = Species evenness index; varH = variance of species diversity value.

### 4.2.3 Forest Structure Description

***Sampling for Vertical forest structure across the forest types***

The top canopy height structure of the three forest types is described in Figures 12 -13b. Kakamega forest structure was more complex and diverse than the two other forest types. Mt Elgon forest, though closed, its foliage allowed more skylight to the floor (i.e. low screening efficiency). On average, as indicated by canopy height, trees in Kakamega were 8 m and 25 m taller than those in moist montane forest and dry woodland forest, respectively (Appendix XIV). The dry woodland forest of Loruk had the least complex and least diverse vertical structure of the three forest types. The tropical rain forest site (31-m-tall dense closed canopy; Figure 12), had a closed canopy (rare canopy gaps) and high screening efficiency (75%). The moist montane forest site (23-m-tall dense closed canopy), also had closed canopy (few canopy gaps), on a gently sloping ground, with moderate light screening efficiency (62%). The dry woodland forest site (5-m-short open canopy), had very low canopy screening efficiency (29.5%) above observer’s head height due to short trees that dominate the ecosystem. Ground cover was inadequate for soil protection.

Measuring forest canopy height based on 20mx20m-plots overesimplified the typical vertical structure of studied forest types as compared to data collection from smaller plots e.g. 5 m x 5 m (Appendix XIV.1.). Relatively small plot size produced well detailed description of canopy height structure for TRF and MMF types (multi-layered) and DWF (least differentiated canopy layers) (Figures 13a-c); implying that the existence of small-scale site conditions that shape variability in tropical forest vertical structure can only be detected and differentiated through use of small plot sizes. Other structural canopy features observed based on 5mx5m-plots were canopy gaps and screening efficiency (Figure 12). We observe that different plot sizes produced different structures for the same forest.

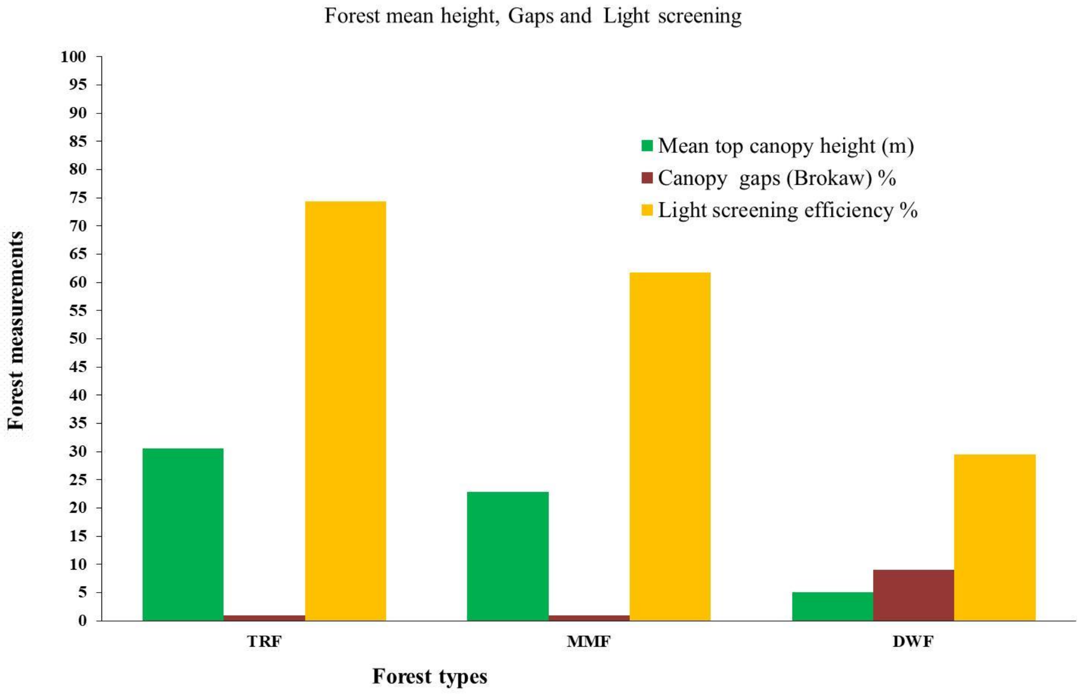


**Figure 12: Average canopy characteristics of the vertical physical forest structure for tropical rain forest, moist montane natural forest and dry woodland forest, Kenya**

The results in Figure 13 indicate that all attributes combined, both the tropical rain forest and the moist montane forest were more complex than tropical dry woodland forest.

### ***Tree diameter size distribution based on 1-ha sample plot data***

The diameter size distribution of trees from sapling to largest individuals was assessed as a component of forest horizontal structure and an indicator of overall structural stability for the studied forest types (Figure 14). This distribution was continuous up to 160 cm dbh and 85 cm dbh for TRF and MMF, respectively. It only extended up to 45 cm dbh in the DWF where majority of trees were below 10-20 cm dbh (Appendix XIV.2). Diameter size structures for studied forest types were characterised by the conventional reverse- J curve (Figure 14) and conformed to the UNO (1994) model for stable tropical natural forests in Eastern Africa (Figure 15). The UNO model was however not well followed by tropical DWF.

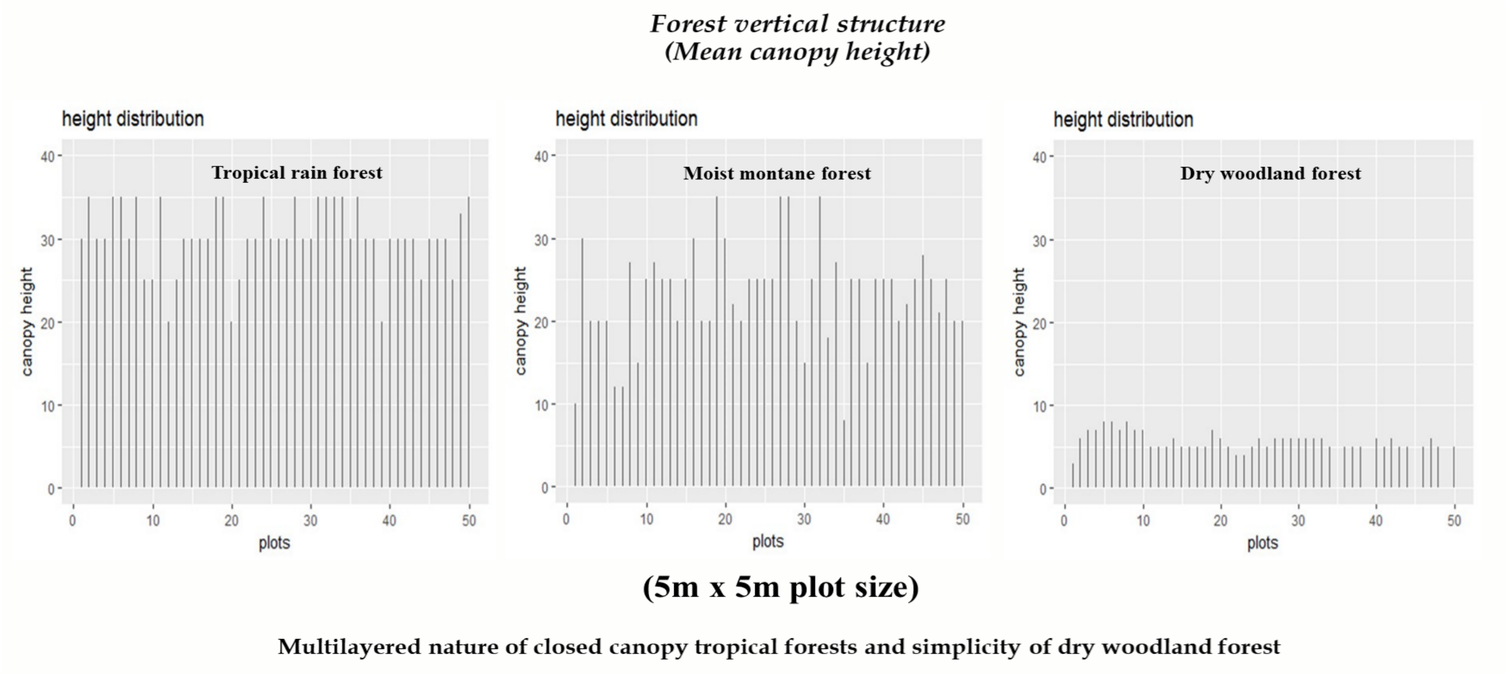


**Figure 13a: Top canopy heights (m) distribution based on 5 m x 5 m plots in tropical rain forest, moist montane natural forest and dry woodland forest in Kenya**

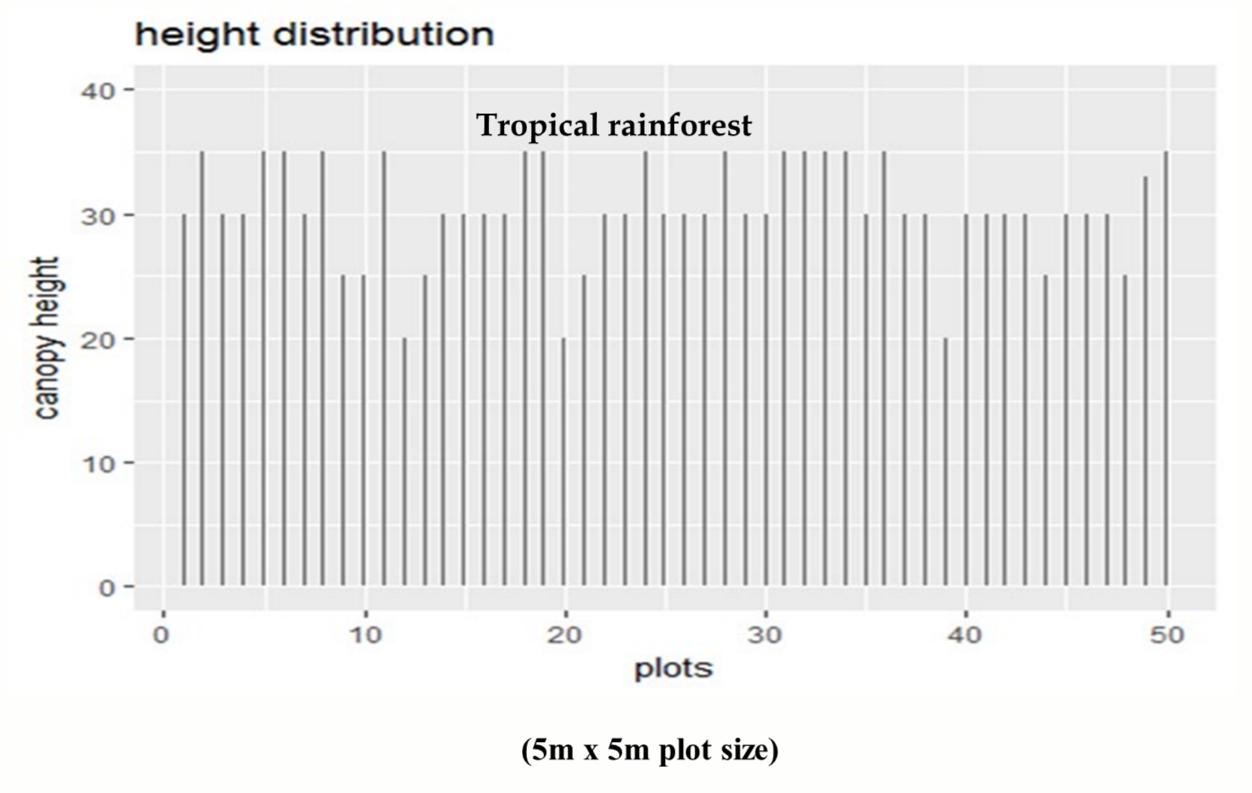


**Figure 13b: Kakamega tropical rainforest with well differentiated distinct four canopy laters: at 20 m, 25 m, 30 m and 35 m mean height**

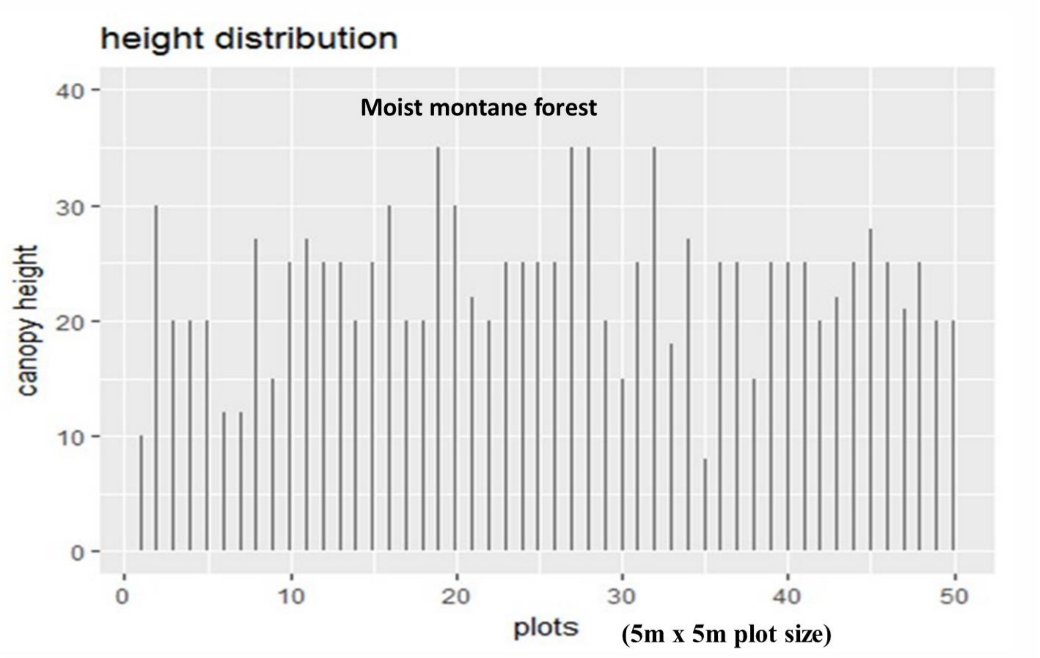


**Figure 13c: Mt Elgon moist montane forest structure characterised by less differentiated multiple canopy layers, generally below 25 m mean canopy height, with few emergent trees up to 35 m mean height.**

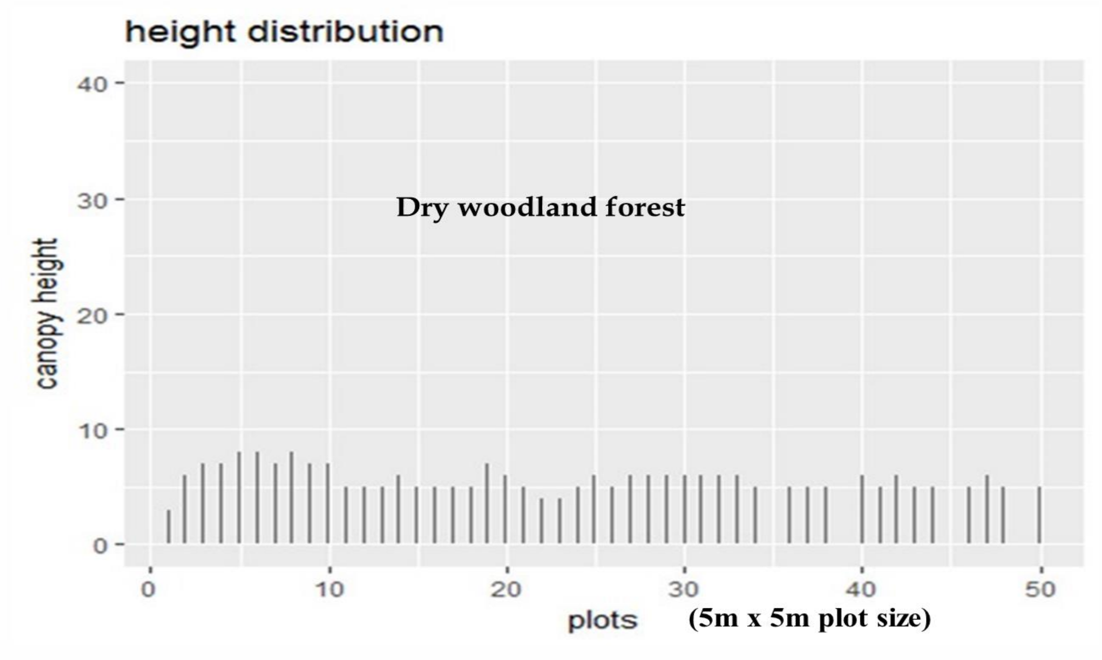


**Figure 13d: Luruk dry woodland forest structure typically characterised by short trees forming one canopy layer around 5 m tall.**

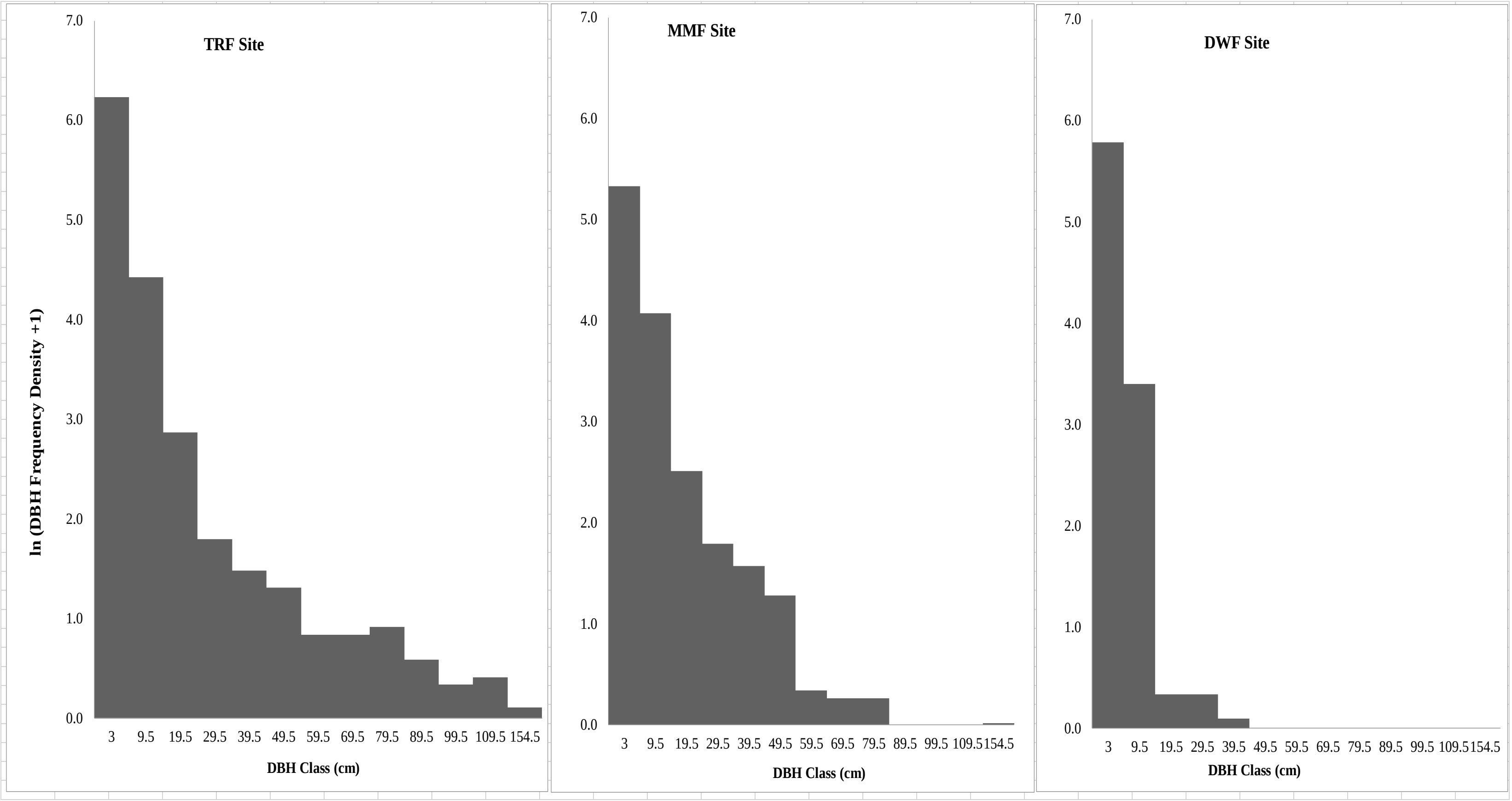


**Figure 14: Diameter size distributions for studied forest types, Kenya**

Overall, graphical data analysis based on UNO model revealed three distinct development phases in terms of forest structure (Figure 15): individuals with DBH below 10cm; DBH between 10 and 35cm, and > 35cm DBH tree category. The small tree sizes were well-stocked to over-stocked except in DWF where regeneration was under-stocked (i.e., below the UNO model expected estimates for individuals less than 5cm dbh). Regeneration and recruitment levels were satisfactory at TRF and MMF Sites. Populations of pole size trees (10 – 35cm DBH) were well stocked in both TRF and MMF but persistently understocked for DWF. The populations of timber-size trees (above 35cm DBH) were consistently understocked in all the three studied forests. Based on the above findings, the DWF type is either not structurally stable or the UNO Model is not suitable for application in the dry woodland forest type; the model having been conceptualised based on data from closed canopy tropical forest. Thus, there may be need to research on suitable model for the woodland ecosystems as a unique context.

### *Forest tree density, basal area and mean diameter structures*

Figure 16 shows the values and relationships between forest tree density, basal area and quadratic mean diameter. Tree densities in moist montane forest (816 stems $ha^{-1}$ for dbh $\geq$ 5cm) and dry woodland forest (299 stems $ha^{-1}$) were lower than in the tropical rainforest (1,166 $ha^{-1}$). Tropical rainforest density was 1.4 times that of moist montane forest density and nearly four (3.9) times that of the dry woodland forest. However, in terms of basal area ($m^2ha^{-1}$), tropical rainforest had 2.7 times that of moist montane forest (69 $m^2ha^{-1}$ against 25.1 $m^2ha^{-1}$). The dry woodland forest supported the lowest stand basal area, 2.1 $m^2$ $ha^{-1}$; 32.9 times lower than in TRF.

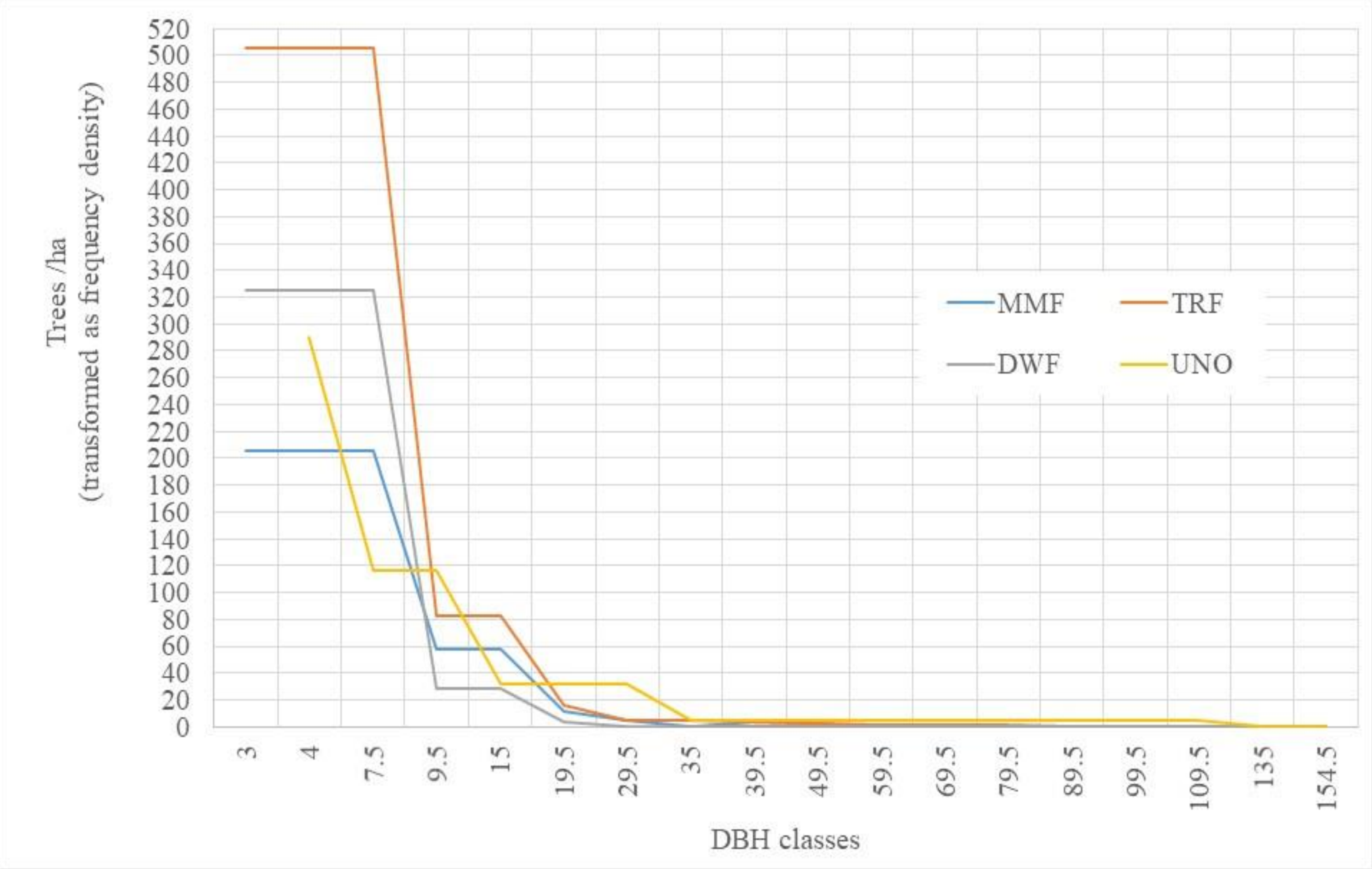


**Figure 15: Forest types models versus UNO (1994) model of tropical forest stability**

Huge tree diameters were measured using diameter tapes, all round the stem at 1.3 m above ground level.

On average, trees from tropical rain and moist montane forests are of larger diameter sizes than in the dry woodland forest. When all the three vegetation types are combined, TRF dominated with 72% for basal area; the least was DWF with 2%. However, the dominance of TRF over other forest ecosystems declined (45%) when quadratic diameter is used (Figure 16). QMD was less variable than BA across different forest types; implying that this diameter is less affected across forest types and is a more stable stand density measure than the basal area. These results indicate that tropical rainforest dominated other forest types mostly in number of trees per hectare. However most of these trees did not contribute much to the basal area. Quadratic mean diameter was nearly in TRF (13.9 cm) and MMF (13.0 cm). As expected, small diameter trees were on average found in DWF. Quadratic diameter mean is less density-dependent than basal area.

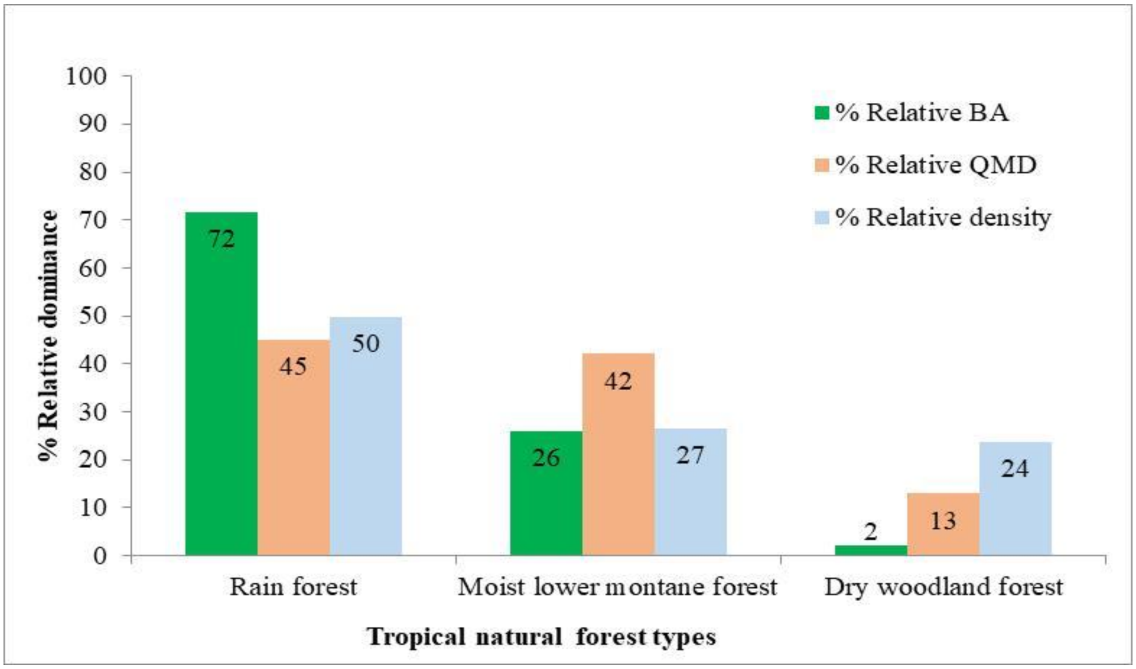


**Figure 16: Relative basal area, relative density (≥5 cm dbh trees ha$^{-1}$) and relative quadratic mean diameter in tropical natural forests, Kenya**

Overall trends from Figure 16 results include the following:

Relative basal area separated varied among the three forest types, with TRF alone carrying over 70%. There was less variability in relative density, with MMF and DWF being comparable and TRF carried 50% only. Relative quadratic mean diameter was least variable between TRF and MMF. Overall, quadratic mean diameter trait was a less density-dependent stand parameter between TRF and MMF. On average, trees in both forest types are of similar diameter sizes and dfference in basal area is due to differences in density (number of stems). Relative density was found to be similar between MMF and DWF but trees were dominated by smaller diameters at DWF than in MMF. TRF and DWF differed in relative tree diameter sizes and density.

### 4.2.4 Recruitment characteristics in studied forests

Figure 17 shows the trend of recruitment of individuals from one development stage of trees into the other. Overall, tropical rainforest had highest density (19,448 individuals $ha^{-1}$) followed by moist montane forest (7,711 individuals $ha^{-1}$), with dry woodland forest having the lowest (3,369 individuals $ha^{-1}$), all sizes combined from seedlings to mature trees (Figure 17a). Each forest had seedlings, saplings and large trees represented but relative contribution of each development stage (Figure 17b) revealed that different size categories balanced out almost in similar manner in TRF and MMF where seedlings dominated most by over 80 %. In dry woodland forest, seedlings and saplings were represented equally, making 87% of all individuals. It implies a deficient seedling stage in comparison with other two forest types. The sapling stage was instead relatively over represented.

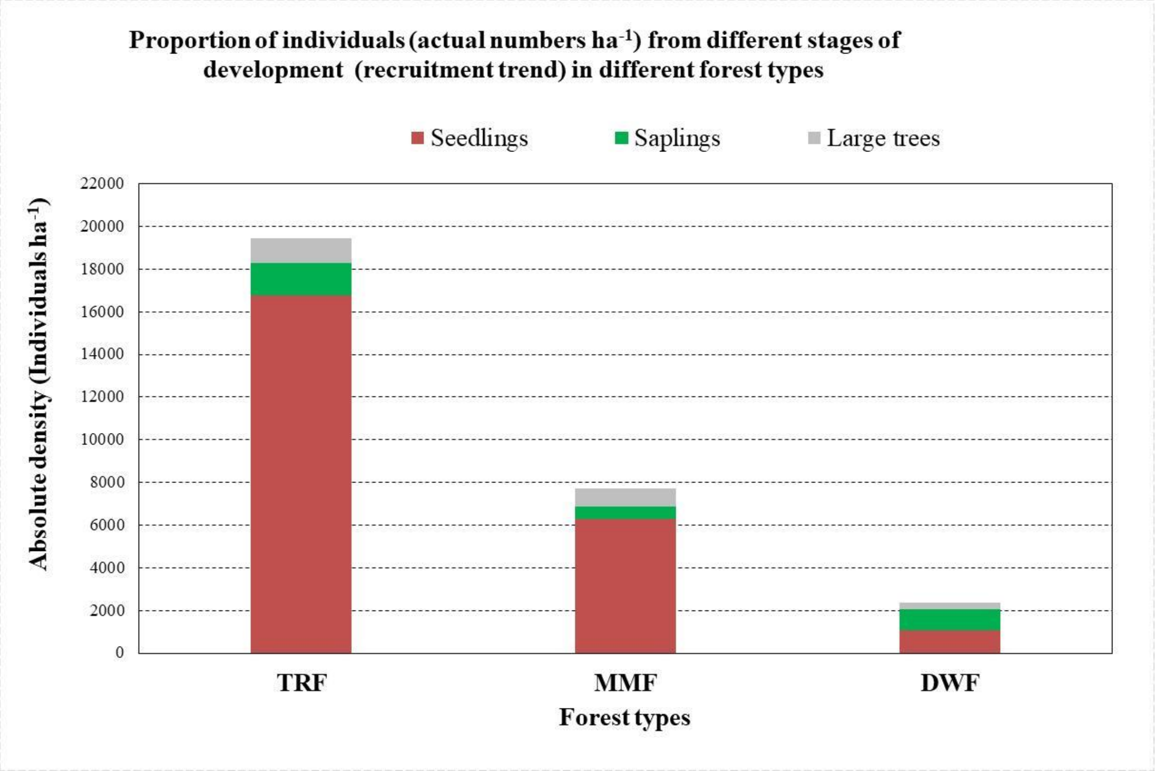


**Figure 17a: Recruitment patterns of trees (expressed in absolute number of trees from different tree development stages) in different tropical natural forest types in Kenya**

TRF = Tropical rainforest, MMF = Moist montane forest, DWF = Dry Woodland Forest.
Seedlings = indiv. < 1 cm dbh and <1.50 m tall; Saplings = small trees with 1 – 5 cm dbh; and large trees = individuals ≥5 cm dbh (Stride et al., 2018).

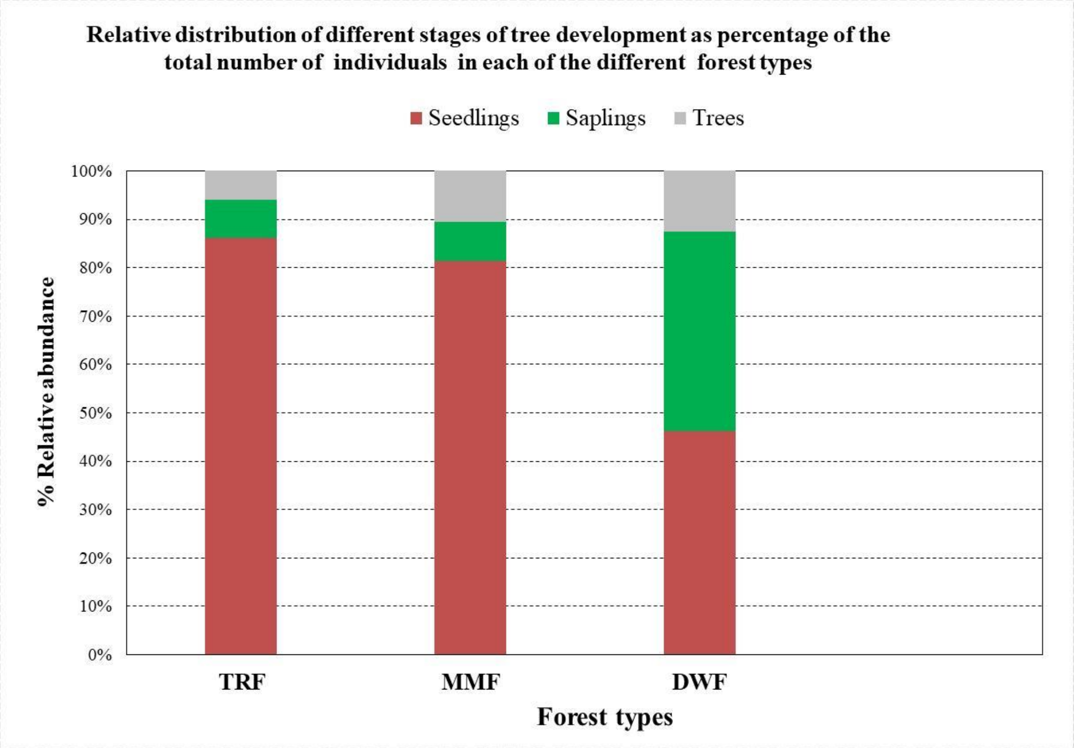


**Figure 17b: Recruitment patterns of trees (expressed in percent relative abundance of different tree development stages) in different tropical natural forest types in Kenya**
TRF = Tropical rainforest, MMF = Moist montane forest, DWF = Dry Woodland Forest.
Seedlings = indiv. < 1 cm dbh and <1.50 m tall; Saplings = small trees with 1 – 5 cm dbh; and large trees = individividuals ≥5 cm dbh (Stride et al., 2018).

Within the dry woodland forest, large trees (≥5 cm dbh) contributed 13 % of total density; a higher percentage than in the moist montane forest (11 %) as well as in the tropical rain forest (6 %) (Figure 17b). The proportion of large trees against saplings population was exceptionally low in Kakamega tropical rain forest. The unique recruitment trend in dry woodland forest could be attributed to environmental hardships working against seed germination and or seedling establishment. Similar trend of low seedling and sapling counts in the wider Baringo woodland was observed for *Acacia tortilis* as a result of high mortality rate occasioned by competition for moisture, drought, shading effects of mature trees and intense browsing (Kiyiapi, 1994). Differences in densities (and representation) may influence sampling schemes to adopt in each forest and for a specified tree development stage. Relative dominance of the respective tree development stages in each forest type was further evaluated based on the "q" ratio

(Equation 26) as an indicator or measure of regular regeneration and recruitment (Marimon & Felfili, 1997; Hitimana et al., 2004). The "q" quotient measures the relationship between successive diameter classes.

$$q = \frac{D_{(i-1)}}{D_i} \text{ ……………………………………………………….... (Equation 26),}$$

where $D_{(i-1)}$ is density in a lower diameter class, and $D_i$ density in the immediate upper diameter class.

Based on the q ratio (Figure 18), regular recuitment was only observed in the tropical rainforest in tree sizes (post sapling size) up to about about 110 cm dbh class. Recruitment of trees in MMF Site follwed same trend as in TRF Site up to 80 cm dbh class. However, at Mt Elgon Site, some exceptional events or processes occurred and distorted diameter size distribution for trees with DBH ≥50 cm; causing drastic departure from the balanced trend observed in Kakamega tropical rain forest site (Figure 18). The narrower range of dbh classes in the DWF Site would suggest, not withstanding environmental and ecological constraints to tree growth, that this ecosystem is the simplest and perhaps the youngest in succession. To this extent, tropical rain forest was judged more stable than the other forest types, and the woodland ecosystem was the least stable. Rising "q" ratio at the tail-end of diameter size distribution in TRF is characteristic of mature, self-regulating tropical forests. Protection and rehabilitation measures are needed in management and conservation of the structurally unstable ecosystems: MMF and DWF. Periodic monitoring programmes, say every 10 years, are encouraged to follow up the recovery and development processes over time.

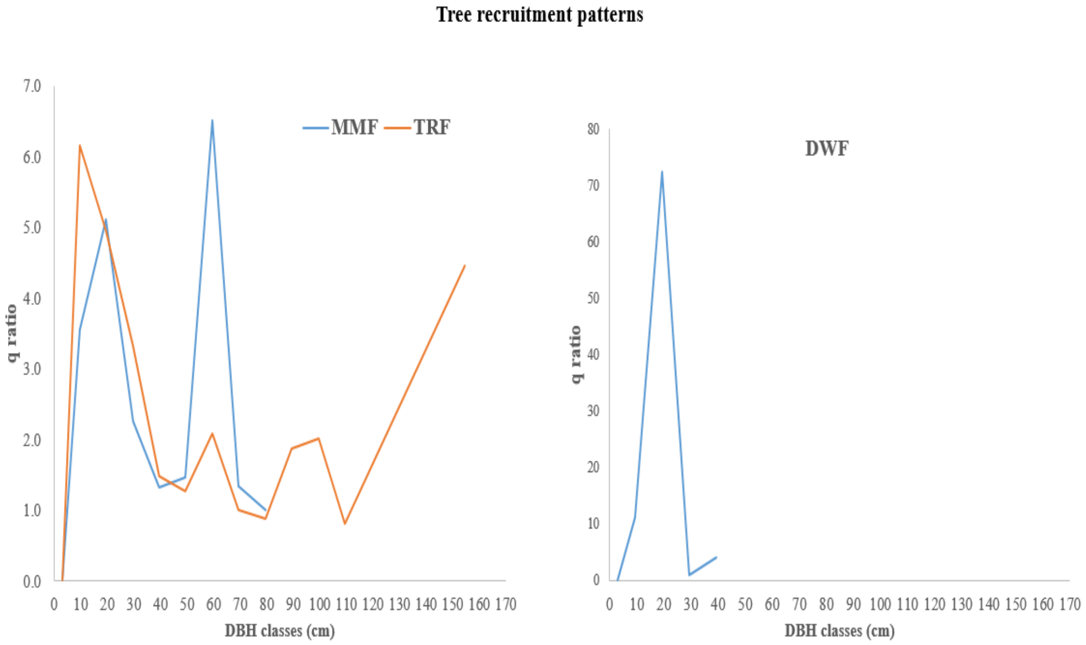


**Figure 18: Trend in regeneration and recruitment process in three natural forest types in Kenya.**
TRF = Tropical rain forest, MMF = Tropical moist montane forest, DWF = Tropical dry woodland forest.

## 4.3 Evaluation of Efficiency of Sampling Schemes in Tropical Natural Forests

### 4.3.1 Sampling Schemes for Tree Species Richness and Diversity

*Use of percentage of species per sampling effort*

Figures 19a-d show how effective different sampling schemes captured the number of species per hectare from three tropical forest types. In TRF, increasing sampling intensity for 25 $m^2$ plot size (Figure 19a) led to progressive increase in the number of species, regardless of the sampling design applied, but, with 30% sampling intensity in SRS, 100%, 90 % and 80 % of the species were captured in DWF, TRF and MMF, respectively. With intensities of 10 % and 20 %, SSV was superior to SSH in MMF, whereas SSH was better than SSV in both TRF and DWF. The slope effect in the montane forest may justify the trend at MMF. Species turn-over gradient from East to West was reflected in the forests where the slope was negligible. Using plot sizes of 50 $m^2$ (Figure 19b), sampling intensity also affected the sampling efficiency of the number of species, with intensity of 30% being efffective in all the three forest types for both SSH and SRS. Based on 100 $m^2$ plot size (Figure 19c), both SSH and SRS were again efficient in all the forest types, for sampling intensities greater than 5 %. Sampling intensities of 10% and 20 % captured 80 % to 90 % of total number of species in a hectare. Finally, when using plot sizes of 400 $m^2$ (Figure 19d), results mirrored (to a larger extent) those with 100 $m^2$ plots. For example, SRS and SSH captured about 85% to 90 % of species richness at 20 % and 30 % intensities, respectively, in all forest types. The decision will be to choose between using few large plots or many small plots. This choice is about cost and or more precise (smaller sampling error).

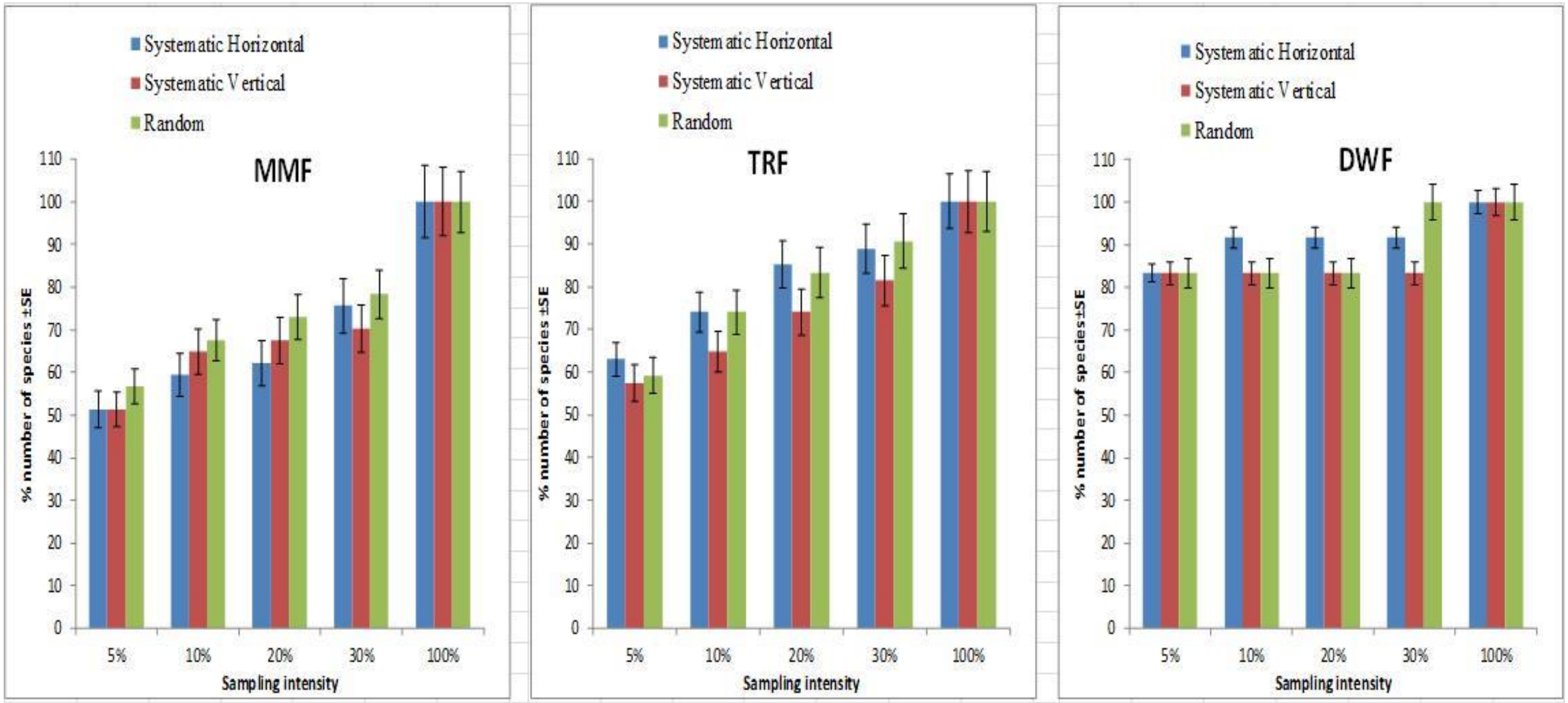


**Figure 19a: Sampling species richness with 5 m x 5 m plots (% species capture per sampling intensity and design)**

MMF = Tropical Moist Montane Forest Site (Mt Elgon; Kaberwa); TRF = Tropical Rain Forest Site (Kakamega; Isecheno); DWF = Tropical Dry woodland Site (Baringo, Loruk)

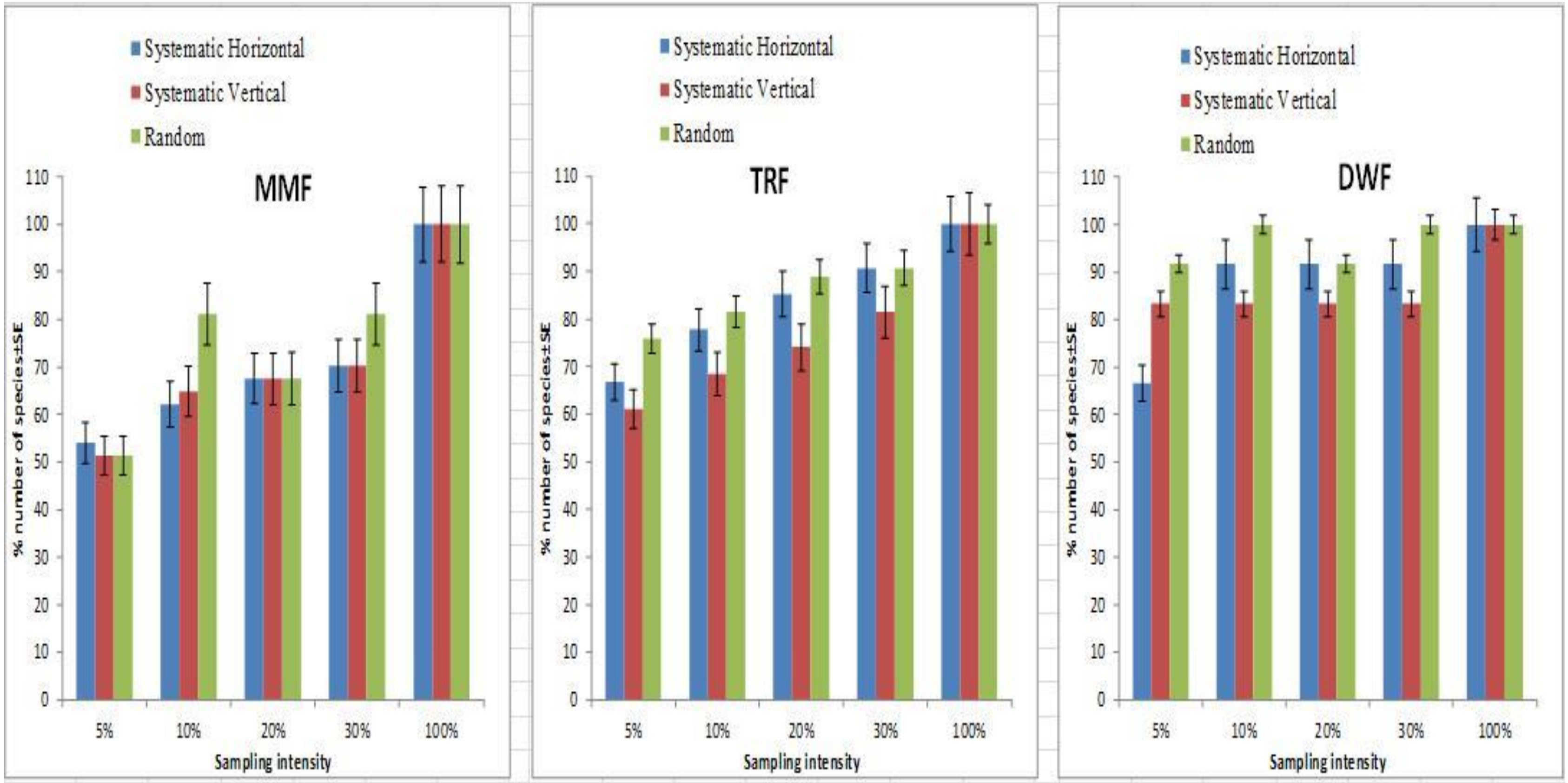


**Figure 19b: Sampling species richness with 10mx5m-plots (% species capture per sampling intensity and design)**

MMF = Tropical Moist Montane Forest Site (Mt Elgon; Kaberwa); TRF = Tropical Rain Forest Site (Kakamega; Isecheno); DWF = Tropical Dry woodland Site (Baringo, Loruk)

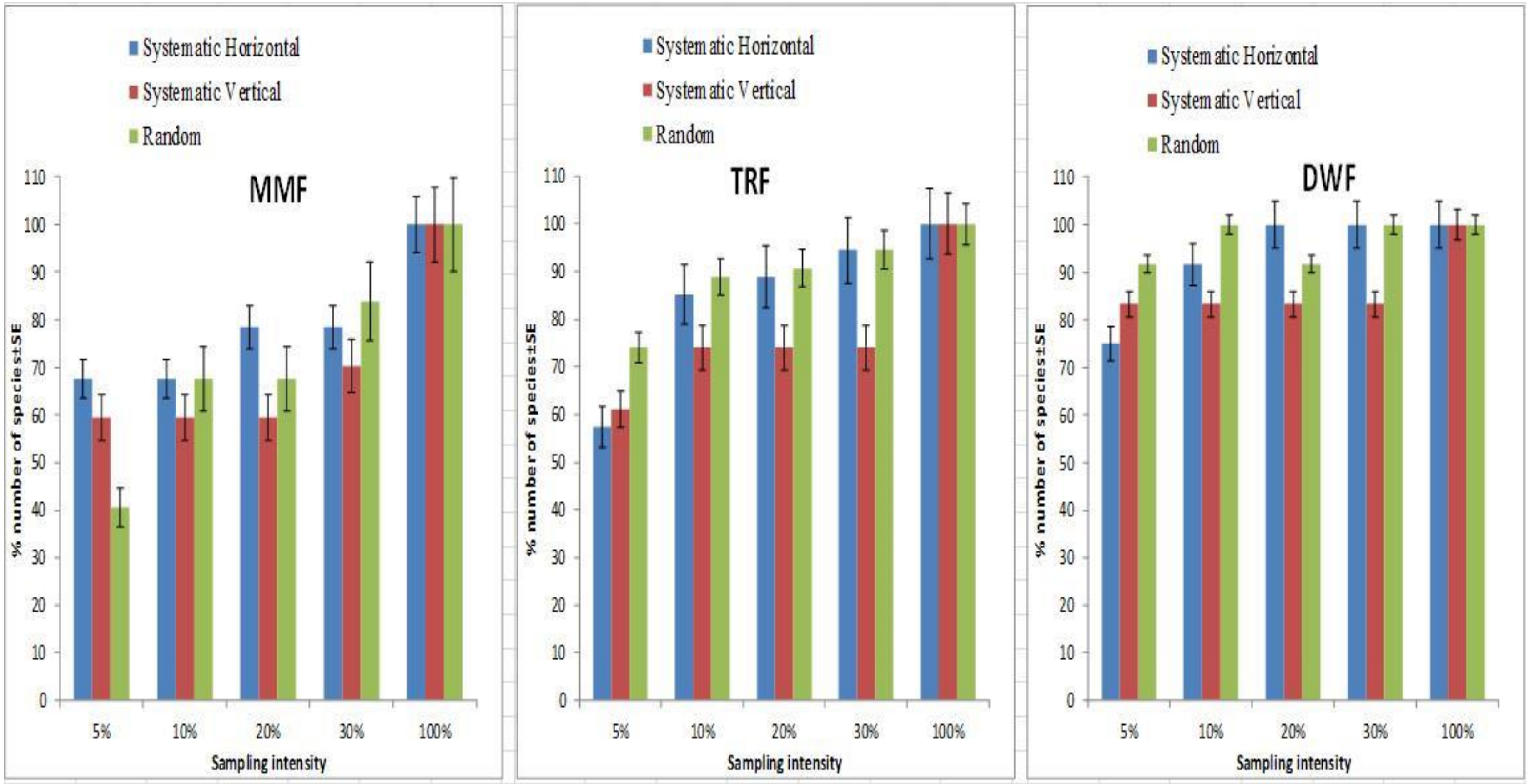


**Figure 19c: Sampling species richness with 10 m x 10 m plots (% species capture per sampling intensity and design)**

MMF = Tropical Moist Montane Forest Site (Mt Elgon; Kaberwa); TRF = Tropical Rain Forest Site (Kakamega; Isecheno); DWF = Tropical Dry woodland Site (Baringo, Loruk)

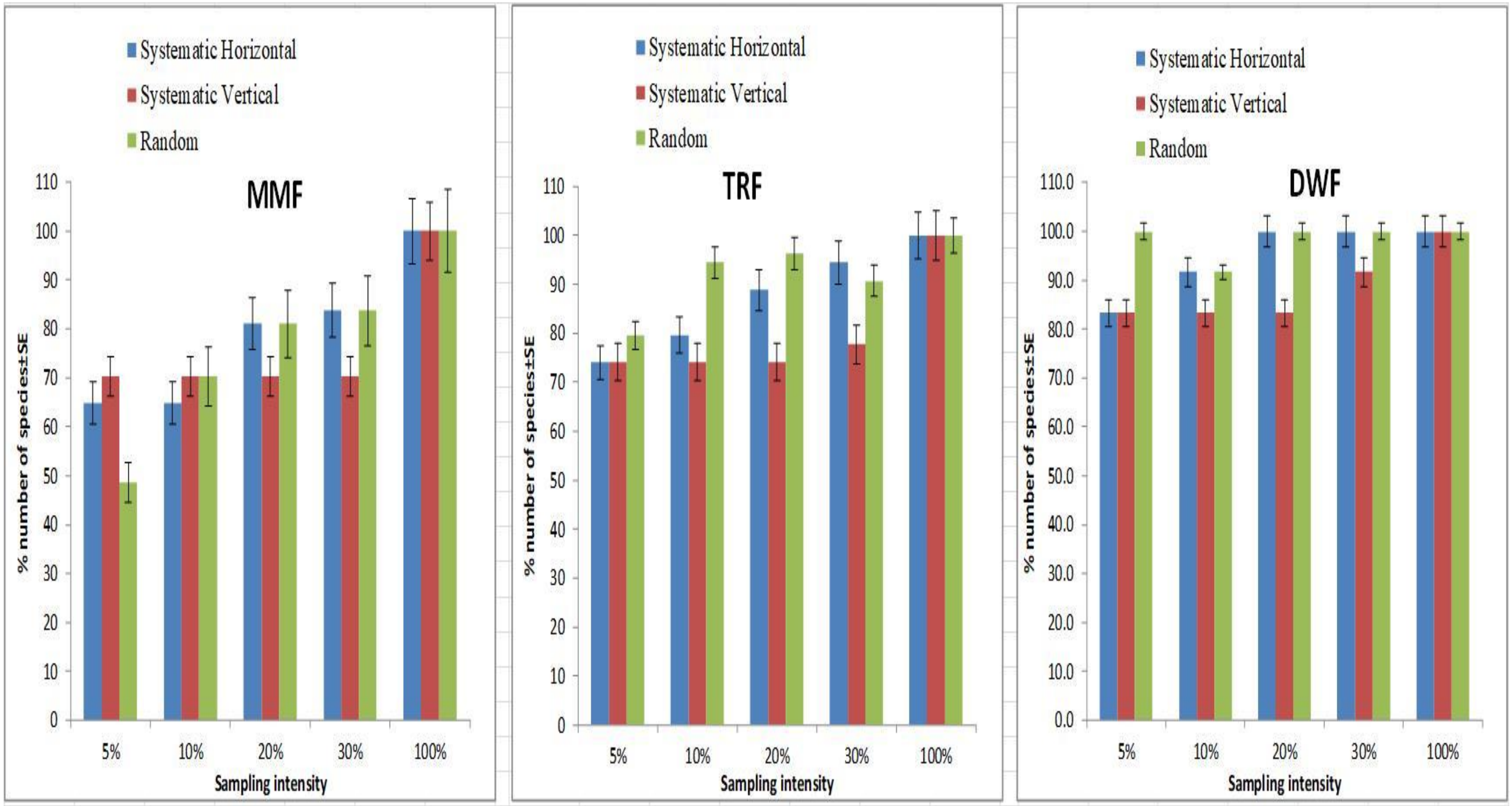


**Figure 19d: Sampling species richness with 20 m x 20 m plots (% species capture per sampling intensity and design)**

MMF = Tropical Moist Montane Forest Site (Mt Elgon; Kaberwa); TRF = Tropical Rain Forest Site (Kakamega; Isecheno); DWF = Tropical Dry woodland Site (Baringo, Loruk)

Figures 19a-c indicate that as one increases the intensity of sampling, the number of species increases for 5mx5m-plots where random sampling captured more species than systematic sampling in all cases in MMF. However, all sampling options significantly underestimated actual number of species in this forest and 100% intensity per hectare is inevitable. All sampling options were not efficient in DWF except 30% intensity SRS and SSH. In TRF, both SSH and SRS with 30% intensity also give same number of species as the 100% intensity for plot sizes below 20 m x 20 m (Figures 19a-c). Where sampling is efficient enough with smaller intensities, there is no need to spend money and time on higher intensities. Observed low numbers of species in DWF at 20% intensity with 10 m x 5 m plots (Figure 19b) and 10 m x10 m plots (Figure 19c) reflect outliers; otherwise SSH and SRS are already efficient at 10% intensity. Species richness can be captured accurately using 10%, 20% or 30% sampling intensities in DWF. With 20 m x 20 m plot size, 5% sampling intensity in SRS can provide needed data with high accuracy in DWF. In TRF, sampling intensity should be at least 10% in SRS and 30% in SSH. An outlier observation occurred at 30% intensity for SRS.

### *Use of cumulative species -area curves for species richness*

Graphs in Figures 20a-c show how efficient different sampling schemes captured species richness based on cumulative species – area curves. Sampling schemes are based on systematic sampling along vertical transect (SSV;- red coloured curve in graphs) or along horizontal transect (SSH; - blue coloured curve in the graphs). Dotted lines used in the graphs represent the projectory curves constructed from 30% of 1 ha. The solid line curves in cumulative species-area graphs indicate predictive regression models which were constructed using all records including the exact number of species found in the entire hectare forest unit through complete 100% census. Mathematical models for the above graphs are found in Appendix XV.

The quality of the models is expressed in terms of (i) reliability as measured by coefficient of determination ($R^2$), (ii) Relative root mean square error (RMSE%) and (iii) Predictive power measured by mean prediction error (MPE %). Two categories of 1-ha models of species-area curves are presented: (i) those models that only used data from sub-sampling of 1 ha up to 30% along vertical (North – South) or horizontal (East-West) transects, and (ii) models that, on top of the sub-sampling data, included total enumeration data during modelling process. The purpose was, in the 1-ha method approach, to find out which strategy to follow to develop models to be applied in estimating species richness (no. of species) on per-hectare basis. In this study, most efficient sampling schemes were those that produced curves that had $R^2$ values > 85%; RMSE % < 5% and MPE % < 5% (Table 9 & Appendix XV).

Sampling for species-area curves in tropical rain forest (Figure 20a) was best realised with 30% intensity when combined with 5 m x 5 m or 10 m x 5 m plot sizes. The most accurate scheme is found along the horizontal transect (East-West direction): SSH-5mx5m-30%, The second best scheme is SSV-10mx5m-30%. Larger plot sizes (10 m x 10 m and 20 m x 20 m) produced curves that deviated much from the expected trends.

In the moist montane forest, using 30% of the hectare underestimated the prediction of the maximum number of tree species in a hectare if we apply small plot sizes of 5 m x 5 m or 10 m x 5 m. Larger plot sizes improved accuracy (contrary to observed trend in TRF). Highest effieciency is achieved using 20 m x 20 m plot size along the vertical transect (South – North direction) up to a sample area of 0.3 ha (ie 30% sampling intensity in one hectare). Best sampling scheme is therefore SSV-20mx20m-30%.

For the dry woodland forest, graphs in Figure 20c show that subsampling of one hectare is not efficient. The minimum size of the sample should be one hectare, subdivided into large plot size (20 m x 20 m along horizontal transect; SSH-20mx20m-100%) or using small plot size 5 m x 5 m along the vertical transect (SSV-5mx5m-100%). Based on the results in Table 9, transect orientation had litlle or none on the quality of models from sampling that included the complete inventory data over 1-ha for species –area curves if the small plot size of 5 m x 5 m is adopted for all the forest types.

It is prudent to use many more small plot sizes than few large plots size for any given sampling intensity. Omitting the total number of species in the 1 ha unit when developing a model, influenced the quality of species – area curve. This design of sub-sampling 1-ha up to 30% was only effective in some cases as earlier described. Overall, sub-sampling of 1 ha produced very few options of having effective schemes. This strategy should be applied with caution outside the tropical rain forests.

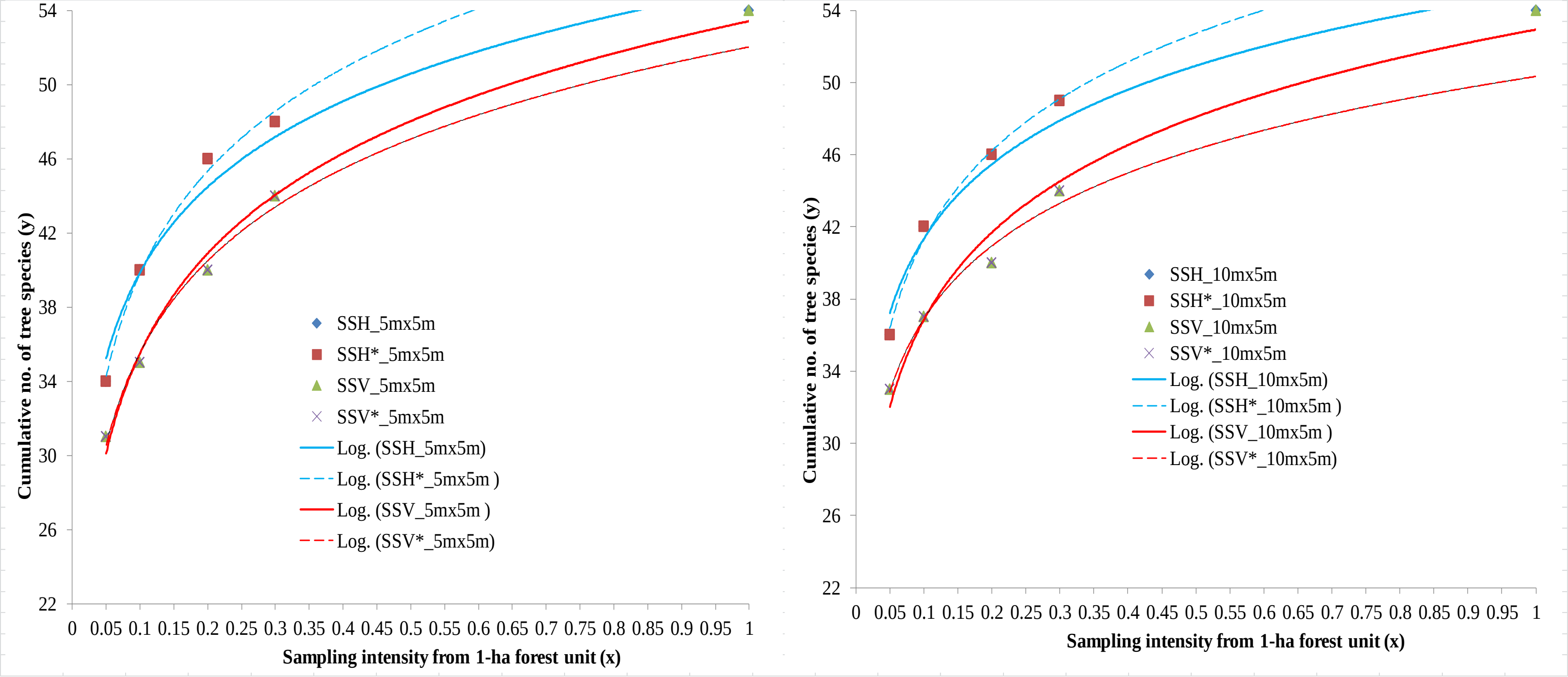


**Figure 20a: Actual and estimated cumulative species –area curves up to 30% and 100% intensity data per- hectare based on 5 m x 5 m and 10 m x 5 m plot sizes, for two transect directions in Kakamega tropical rainforest, Kenya.**

Equations with asterisk (*) indicate trajectory species –area models from the 30% sample data of a hectare forest.  Those without the asterisk indicate trajectory models based on a series of sampling intensities up to including100 % i.e. entire 1-ha data (reference model). H = Horizontal transect (East-West), coloured blue; V = Vertical transect (North-South), coloured red.

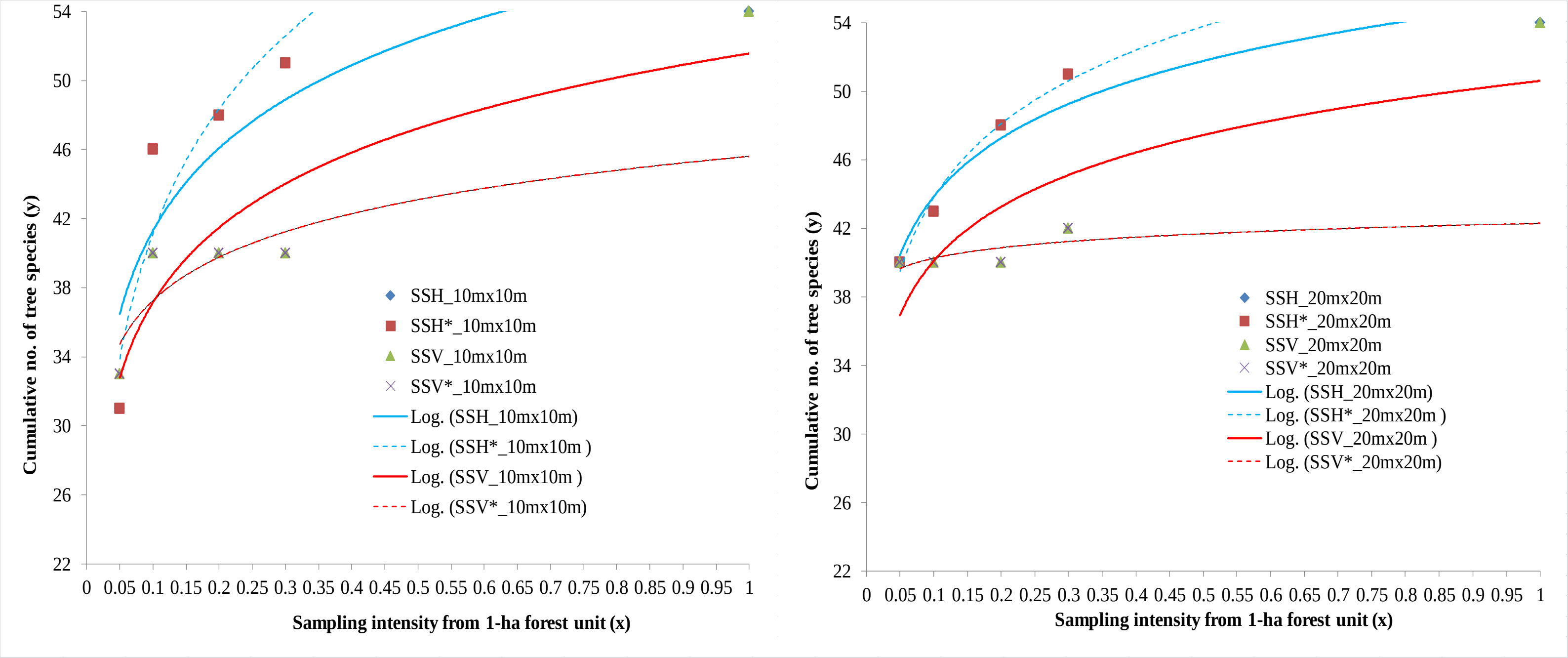


**Figure 20a (Cont.): Actual and estimated cumulative species –area curves up to 30% and 100% intensity data per- hectare based on 10 m x 10 m and 20 m x 20 m plot sizes, for two transect directions in Kakamega tropical rainforest, Kenya.**

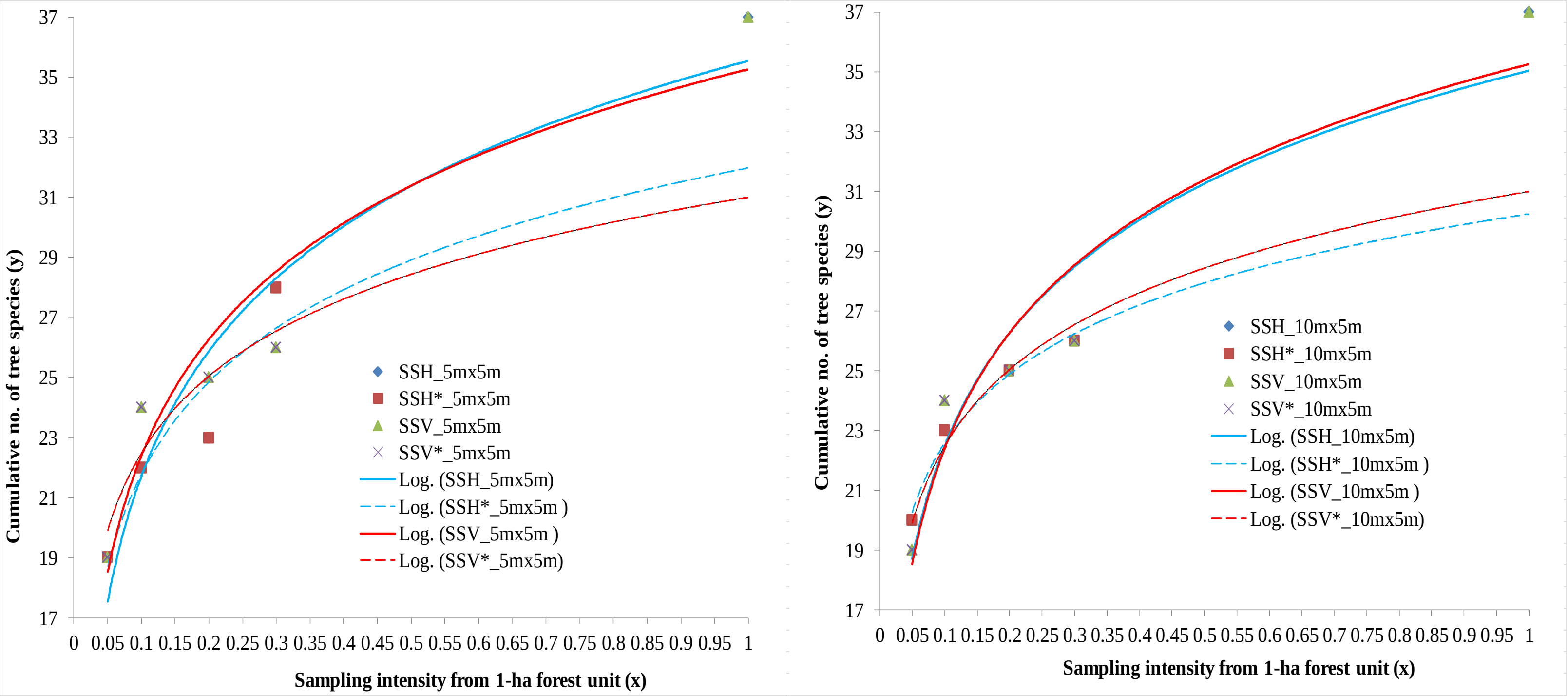


**Figure 20b: Actual and estimated cumulative species –area curves up to 30% and 100% intensity data per- hectare based on 5 m x 5 m and 10 m x 5 m plot sizes, for two transect directions in Mt Elgon moist montane forest, Kenya.**

Equations with asterisk (*) indicate trajectory species –area models from the 30% sample data of a hectare forest. Those without the asterisk indicate trajectory models based on a series of sampling intensities up to including100 % i.e. entire 1-ha data (reference model). H = Horizontal transect (East-West), coloured blue; V = Vertical transect (North-South), coloured red.

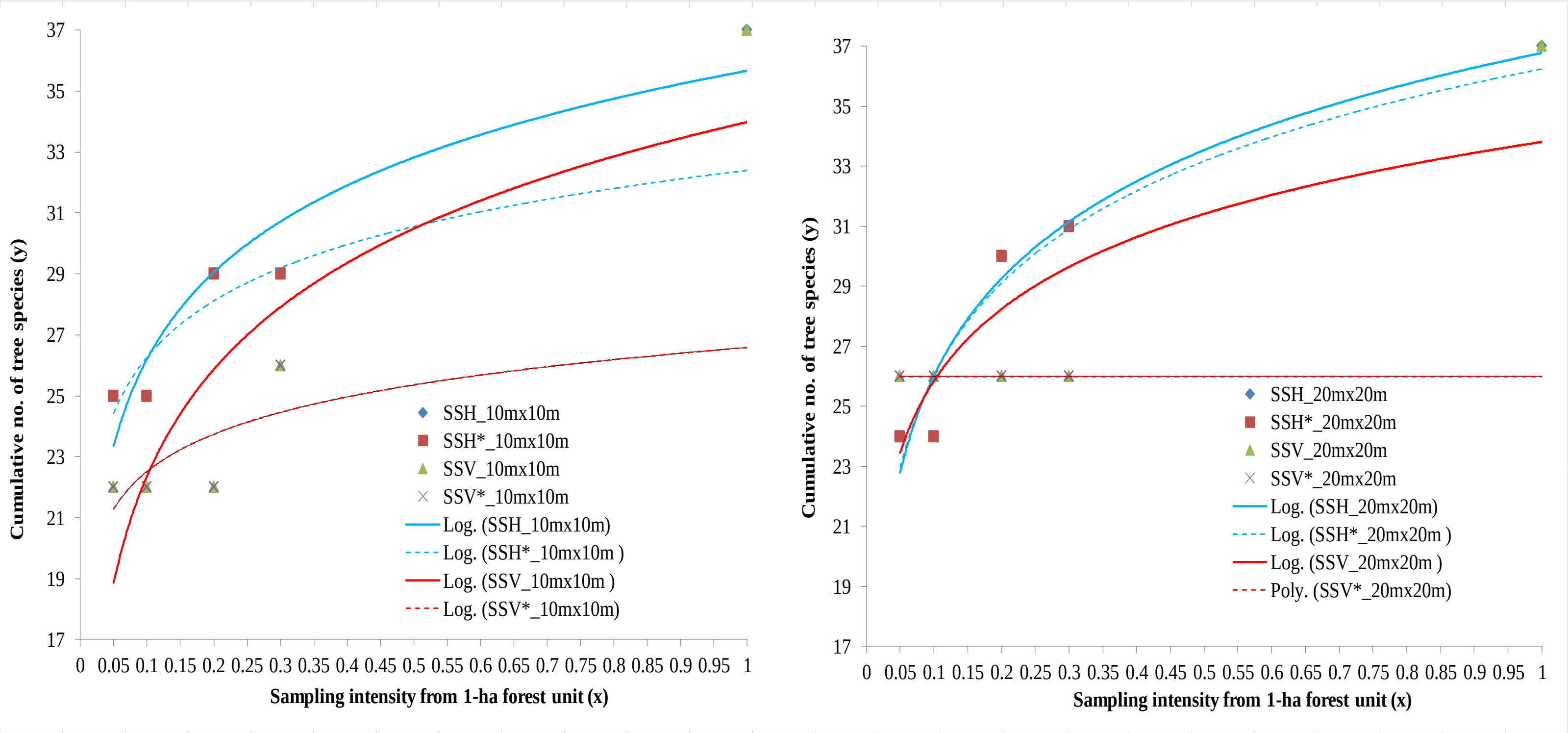


**Figure 20b (Cont.): Actual and estimated cumulative species –area curves up to 30% and 100% intensity data per- hectare based on 10 m x 10 m and 20 m x 20 m plot sizes, for two transect directions in Mt Elgon moist montane forest, Kenya.**

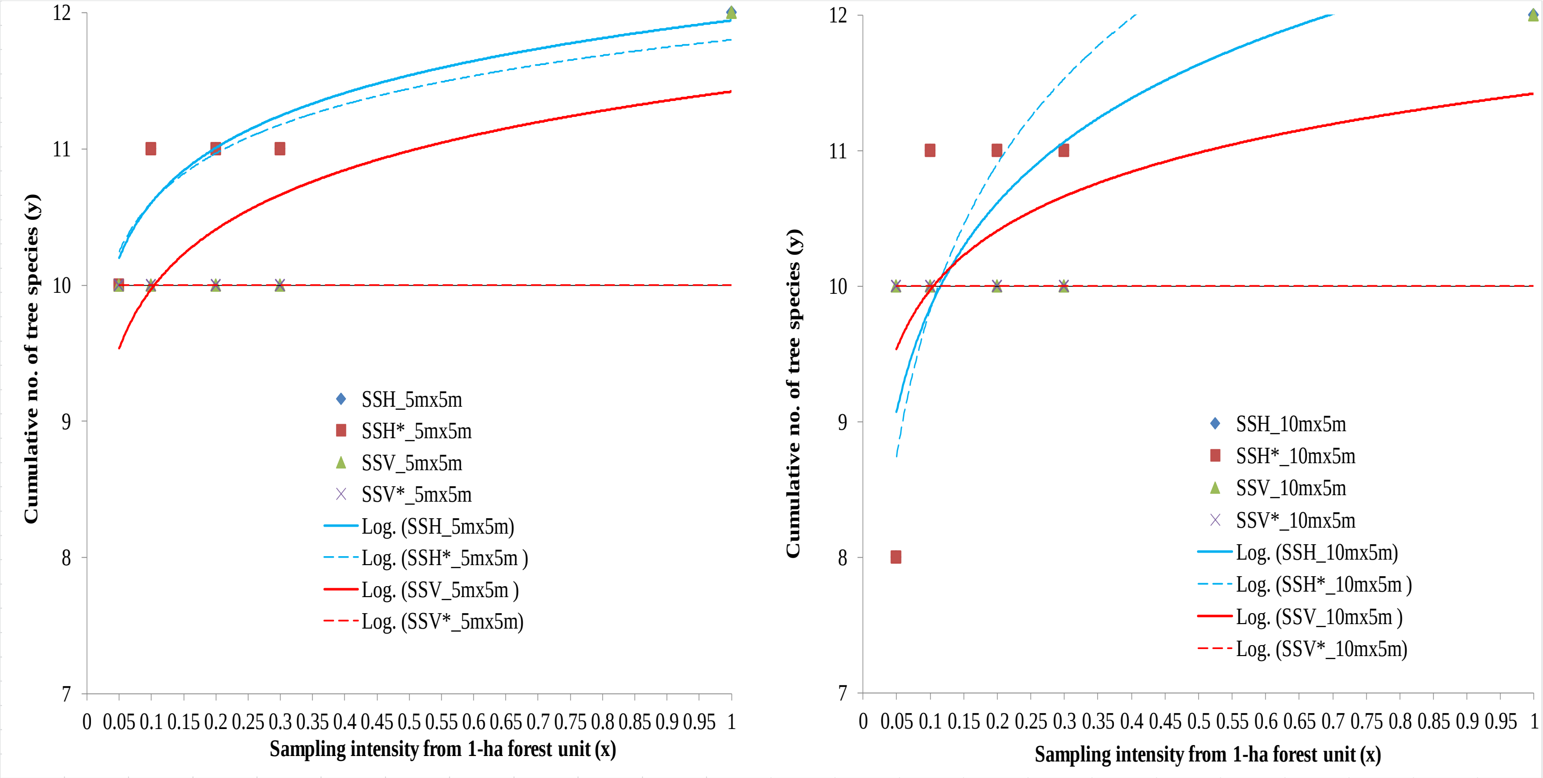


**Figure 20c: Actual and estimated cumulative species –area curves up to 30% and 100% intensity data per- hectare based on 5 m x 5 m and 10 m x 5 m plot sizes, for two transect directions in Loruk dry woodland forest, Kenya.**

Equations with asterisk (*) indicate trajectory species –area models from the 30% sample data of a hectare forest. Those without the asterisk indicate trajectory models based on a series of sampling intensities up to including100 % i.e. entire 1-ha data (reference model). H = Horizontal transect (East-West), coloured blue; V = Vertical transect (North-South), coloured red.

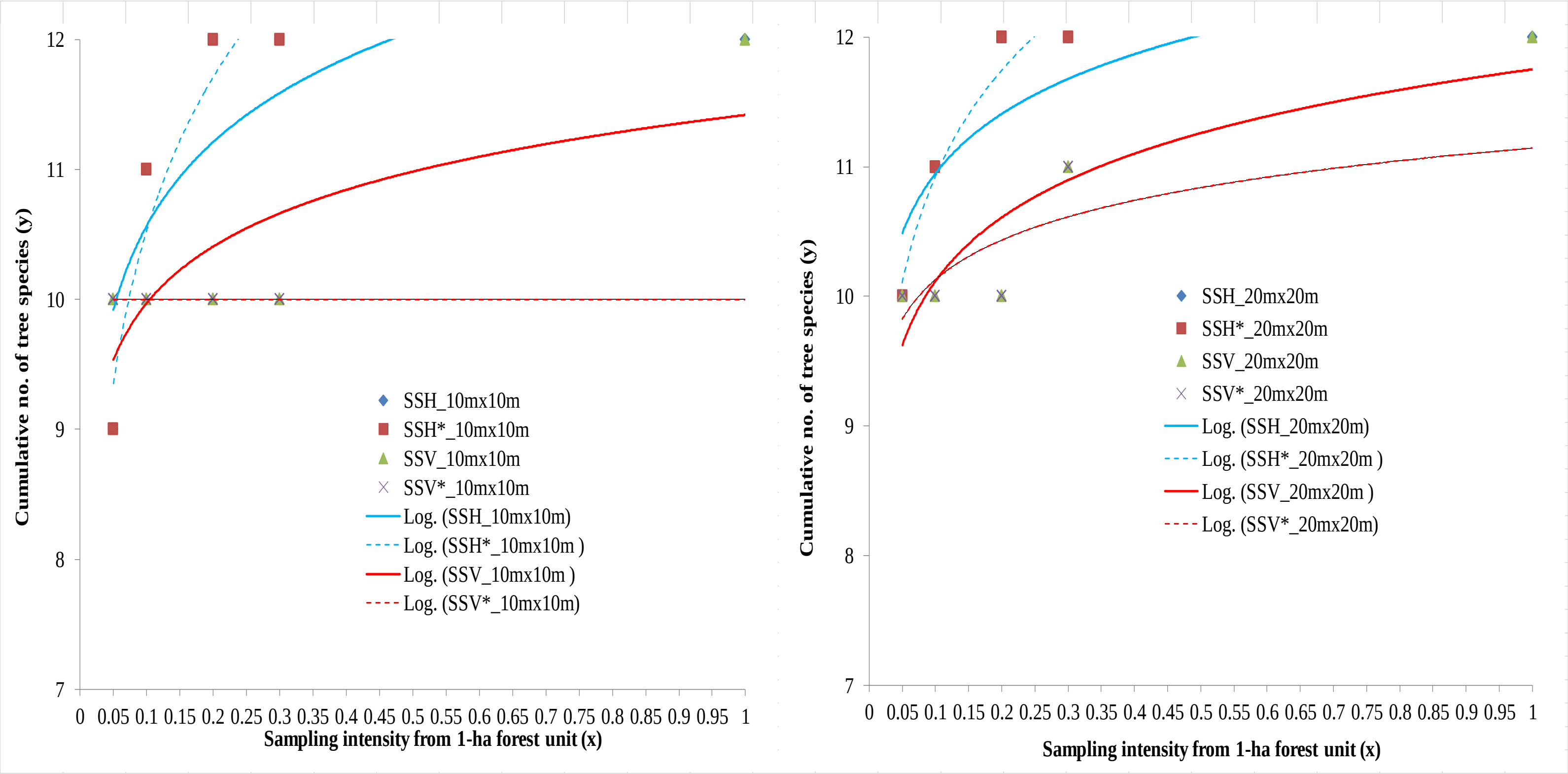


**Figure 20c (Cont.): Actual and estimated cumulative species –area curves up to 30% and 100% intensity data per- hectare based on 10 m x 10m and 20 m x 20 m plot sizes, for two transect directions in Loruk dry woodland forest, Kenya.**

**Table 9: Most efficient sampling schemes for constructing species accumulation–area curves in tropical forests**

| Plot size | Forest | Sampling up to 1 ha | Reliability $(R^2)$ | RMSE% | MPE% | Sub-sampling 1 ha up to 0.3 ha | Predictive power | RMSE% | MPE% |
|---|---|---|---|---|---|---|---|---|---|
| 5 m x 5 m | TRF | $y(H) = 6.6673*\ln(x) + 55.217$ | $R^2 = 0.974$ | 2.0275 | -0.0006 | $y(H^*) = 7.9895*\ln(x) + 58.202$ | $R^2 = 0.992$ | 3.5657 | -1.5561 |
| | | $y(V) = 7.7865*\ln(x) + 53.432$ | $R^2 = 0.99$ | 1.2252 | 0.0007 | $y(V^*) = 7.1696*\ln(x) + 52.039$ | $R^2 = 0.988$ | 1.8372 | 0.7270 |
| | MMF | $y(H) = 6.0081*\ln(x) + 35.547$ | $R^2 = 0.9362$ | 4.3037 | 0.0006 | | | | |
| | | $y(V) = 5.587*\ln(x) + 35.264$ | $R^2 = 0.9207$ | 4.4992 | 0.0001 | | | | |
| | DWF | $y(H)= 0.581*\ln(x) + 11.943$ | $R^2 = 0.8703$ | 1.8983 | -0.0035 | | | | |
| 5 m x 10 m | TRF | $y(H) = 5.9519*\ln(x) + 55.056$ | $R^2 = 0.975$ | 1.7654 | 0.0001 | $y(H^*) = 7.0995*\ln(x) + 57.647$ | $R^2 = 0.992$ | 3.0980 | -1.3503 |
| | | $y(V) = 6.9899*\ln(x) + 52.94$ | $R^2 = 0.979$ | 1.9028 | 0.0001 | $y(V^*) = 5.838*\ln(x) + 50.339$ | $R^2 = 0.9785$ | 3.1862 | 1.3560 |
| | MMF | $y(H) = 6.0081*\ln(x) + 35.547$ | $R^2 = 0.9362$ | 4.8196 | 1.0817 | | | | |
| | | $y(V) = 5.587*\ln(x) + 35.264$ | $R^2 = 0.9207$ | 4.4992 | 0.0001 | | | | |
| | DWF | | | | | | | | |
| 10 m x 10 m | TRF | $y(V)= 6.2695*\ln(x) + 51.571$ | $R^2 = 0.861$ | 4.7233 | 0.0005 | | | | |
| | MMF | $y(H)= 4.1103*\ln(x) + 35.668$ | $R^2 = 0.9074$ | 3.6036 | 0.0009 | | | | |
| | DWF | | | | | | | | |
| 20 m x 20m | TRF | $y(H)= 4.9218*\ln(x) + 55.185$ | $R^2 = 0.954$ | 2.0111 | -0.0003 | $y(H^*) = 6.2094*\ln(x) + 58.092$ | $R^2 = 0.985$ | 3.4933 | -1.5152 |
| | MMF | $y(H) = 4.6734*\ln(x) + 36.782$ | $R^2 = 0.947$ | 3.0066 | -0.0004 | $y(H^*) = 4.4363*\ln(x) + 36.247$ | $R^2 = 0.859$ | 3.1029 | 0.4060 |
| | DWF | | | | | | | | |

### 4.3.2 Sampling Schemes for Forest Regeneration Inventory

Figure 21 show the extent to which different sample statistics departed from the true population values for each forest type. Results in Tables 10-12 provide deviations, averages and measures of variability associated with the sampling intensities and plot sizes that were applied within each sampling design: SRS, SSH and SSV. The study found that, with SRS, the estimates of seedlings per hectare from all intensities and plot sizes, across all forest types, did not significantly differ from actual population values ($p > 0.05$). In TRF, estimates of seedlings from 10 % to 30% sampling intensities (expressed on per-hectare basis) were all accurate; being not significantly different from total number of seedlings systematically counted from a hectare at 100% intensity ($p > 0.05$). Regeneration estimates based on different plot sizes used in the inventory (5 m x 5 m to 20 m x 20 m) were also not significantly different ($p > 0.05$). However, relative levels of accuracy of estimates (based on deviation %) varied between 0.5% and 58%, among intensities and plot sizes. In MMF, 10 % and 20 % intensities were not adequate ($p < 0.05$). All sampling intensities and plot sizes were adequate for regenertation assessment in DWF. Statistical significance was also detected along the vertical (North – South) oriented transect but with different levels of intensities performing adequately: 5% - 10 % in TRF and 5% - 20% in MMF. Figure 22 shows that in TRF, sampling schemes with highest efficiency levels were two: SSV-5mx5m-30% (83.2% efficient in relation to reference treatment) and SSH-10mx5m-5% (79.8% efficient). Systematic sampling designs performed better than SRS while small plot sizes were most efficient in comparison with larger plots. In MMF, sampling plot size below 1- ha plot is inefficient. Seedling surveys should be done over the entire 1 ha, using plot size as small as 5 m x 5 m (optimum plot size). In the DWF, efficient sampling schemes were five with the best three performing being SRS-10mx10m-30% (90.9 % efficient), SSV-10mx10m-30% (74.6 % efficient) and SSV-10mx5m-30% (74.3% efficient). Both 10 m x 5 m and 10 m x 10 m plot sizes are found adequate for regeneration assessment and compilation in DWF.

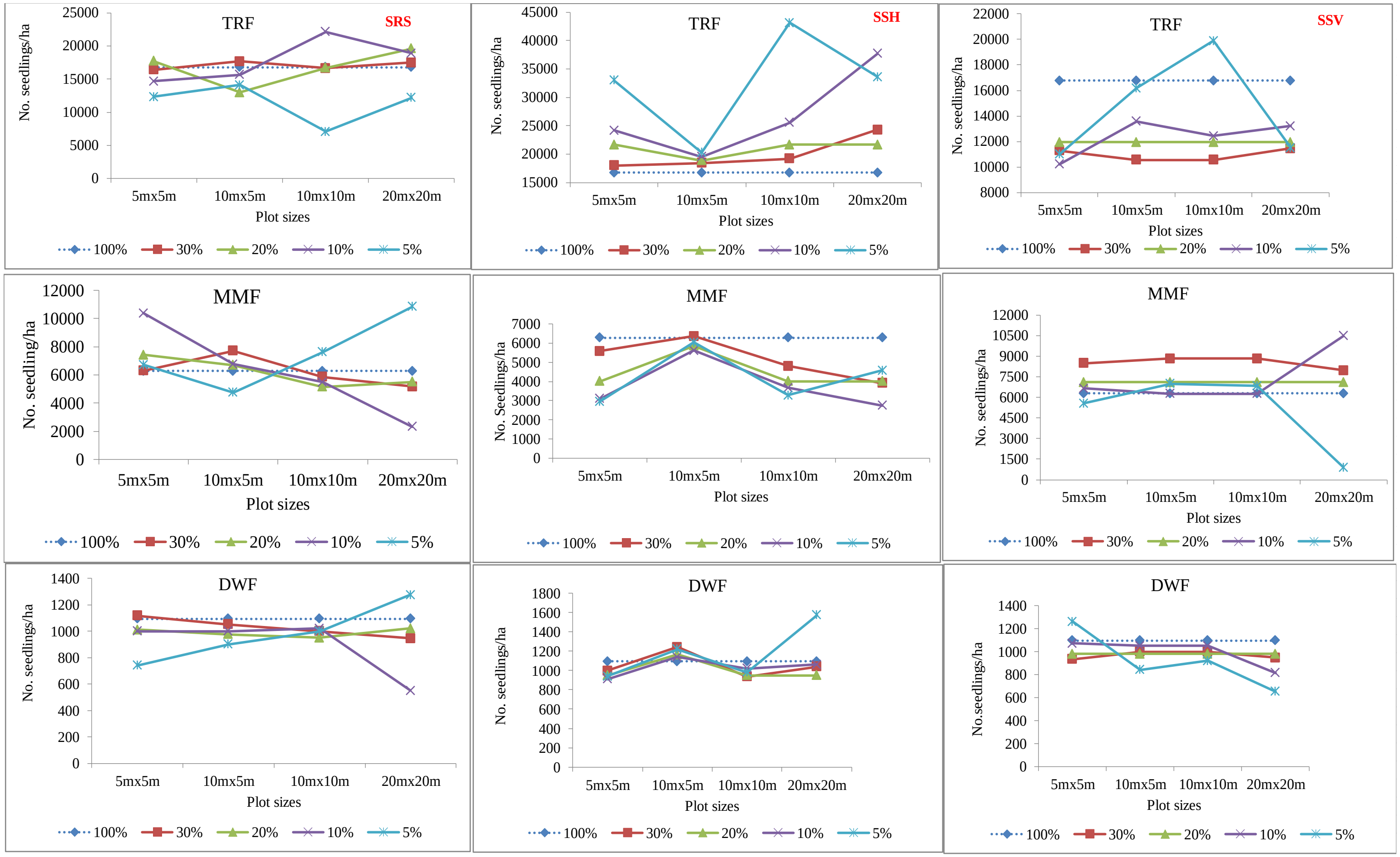


**Figure 21: Sampling for forest regeneration (no. seedlings ha$^{-1}$) under simple random sampling (SRS), systematic sampling horizontal (SSH) and vertical (SSV) in tropical rain forest (TRF), moist montane forest (MMF) and dry woodland (DWF), Kenya**

**Table 10: Simple random sampling (SRS) outputs for number of seedlings per hectare forest unit**

| Plot size ($m^2$) [i] | S.I. % [ii] | Rainforest | | | | Moist forest | | | | Dry woodland forest | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SE | Dev.% [iii] | CV% | Mean | SE | Dev.% | CV% | Mean | SE | Dev.% | CV% |
| 25 | 5 | 12,320$^{a}$ | 2,598 | -26.5 | 94 | 6,720$^{a}$ | 2,070 | 7.0 | 138 | 740$^{a}$ | 170 | -32.4 | 103 |
| 25 | 10 | 14,690$^{a}$ | 3,286 | -12.4 | 141 | 10,370$^{a}$ | 2,792 | 65.2 | 170 | 1,000$^{a}$ | 194 | -8.6 | 123 |
| 25 | 20 | 17,715$^{a}$ | 3,694 | 5.7 | 186 | 7,415$^{a}$ | 1,246 | 18.1 | 150 | 1,010$^{a}$ | 123 | -7.7 | 109 |
| 25 | 30 | 16,423$^{a}$ | 2,639 | -2.0 | 176 | 6,290$^{a}$ | 804 | 0.2 | 140 | 1,117$^{a}$ | 104 | 2.1 | 102 |
| 25 | 100 | 16,764$^{a}$ | 1,314 | 0.0 | 157 | 6,279$^{a}$ | 472 | 0.0 | 150 | 1,094$^{a}$ | 55 | 0.0 | 101 |
| 50 | 5 | 14,100$^{a}$ | 3,162 | -15.9 | 71 | 4,740$^{a}$ | 1,421 | -24.5 | 95 | 900$^{a}$ | 291 | -17.7 | 102 |
| 50 | 10 | 15,680$^{a}$ | 4,444 | -6.5 | 127 | 6,750$^{a}$ | 1,726 | 7.5 | 114 | 1,000$^{a}$ | 186 | -8.6 | 83 |
| 50 | 20 | 13,010$^{a}$ | 2,182 | -22.4 | 106 | 6,685$^{a}$ | 1,324 | 6.5 | 125 | 975$^{a}$ | 103 | -10.9 | 67 |
| 50 | 30 | 17,660$^{a}$ | 2,495 | 5.3 | 109 | 7,707$^{a}$ | 1,211 | 22.7 | 122 | 1,050$^{a}$ | 108 | -4.0 | 80 |
| 50 | 100 | 16,764$^{a}$ | 1,383 | 0.0 | 117 | 6,279$^{a}$ | 500 | 0.0 | 113 | 1,094$^{a}$ | 60 | 0.0 | 77 |
| 100 | 5 | 7,100$^{a}$ | 1,914 | -57.6 | 60 | 7,620$^{a}$ | 1,850 | 21.4 | 54 | 1,000$^{a}$ | 270 | -8.6 | 60 |
| 100 | 10 | 22,140$^{a}$ | 6,134 | 32.1 | 88 | 5,470$^{a}$ | 1,206 | -12.9 | 70 | 1,020$^{a}$ | 188 | -6.8 | 58 |
| 100 | 20 | 16,685$^{a}$ | 4,215 | -0.5 | 113 | 5,145$^{a}$ | 1,201 | -18.1 | 104 | 950$^{a}$ | 157 | -13.2 | 74 |
| 100 | 30 | 16,630$^{a}$ | 2,892 | -0.8 | 95 | 5,843$^{a}$ | 808 | -6.9 | 76 | 1,000$^{a}$ | 104 | -8.6 | 57 |
| 100 | 100 | 16,764$^{a}$ | 1,543 | 0.0 | 92 | 6,279$^{a}$ | 572 | 0.0 | 91 | 1,094$^{a}$ | 66 | 0.0 | 61 |
| 400 | 5 | 12,175$^{a}$ | NA | -27.4 | NA | 10,850$^{a}$ | NA | 72.8 | NA | 1,275$^{a}$ | NA | 16.5 | NA |
| 400 | 10 | 18,913$^{a}$ | 12,038 | 12.8 | 90 | 2,313$^{a}$ | 1,388 | -63.2 | 85 | 550$^{a}$ | 0 | -49.7 | 0 |
| 400 | 20 | 19,610$^{a}$ | 5,997 | 17.0 | 68 | 5,510$^{a}$ | 1,673 | -12.2 | 68 | 1,020$^{a}$ | 271 | -6.8 | 59 |
| 400 | 30 | 17,496$^{a}$ | 5,478 | 4.4 | 83 | 5,179$^{a}$ | 1,014 | -17.5 | 52 | 946$^{a}$ | 188 | -13.5 | 52 |
| 400 | 100 | 16,764$^{a}$ | 2,356 | 0.0 | 70 | 6,279$^{a}$ | 733 | 0.0 | 58 | 1,094$^{a}$ | 99 | 0.0 | 45 |

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[i] Plot size ($m^2$): 25 → 5 m x 5 m; 50 → 10 m x 5 m; 100 → 10 m x 10 m; 400 → 20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev. % = 100 x (Sample statistic – Population parameter)/population parameter

**Table 11: Systematic sampling along horizontal transect (SSH) outputs for number of tree seedlings per hectare forest unit**

| Plot size (m$^2$) [i] | S.I. %[ii] | Tropical rain forest | | | | Moist montane forest | | | | Dry woodland forest | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Mean** | **SE** | **Dev. %[iii]** | **CV%** | **Mean** | **SE** | **Dev.%** | **CV%** | **Mean** | **SE** | **Dev.%** | **CV%** |
| 25 | 5 | 33,020$^{a}$ | 8,986 | 97.0 | 122 | 2,960$^{ab}$ | 724 | -52.9 | 109 | 940$^{a}$ | 195 | -14.1 | 93 |
| 25 | 10 | 24,170$^{ab}$ | 5,212 | 44.2 | 136 | 3,100$^{a}$ | 498 | -50.6 | 102 | 910$^{a}$ | 134 | -16.8 | 93 |
| 25 | 20 | 21,685$^{ab}$ | 3,416 | 29.4 | 141 | 4,005$^{a}$ | 600 | -36.2 | 134 | 950$^{a}$ | 101 | -13.2 | 95 |
| 25 | 30 | 17,977$^{b}$ | 2,442 | 7.2 | 149 | 5,590$^{ab}$ | 940 | -11.0 | 184 | 997$^{a}$ | 94 | -8.9 | 104 |
| 25 | 100 | 16,764$^{b}$ | 1,314 | 0.0 | 157 | 6,279$^{b}$ | 472 | 0.0 | 150 | 1,094$^{a}$ | 55 | 0.0 | 101 |
| 50 | 5 | 20,280$^{a}$ | 2,049 | 21.0 | 32 | 6,040$^{ab}$ | 1,450 | -3.8 | 76 | 1,220$^{a}$ | 185 | 11.5 | 48 |
| 50 | 10 | 19,560$^{ab}$ | 2,735 | 16.7 | 63 | 5,610$^{a}$ | 1,075 | -10.7 | 86 | 1,140$^{a}$ | 115 | 4.2 | 45 |
| 50 | 20 | 18,850$^{ab}$ | 4,579 | 12.4 | 154 | 5,855$^{a}$ | 969 | -6.8 | 105 | 1,165$^{a}$ | 126 | 6.5 | 69 |
| 50 | 30 | 18,423$^{b}$ | 3,466 | 9.9 | 146 | 6,367$^{ab}$ | 886 | 1.4 | 108 | 1,243$^{a}$ | 119 | 13.6 | 74 |
| 50 | 100 | 16,764$^{b}$ | 1,383 | 0.0 | 117 | 6,279$^{b}$ | 500 | 0.0 | 113 | 1,094$^{a}$ | 60 | 0.0 | 77 |
| 100 | 5 | 43,140$^{a}$ | 6,946 | 157.3 | 36 | 3,280$^{ab}$ | 973 | -47.8 | 66 | 980$^{a}$ | 282 | -10.4 | 64 |
| 100 | 10 | 25,540$^{ab}$ | 6,780 | 52.4 | 84 | 3,670$^{a}$ | 942 | -41.6 | 81 | 1,020$^{a}$ | 172 | -6.8 | 53 |
| 100 | 20 | 21,685$^{ab}$ | 4,010 | 29.4 | 83 | 4,005$^{a}$ | 665 | -36.2 | 74 | 950$^{a}$ | 127 | -13.2 | 60 |
| 100 | 30 | 19,217$^{b}$ | 3,152 | 14.6 | 88 | 4,797$^{ab}$ | 791 | -23.6 | 90 | 937$^{a}$ | 125 | -14.4 | 73 |
| 100 | 100 | 16,764$^{b}$ | 1,543 | 0.0 | 92 | 6,279$^{b}$ | 572 | 0.0 | 91 | 1,094$^{a}$ | 66 | 0.0 | 61 |
| 400 | 5 | 33,625$^{a}$ | NA | 100.6 | NA | 4,575$^{ab}$ | NA | -27.1 | NA | 1,575$^{a}$ | NA | 44.0 | NA |
| 400 | 10 | 37,713$^{ab}$ | 4,088 | 125.0 | 15 | 2,750$^{a}$ | 1,825 | -56.2 | 94 | 1,063$^{a}$ | 513 | -2.8 | 68 |
| 400 | 20 | 21,685$^{ab}$ | 6,956 | 29.4 | 72 | 4,005$^{a}$ | 1,102 | -36.2 | 62 | 950$^{a}$ | 209 | -13.2 | 49 |
| 400 | 30 | 24,314$^{b}$ | 5,536 | 45.0 | 60 | 3,904$^{ab}$ | 893 | -37.8 | 61 | 1,039$^{a}$ | 232 | -5.0 | 59 |
| 400 | 100 | 16,764$^{b}$ | 2,356 | 0.0 | 70 | 6,279$^{b}$ | 733 | 0.0 | 58 | 1,094$^{a}$ | 99 | 0.0 | 45 |

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[i] Plot size (m$^2$): 25 → 5 m x 5 m; 50 → 10 m x 5 m; 100 → 10 m x 10 m; 400 → 20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

**Table 12: Systematic sampling along vertical transect (SSV) outputs for number of tree seedlings per hectare forest unit**

| **Plot size (m$^2$)** [i] | **S.I. %**[ii] | **Tropical rain forest** | | | | **Moist montane forest** | | | | **Dry woodland forest** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SE | Dev.%[iii] | CV% | Mean | SE | Dev.% | CV% | Mean | SE | Dev.% | CV% |
| 25 | 5 | 10,980$^{ab}$ | 3,037 | -34.5 | 124 | 5,560$^{ab}$ | 1,546 | -11.5 | 124 | 1,260$^{a}$ | 291 | 15.2 | 103 |
| 25 | 10 | 10,200$^{ab}$ | 1,739 | -39.2 | 108 | 6,650$^{ab}$ | 1,392 | 5.9 | 132 | 1,070$^{a}$ | 170 | -2.2 | 101 |
| 25 | 20 | 11,930$^{a}$ | 1,543 | -28.8 | 116 | 7,100$^{ab}$ | 1,087 | 13.1 | 137 | 980$^{a}$ | 112 | -10.4 | 102 |
| 25 | 30 | 11,290$^{a}$ | 1,193 | -32.7 | 116 | 8,493$^{a}$ | 1,167 | 35.3 | 151 | 933$^{a}$ | 85 | -14.7 | 99 |
| 25 | 100 | 16,764$^{b}$ | 1,314 | 0.0 | 157 | 6,279$^{b}$ | 472 | 0.0 | 150 | 1,094$^{a}$ | 55 | 0.0 | 101 |
| 50 | 5 | 16,180$^{ab}$ | 4,907 | -3.5 | 96 | 6,980$^{ab}$ | 2,831 | 11.2 | 128 | 840$^{a}$ | 181 | -23.2 | 68 |
| 50 | 10 | 13,580$^{ab}$ | 2,912 | -19.0 | 96 | 6,270$^{ab}$ | 1,645 | -0.1 | 117 | 1,050$^{a}$ | 200 | -4.0 | 85 |
| 50 | 20 | 11,930$^{a}$ | 1,700 | -28.8 | 90 | 7,100$^{ab}$ | 1,222 | 13.1 | 109 | 980$^{a}$ | 118 | -10.4 | 76 |
| 50 | 30 | 10,557$^{a}$ | 1,242 | -37.0 | 91 | 8,833$^{a}$ | 1,299 | 40.7 | 114 | 997$^{a}$ | 92 | -8.9 | 71 |
| 50 | 100 | 16,764$^{b}$ | 1,383 | 0.0 | 117 | 6,279$^{b}$ | 500 | 0.0 | 113 | 1,094$^{a}$ | 60 | 0.0 | 77 |
| 100 | 5 | 19,880$^{ab}$ | 3,773 | 18.6 | 42 | 6,840$^{ab}$ | 2,346 | 8.9 | 77 | 920$^{a}$ | 146 | -15.9 | 36 |
| 100 | 10 | 12,428$^{ab}$ | 3,092 | -25.9 | 79 | 6,270$^{ab}$ | 1,660 | -0.1 | 84 | 1,050$^{a}$ | 211 | -4.0 | 64 |
| 100 | 20 | 11,930$^{a}$ | 1,729 | -28.8 | 65 | 7,100$^{ab}$ | 1,503 | 13.1 | 95 | 980$^{a}$ | 123 | -10.4 | 56 |
| 100 | 30 | 10,557$^{a}$ | 1,294 | -37.0 | 67 | 8,833$^{a}$ | 1,492 | 40.7 | 93 | 997$^{a}$ | 96 | -8.9 | 53 |
| 100 | 100 | 16,764$^{b}$ | 1,543 | 0.0 | 92 | 6,279$^{b}$ | 572 | 0.0 | 91 | 1,094$^{a}$ | 66 | 0.0 | 61 |
| 400 | 5 | 11,500$^{ab}$ | NA | -31.4 | NA | 900$^{ab}$ | NA | -85.7 | NA | 650$^{a}$ | NA | -40.6 | NA |
| 400 | 10 | 13,200$^{ab}$ | 1,700 | -21.3 | 18 | 10,475$^{ab}$ | 3,500 | 66.8 | 47 | 813$^{a}$ | 163 | -25.7 | 28 |
| 400 | 20 | 11,930$^{a}$ | 2,153 | -28.8 | 40 | 7,100$^{ab}$ | 1,987 | 13.1 | 63 | 980$^{a}$ | 97 | -10.4 | 22 |
| 400 | 30 | 11,450$^{a}$ | 1,687 | -31.7 | 39 | 7,971$^{a}$ | 1,547 | 26.9 | 51 | 946$^{a}$ | 79 | -13.5 | 22 |
| 400 | 100 | 16,764$^{b}$ | 2,322 | 0.0 | 70 | 6,279$^{b}$ | 733 | 0.0 | 58 | 1,094$^{a}$ | 99 | 0.0 | 45 |

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[i] Plot size (m$^2$): 25 →5 m x 5 m; 50 →10 m x 5 m; 100 →10 m x 10 m; 400 →20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

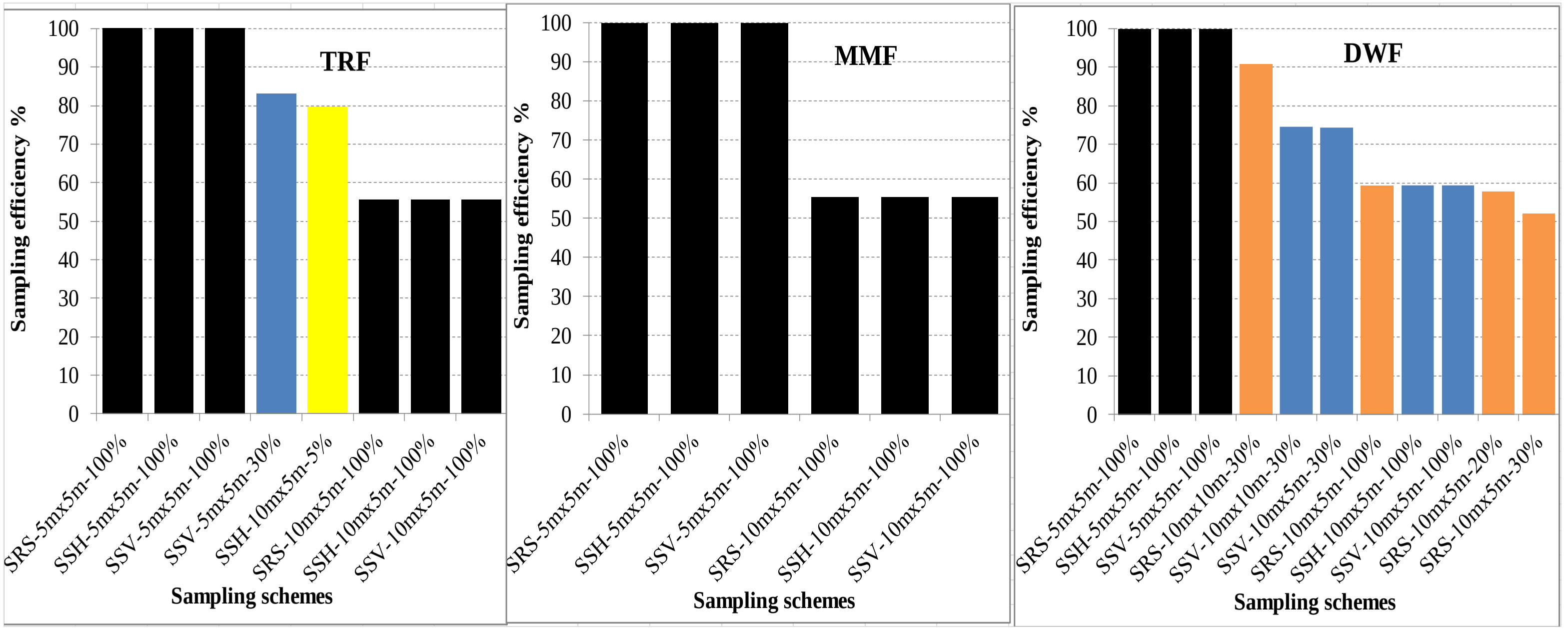

**Figure 22: Relative efficiencies of candidate sampling schemes in assessing forest regeneration (no. seedlings ha$^{-1}$) in tropical rain forest (TRF), moist montane forest (MMF) and dry woodland forest (DWF), Kenya**

**Black bars** = complete inventory schemes (100% intensity);
**Blue bars** = SSV sampling schemes with intensity < 100%
**Yellow bars** = SSH sampling schemes with intensity < 100%;
**Orange bars** = SRS sampling schemes with intensity < 100%;

### 4.3.3 Sampling Schemes for Forest Density

Forest density measured in number of stems per hectare for tree individuals with a minimum diameter at breast height of 1cm (i.e. from sapling to large trees) were evaluated to determine suitable sampling schemes. Figure 23 show patterns of sample estimates departure from the actual population parameter. With SRS (Table 13) and SSH (Table 14) designs, the estimates of the number trees per hectare from different sampling intensities and plot sizes did not differ significantly from the true population values ($p > 0.05$), across the studied forest types. It implies that deviations reflected through the graph are product of random errors, and that schemes with “5 % intensity and 5 m x 5 m plot size” are as good as those with “100% intensity and 20 m x 20 m plot size”. Whereas SSV design (Table 15) produced similar results as the other designs in both TRF and MMF, it is not adequate for inventory in DWF with sample size less than one hectare; effect of 100 % intensity was significantly different from that of 30 % ($p < 0.05$). Consequently, it is prudent to avoid the use of SSV (N-S oriented) in DWF altogether.

Figure 24 shows that many efficient sampling schemes exist for each forest type based on maximum allowable sampling error of 25% of the mean. Three most efficient schemes per forest types were: SRS-10mx10m-30%, SSV-20mx20m-20%, SSH-10mx10m-30% in TRF; SSH-10mx10m-20%, SRS-10mx10m-20% and SSH-10mx10m-30% in MMF; and for DWF, highest efficiency levels were associated with SSV-10mx5m-30%, SRS-10mx10m-30% and SSH-10mx10m-30%. All tested sampling designs are applicable by ensuring that the right combination with plot size and sampling intensitiy is adopted. Overall, optimum plot size for forest density varies from 10 m x 5 m to 10 m x 10 m depending on forest type and efficient sampling intensity varied from 20% to 30% depending on sampling design and forest type.

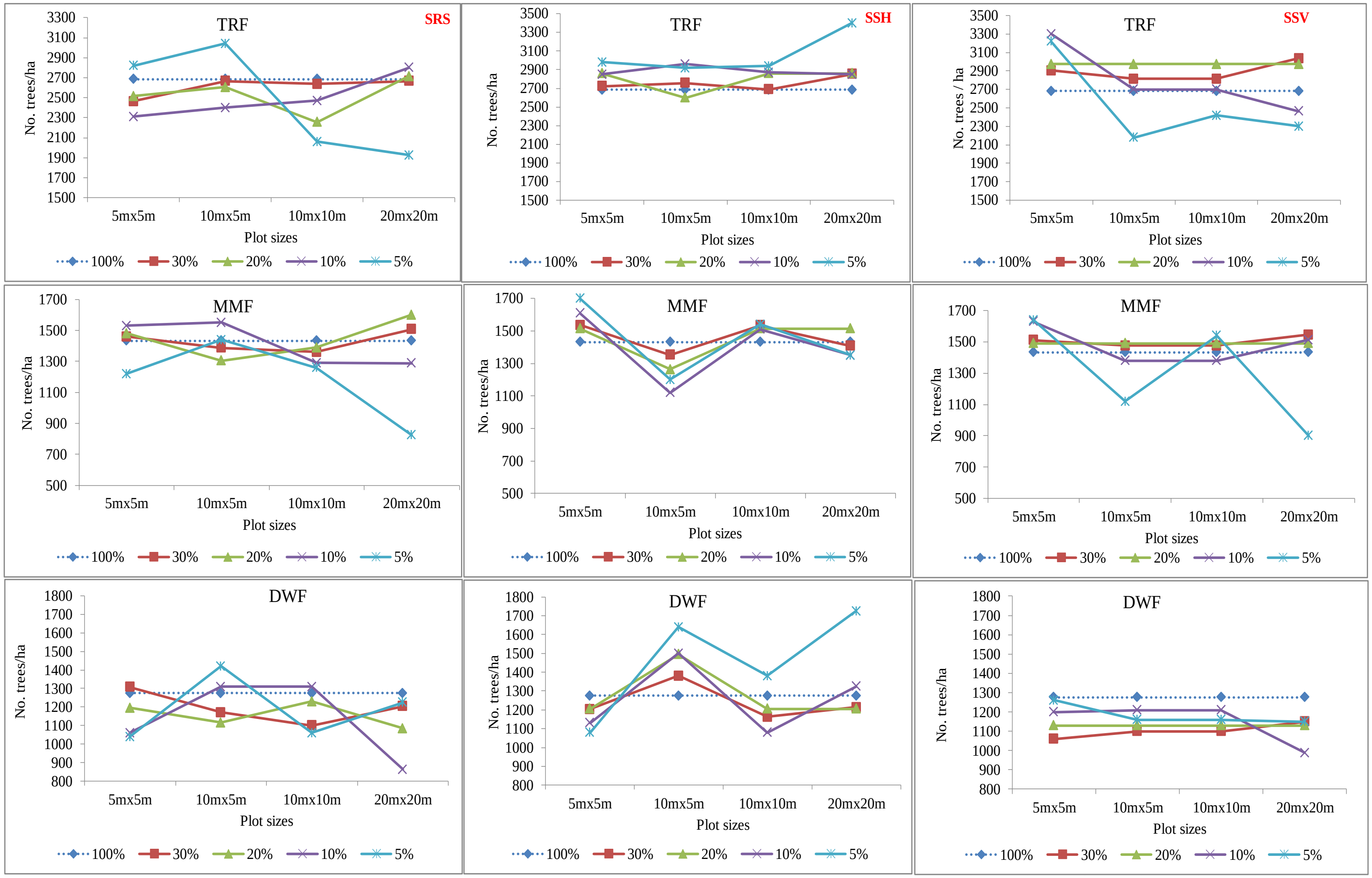

**Figure 23: Sampling for forest density (no. trees ha$^{-1}$) under simple random sampling (SRS), systematic sampling horizontal (SSH) and vertical (SSV) in tropical rain forest (TRF), moist montane forest (MMF) and dry woodland (DWF), Kenya**

**Table 13: Simple random sampling (SRS) outputs for number of trees per hectare forest unit**

| Plot size ($m^2$) [i] | S.I.% [ii] | Rainforest | | | | Moist forest | | | | Dry woodland | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Number of trees $ha^{-1}$ | | | | Number of trees $ha^{-1}$ | | | | Number of trees $ha^{-1}$ | | | |
| | | Mean | SE | Dev.% [iii] | CV% | Mean | SE | Dev.% | CV% | Mean | SE | Dev.% | CV % |
| 25 | 5 | 2,820$^{a}$ | 403 | 5.1 | 64 | 1,220$^{a}$ | 206 | -14.8 | 76 | 1,040$^{a}$ | 177 | -18.4 | 76 |
| 25 | 10 | 2,310$^{a}$ | 203 | -13.9 | 56 | 1,530$^{a}$ | 159 | 6.8 | 66 | 1,060$^{a}$ | 143 | -16.9 | 85 |
| 25 | 20 | 2,515$^{a}$ | 174 | -6.3 | 62 | 1,480$^{a}$ | 123 | 3.4 | 74 | 1,195$^{a}$ | 102 | -6.3 | 76 |
| 25 | 30 | 2,463$^{a}$ | 134 | -8.2 | 60 | 1,460$^{a}$ | 100 | 2.0 | 75 | 1,307$^{a}$ | 85 | 2.5 | 71 |
| 25 | 100 | 2,684$^{a}$ | 72 | 0.0 | 54 | 1,432$^{a}$ | 53 | 0.0 | 75 | 1,275$^{a}$ | 49 | 0.0 | 77 |
| 50 | 5 | 3,040$^{a}$ | 451 | 13.3 | 47 | 1,440$^{a}$ | 321 | 0.6 | 70 | 1,420$^{a}$ | 250 | 11.4 | 56 |
| 50 | 10 | 2,400$^{a}$ | 272 | -10.6 | 51 | 1,550$^{a}$ | 193 | 8.2 | 56 | 1,310$^{a}$ | 131 | 2.7 | 45 |
| 50 | 20 | 2,605$^{a}$ | 169 | -2.9 | 41 | 1,305$^{a}$ | 109 | -8.9 | 53 | 1,115$^{a}$ | 98 | -12.5 | 56 |
| 50 | 30 | 2,667$^{a}$ | 127 | -0.6 | 37 | 1,387$^{a}$ | 102 | -3.1 | 57 | 1,170$^{a}$ | 104 | -8.2 | 69 |
| 50 | 100 | 2,684$^{a}$ | 77 | 0.0 | 41 | 1,432$^{a}$ | 55 | 0.0 | 55 | 1,275$^{a}$ | 59 | 0.0 | 66 |
| 100 | 5 | 2,060$^{a}$ | 121 | -23.2 | 13 | 1,260$^{a}$ | 216 | -12.0 | 38 | 1,060$^{a}$ | 112 | -16.9 | 24 |
| 100 | 10 | 2,470$^{a}$ | 285 | -8.0 | 36 | 1,290$^{a}$ | 125 | -9.9 | 31 | 1,310$^{a}$ | 234 | 2.7 | 56 |
| 100 | 20 | 2,255$^{a}$ | 165 | -16.0 | 33 | 1,390$^{a}$ | 104 | -2.9 | 33 | 1,230$^{a}$ | 154 | -3.5 | 56 |
| 100 | 30 | 2,637$^{a}$ | 146 | -1.8 | 30 | 1,360$^{a}$ | 90 | -5.0 | 36 | 1,100$^{a}$ | 92 | -13.7 | 46 |
| 100 | 100 | 2,684$^{a}$ | 81 | 0.0 | 30 | 1,432$^{a}$ | 58 | 0.0 | 41 | 1,275$^{a}$ | 65 | 0.0 | 51 |
| 400 | 5 | 1925$^{a}$ | NA | -28.3 | NA | 825$^{a}$ | NA | -42.4 | NA | 1,225$^{a}$ | NA | -3.9 | NA |
| 400 | 10 | 2800$^{a}$ | 400 | 4.3 | 20 | 1,288$^{a}$ | 63 | -10.1 | 7 | 863$^{a}$ | 63 | -32.3 | 10 |
| 400 | 20 | 2715$^{a}$ | 269 | 1.2 | 22 | 1,600$^{a}$ | 197 | 11.7 | 28 | 1,085$^{a}$ | 196 | -14.9 | 40 |
| 400 | 30 | 2668$^{a}$ | 171 | -0.6 | 17 | 1,507$^{a}$ | 86 | 5.2 | 15 | 1,204$^{a}$ | 172 | -5.6 | 38 |
| 400 | 100 | 2,684$^{a}$ | 100 | 0.0 | 19 | 1,432$^{a}$ | 74 | 0.0 | 26 | 1,275$^{a}$ | 104 | 0.0 | 41 |

All evaluated sampling intensities and plot sizes were not significanlt different from total census of the forest parameters in a one-hectare reference unit across the three natural forest types ($p > 0.05$). Values followed by same letter in a column are not significantly different at $\alpha = 0.05$.

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[i] Plot size ($m^2$): 25 →5 m x 5 m; 50 →10 m x 5 m; 100 →10 m x 10 m; 400 →20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

**Table 14: Systematic sampling along horizontal transect (SSH) outputs for number of trees per hectare forest unit**

| Plot size (m$^2$) [i] | S.I.% [ii] | Rainforest | | | | Moist forest | | | | Dry woodland | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Number of trees ha$^{-1}$ | | | | Number of trees ha$^{-1}$ | | | | Number of trees ha$^{-1}$ | | | |
| | | Mean | SE | Dev.%[iii] | CV% | Mean | SE | Dev.% | CV% | Mean | SE | Dev.% | CV% |
| 25 | 5 | 2,980$^{a}$ | 288 | 11.0 | 43 | 1,700$^{a}$ | 297 | 18.7 | 78 | 1,080$^{a}$ | 314 | -15.3 | 130 |
| 25 | 10 | 2,850$^{a}$ | 214 | 6.2 | 48 | 1,610$^{a}$ | 198 | 12.4 | 78 | 1,130$^{a}$ | 189 | -11.4 | 106 |
| 25 | 20 | 2,860$^{a}$ | 155 | 6.6 | 49 | 1,515$^{a}$ | 128 | 5.8 | 75 | 1,205$^{a}$ | 123 | -5.5 | 91 |
| 25 | 30 | 2,723$^{a}$ | 125 | 1.5 | 50 | 1,537$^{a}$ | 103 | 7.3 | 73 | 1,203$^{a}$ | 95 | -5.6 | 86 |
| 25 | 100 | 2,684$^{a}$ | 72 | 0.0 | 54 | 1,432$^{a}$ | 53 | 0.0 | 75 | 1,275$^{a}$ | 49 | 0.0 | 77 |
| 50 | 5 | 2,920$^{a}$ | 260 | 8.8 | 28 | 1,200$^{a}$ | 191 | -16.2 | 50 | 1,640$^{a}$ | 392 | 28.6 | 76 |
| 50 | 10 | 2,960$^{a}$ | 192 | 10.3 | 29 | 1,120$^{a}$ | 155 | -21.8 | 62 | 1,500$^{a}$ | 212 | 17.6 | 63 |
| 50 | 20 | 2,600$^{a}$ | 153 | -3.1 | 37 | 1,265$^{a}$ | 127 | -11.7 | 63 | 1,495$^{a}$ | 130 | 17.3 | 55 |
| 50 | 30 | 2,757$^{a}$ | 140 | 2.7 | 39 | 1,353$^{a}$ | 98 | -5.5 | 56 | 1,380$^{a}$ | 106 | 8.2 | 60 |
| 50 | 100 | 2,684$^{a}$ | 77 | 0.0 | 41 | 1,432$^{a}$ | 55 | 0.0 | 55 | 1,275$^{a}$ | 59 | 0.0 | 66 |
| 100 | 5 | 2,940$^{a}$ | 372 | 9.5 | 28 | 1,540$^{a}$ | 216 | 7.5 | 31 | 1,380$^{a}$ | 275 | 8.2 | 44 |
| 100 | 10 | 2,870$^{a}$ | 284 | 6.9 | 31 | 1,510$^{a}$ | 157 | 5.4 | 33 | 1,080$^{a}$ | 187 | -15.3 | 55 |
| 100 | 20 | 2,860$^{a}$ | 211 | 6.6 | 33 | 1,515$^{a}$ | 115 | 5.8 | 34 | 1,205$^{a}$ | 122 | -5.5 | 45 |
| 100 | 30 | 2,690$^{a}$ | 153 | 0.2 | 31 | 1,533$^{a}$ | 104 | 7.1 | 37 | 1,163$^{a}$ | 104 | -8.8 | 49 |
| 100 | 100 | 2,684$^{a}$ | 81 | 0.0 | 30 | 1,432$^{a}$ | 58 | 0.0 | 41 | 1,275$^{a}$ | 65 | 0.0 | 51 |
| 400 | 5 | 3,400$^{a}$ | NA | 26.7 | NA | 1,350$^{a}$ | NA | -5.7 | NA | 1,725$^{a}$ | NA | 35.3 | NA |
| 400 | 10 | 2,850$^{a}$ | 550 | 6.2 | 27 | 1,350$^{a}$ | NA | -5.7 | 0 | 1,325$^{a}$ | 400 | 3.9 | 43 |
| 400 | 20 | 2,860$^{a}$ | 299 | 6.6 | 23 | 1,515$^{a}$ | 147 | 5.8 | 22 | 1,205$^{a}$ | 165 | -5.5 | 31 |
| 400 | 30 | 2854$^{a}$ | 206 | 6.3 | 19 | 1,407$^{a}$ | 128 | -1.7 | 24 | 1,214$^{a}$ | 172 | -4.8 | 37 |
| 400 | 100 | 2,684$^{a}$ | 100 | 0.0 | 19 | 1,432$^{a}$ | 74 | 0.0 | 26 | 1,275$^{a}$ | 104 | 0.0 | 41 |

All evaluated sampling intensities and plot sizes were not significanlt different from total census of the forest parameters in a one-hectare reference unit across the three natural forest types ($p > 0.05$). Values followed by same letter in a column are not significantly different at $\alpha = 0.05$.

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[i] Plot size (m$^2$): 25 → 5m x 5m; 50 → 10m x 5m; 100 → 10m x 10m; 400 → 20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

**Table 15: Systematic sampling along vertical transect (SSV) outputs for number of trees per hectare forest unit**

| Plot size (m$^2$)[i] | S.I.%[ii] | Rainforest | | | | Moist forest | | | | Dry woodland | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Number of trees ha$^{-1}$ | | | | Number of trees ha$^{-1}$ | | | | Number of trees ha$^{-1}$ | | | |
| | | Mean | SE | Dev.%[iii] | CV% | Mean | SE | Dev.% | CV% | Mean | SE | Dev.% | CV% |
| 25 | 5 | 3,220$^{a}$ | 294 | 20.0 | 41 | 1,640$^{a}$ | 213 | 14.5 | 58 | 1,260$^{ab}$ | 160 | -1.2 | 57 |
| 25 | 10 | 3,300$^{a}$ | 219 | 23.0 | 42 | 1,630$^{a}$ | 164 | 13.8 | 63 | 1,200$^{ab}$ | 138 | -5.9 | 73 |
| 25 | 20 | 2,975$^{a}$ | 168 | 10.8 | 50 | 1,490$^{a}$ | 106 | 4.1 | 64 | 1,130$^{ab}$ | 81 | -11.4 | 64 |
| 25 | 30 | 2,907$^{a}$ | 135 | 8.3 | 51 | 1,510$^{a}$ | 99 | 5.4 | 72 | 1,060$^{a}$ | 65 | -16.9 | 67 |
| 25 | 100 | 2,684$^{a}$ | 72 | 0.0 | 54 | 1,432$^{a}$ | 53 | 0.0 | 75 | 1,275$^{b}$ | 49 | 0.0 | 77 |
| 50 | 5 | 2,180$^{a}$ | 150 | -18.8 | 22 | 1,120$^{a}$ | 213 | -21.8 | 60 | 1,160$^{ab}$ | 126 | -9.0 | 34 |
| 50 | 10 | 2,700$^{a}$ | 218 | 0.6 | 36 | 1,380$^{a}$ | 162 | -3.6 | 53 | 1,210$^{ab}$ | 109 | -5.1 | 40 |
| 50 | 20 | 2,975$^{a}$ | 184 | 10.8 | 39 | 1,490$^{a}$ | 109 | 4.1 | 46 | 1,130$^{ab}$ | 81 | -11.4 | 45 |
| 50 | 30 | 2,813$^{a}$ | 147 | 4.8 | 41 | 1,477$^{a}$ | 97 | 3.1 | 51 | 1,100$^{a}$ | 68 | -13.7 | 48 |
| 50 | 100 | 2,684$^{a}$ | 77 | 0.0 | 41 | 1,432$^{a}$ | 55 | 0.0 | 55 | 1,275$^{b}$ | 59 | 0.0 | 66 |
| 100 | 5 | 2,420$^{a}$ | 188 | -9.8 | 17 | 1,540$^{a}$ | 191 | 7.5 | 28 | 1,160$^{ab}$ | 150 | -9.0 | 29 |
| 100 | 10 | 2,700$^{a}$ | 186 | 0.6 | 22 | 1,380$^{a}$ | 169 | -3.6 | 39 | 1,210$^{ab}$ | 124 | -5.1 | 32 |
| 100 | 20 | 2,975$^{a}$ | 185 | 10.8 | 28 | 1,490$^{a}$ | 103 | 4.1 | 31 | 1,130$^{ab}$ | 85 | -11.4 | 34 |
| 100 | 30 | 2,813$^{a}$ | 152 | 4.8 | 30 | 1,477$^{a}$ | 103 | 3.1 | 38 | 1,100$^{a}$ | 68 | -13.7 | 34 |
| 100 | 100 | 2,684$^{a}$ | 81 | 0.0 | 30 | 1,432$^{a}$ | 58 | 0.0 | 41 | 1,275$^{b}$ | 65 | 0.0 | 51 |
| 400 | 5 | 2,300$^{a}$ | NA | -14.3 | NA | 900$^{a}$ | NA | -37.2 | NA | 1,150$^{ab}$ | NA | -9.8 | NA |
| 400 | 10 | 2,463$^{a}$ | 163 | -8.2 | 9 | 1,513$^{a}$ | 288 | 5.7 | 27 | 988$^{ab}$ | 163 | -22.5 | 23 |
| 400 | 20 | 2,975$^{a}$ | 288 | 10.8 | 22 | 1,490$^{a}$ | 150 | 4.1 | 22 | 1,130$^{ab}$ | 83 | -11.4 | 17 |
| 400 | 30 | 3,036$^{a}$ | 203 | 13.1 | 18 | 1,546$^{a}$ | 110 | 8.0 | 19 | 1,150$^{a}$ | 65 | -9.8 | 15 |
| 400 | 100 | 2,684$^{a}$ | 103 | 0.0 | 19 | 1,432$^{a}$ | 74 | 0.0 | 26 | 1,275$^{b}$ | 104 | 0.0 | 41 |

Values followed by same letter in a column are not significantly different at $\alpha = 0.05$.

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[i] Plot size (m$^2$): 25 → 5m x 5m; 50 → 10m x 5m; 100 → 10m x 10m; 400 → 20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

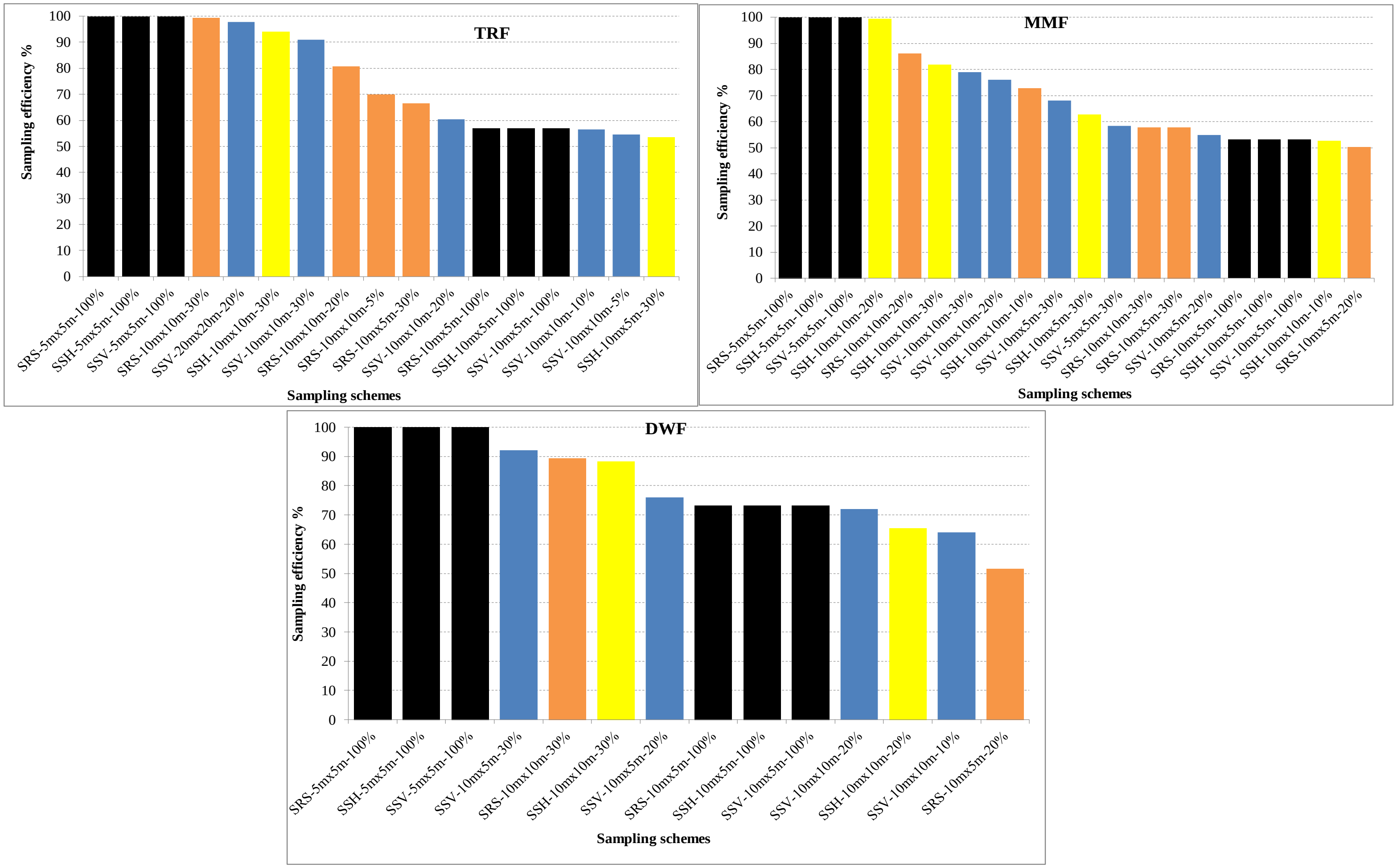

**Figure 24: Efficient sampling schemes for forest stocking (no. trees ha$^{-1}$) under simple random sampling in tropical rain forest (TRF), moist montane forest (MMF) and Dry woodland (DWF), Kenya**

**Black bars** = complete inventory schemes (100% intensity);
**Blue bars** = SSV sampling schemes with intensity < 100%
**Orange bars** = SRS sampling schemes with intensity < 100%;
**Yellow bars** = SSH sampling schemes with intensity < 100%.

### 4.3.4 Sampling Schemes for Basal Area

Figure 25 illustrates how samples from different plot sizes and sampling intensities fluctuated around the true population value. However, ANOVA test of significance (Table 16) revealed that, with SRS, all sampling intensities and plot sizes produced estimates that are not significantly different from population true value ($p > 0.05$), in each of the studied forest type. SSH (Table 17) and SSV (Table 18) designs produced similar results as with SRS. No single sampling scheme is superior over the other for basal area inventory per hectare. Results in Figure 26 also show that there was no efficient sampling scheme within the “one-hectare” forest unit, for basal area assessment. Trees on the entire one-hectare forest unit should be measured with 10 m x 10 m subdivision units being used; this size produced the smallest sampling error.

### 4.3.5 Sampling Schemes for Quadratic Mean Diameter

In TRF, sampling intensities effect on true QMD was not significant (Table 19). SSH (Table 20) gave results of QMD without any influence being observed from varying plot sizes and sampling intensities. However, SSV (Table 21) produced different results from SRS and SSH. A trend emerged that 10 m x 10 m plot size produced more acciurate average QMD, closest to the true value. In MMF, all sampling schemes produced accuarate QMD. Sampling overestimated significantly ($p < 0.05$) estimate of tree dimeter size in DWF. Figure 27 shows sampling schemes with highest efficiency to be SSH-20mx20m-20% and SRS-20mx20m-30% in TRF; SRS-10mx10m-20% and SRS-10mx10m-30% in MMF; and SRS-10mx10m-20% and SRS-20mx20m-30% in DWF.

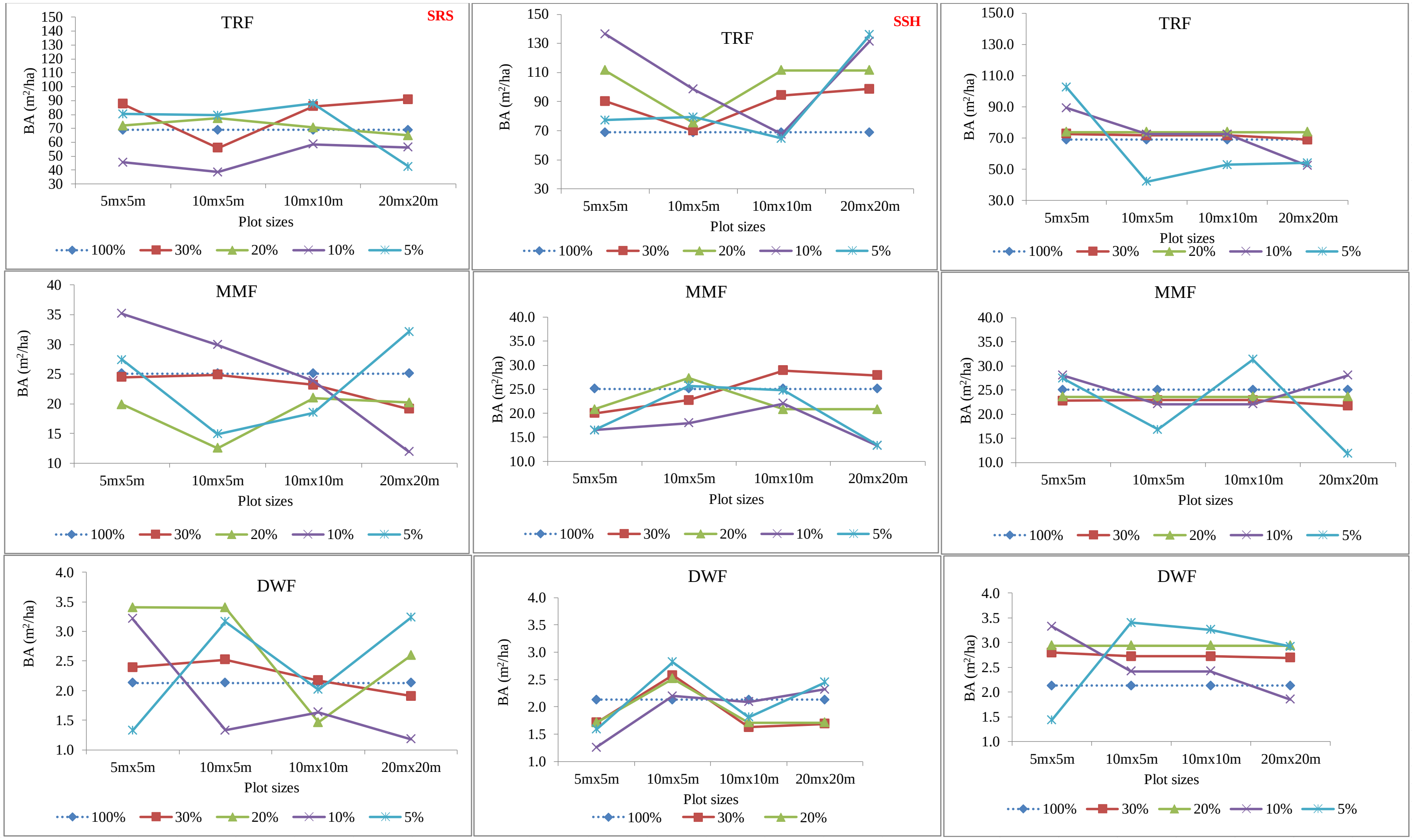

**Figure 25: Sampling for forest basal area ($m^2ha^{-1}$) under simple random sampling (SRS), systematic sampling horizontal (SSH) and vertical (SSV) in tropical rain forest (TRF), moist montane forest (MMF) and dry woodland (DWF), Kenya**

**Table 16: Simple random sampling (SRS) outputs for basal area per hectare ($m^2ha^{-1}$) forest unit**

| Plot size ($m^2$)[i] | S.I.% [ii] | Tropical rain forest | | | | Moist montane forest | | | | Dry woodland forest | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **$m^2$ $ha^{-1}$** | | | | **$m^2$ $ha^{-1}$** | | | | **$m^2$ $ha^{-1}$** | | | |
| | | Mean | SE | Dev.%[iii] | *CV%* | Mean | SE | Dev.% | *CV%* | Mean | SE | Dev.% | *CV%* |
| 25 | 5 | 80.4$^{a}$ | 26.4 | 16.6 | 147 | 27.4$^{a}$ | 11.3 | 9.4 | 185 | 1.3$^{a}$ | 0.3 | -38.0 | 90 |
| 25 | 10 | 45.6$^{a}$ | 12.9 | -33.9 | 179 | 35.2$^{a}$ | 8.1 | 40.3 | 146 | 3.2$^{a}$ | 0.9 | 51.2 | 178 |
| 25 | 20 | 71.9$^{a}$ | 17.2 | 4.2 | 214 | 19.9$^{a}$ | 3.0 | -20.6 | 134 | 3.4$^{a}$ | 0.9 | 59.6 | 241 |
| 25 | 30 | 87.5$^{a}$ | 16.9 | 26.9 | 211 | 24.5$^{a}$ | 3.5 | -2.5 | 158 | 2.4$^{a}$ | 0.6 | 12.2 | 254 |
| 25 | 100 | 69.0$^{a}$ | 7.2 | 0.0 | 210 | 25.1$^{a}$ | 2.7 | 0.0 | 215 | 2.1$^{a}$ | 0.2 | 0.0 | 211 |
| 50 | 5 | 79.5$^{a}$ | 31.0 | 15.3 | 123 | 14.9$^{a}$ | 7.5 | -40.5 | 159 | 3.2$^{a}$ | 1.1 | 48.4 | 113 |
| 50 | 10 | 38.6$^{a}$ | 10.5 | -44.1 | 122 | 29.9$^{a}$ | 7.5 | 19.4 | 112 | 1.3$^{a}$ | 0.2 | -37.6 | 68 |
| 50 | 20 | 77.2$^{a}$ | 20.7 | 12.0 | 169 | 12.6$^{a}$ | 2.0 | -50.0 | 102 | 3.4$^{a}$ | 0.9 | 59.6 | 163 |
| 50 | 30 | 56.0$^{a}$ | 8.9 | -18.8 | 124 | 24.9$^{a}$ | 3.8 | -0.8 | 118 | 2.5$^{a}$ | 0.5 | 18.3 | 148 |
| 50 | 100 | 69.0$^{a}$ | 7.5 | 0.0 | 154 | 25.1$^{a}$ | 2.8 | 0.0 | 158 | 2.1$^{a}$ | 0.2 | 0.0 | 154 |
| 100 | 5 | 87.8$^{a}$ | 54.6 | 27.3 | 139 | 18.5$^{a}$ | 7.9 | -26.1 | 95 | 2.0$^{a}$ | 0.7 | -5.2 | 72 |
| 100 | 10 | 58.6$^{a}$ | 21.0 | -15.0 | 113 | 23.9$^{a}$ | 4.6 | -4.7 | 60 | 1.6$^{a}$ | 0.3 | -23.0 | 48 |
| 100 | 20 | 70.7$^{a}$ | 15.1 | 2.5 | 95 | 21.0$^{a}$ | 2.6 | -16.4 | 55 | 1.5$^{a}$ | 0.2 | -31.5 | 73 |
| 100 | 30 | 85.8$^{a}$ | 15.5 | 24.4 | 99 | 23.2$^{a}$ | 3.3 | -7.6 | 77 | 2.2$^{a}$ | 0.6 | 1.9 | 154 |
| 100 | 100 | 69.0$^{a}$ | 6.9 | 0.0 | 99 | 25.1$^{a}$ | 2.7 | 0.0 | 108 | 2.1$^{a}$ | 0.2 | 0.0 | 108 |
| 400 | 5 | 42.5$^{a}$ | NA | -38.4 | NA | 32.1$^{a}$ | NA | 28.1 | NA | 4.0$^{a}$ | NA | 89.7 | NA |
| 400 | 10 | 56.4$^{a}$ | 10.7 | -18.2 | 27 | 11.9$^{a}$ | 1.7 | -52.5 | 20 | 1.5$^{a}$ | 0.7 | -30.5 | 67 |
| 400 | 20 | 65.0$^{a}$ | 16.8 | -5.7 | 58 | 20.2$^{a}$ | 4.7 | -19.3 | 52 | 2.6$^{a}$ | 0.7 | 21.6 | 59 |
| 400 | 30 | 90.8$^{a}$ | 15.7 | 31.7 | 46 | 19.1$^{a}$ | 3.5 | -23.8 | 49 | 2.0$^{a}$ | 0.3 | -4.2 | 36 |
| 400 | 100 | 69.0$^{a}$ | 7.2 | 0.0 | 52 | 25.1$^{a}$ | 2.7 | 0.0 | 53 | 2.1$^{a}$ | 0.2 | 0.0 | 55 |

Mean values followed by same letter in a column for each forest type are not significantly different ($p > 0.05$).
Smaller plots in TRF and MMF overestimate basal area.

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[i] Plot size ($m^2$): 25 → 5m x 5m; 50 → 10m x 5m; 100 → 10m x 10m; 400 → 20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

**Table 17: Systematic sampling along horizontal transect (SSH) outputs for basal area per hectare (m$^2$ha$^{-1}$) forest unit**

| Plot size (m$^2$)[i] | S.I.% [ii] | Tropical rain forest | | | | Moist montane forest | | | | Dry woodland forest | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | m$^2$ ha$^{-1}$ | | | | m$^2$ ha$^{-1}$ | | | | m$^2$ ha$^{-1}$ | | | |
| | | Mean | SE | Dev.%[iii] | *CV%* | Mean | SE | Dev.% | *CV%* | Mean | SE | Dev.% | *CV%* |
| 25 | 5 | 77.3$^{a}$ | 215.2 | 12.0 | 208 | 16.5$^{a}$ | 5.5 | -34.3 | 150 | 1.6$^{c}$ | 0.5 | -25.4 | 152 |
| 25 | 10 | 136.6$^{a}$ | 140.9 | 98.0 | 217 | 16.5$^{b}$ | 4.1 | -34.4 | 159 | 1.3$^{c}$ | 0.3 | -40.8 | 144 |
| 25 | 20 | 111.5$^{a}$ | 26.9 | 61.7 | 216 | 20.8$^{b}$ | 3.8 | -17.0 | 165 | 1.7$^{c}$ | 0.3 | -19.7 | 158 |
| 25 | 30 | 90.3$^{a}$ | 18.7 | 30.9 | 227 | 20.0$^{b}$ | 2.9 | -20.3 | 156 | 1.7$^{c}$ | 0.2 | -19.7 | 153 |
| 25 | 100 | 69.0$^{a}$ | 7.2 | 0.0 | 210 | 25.1$^{b}$ | 2.7 | 0.0 | 215 | 2.1$^{c}$ | 0.2 | 0.0 | 211 |
| 50 | 5 | 79.3$^{a}$ | 24.4 | 15.0 | 97 | 25.7$^{b}$ | 6.1 | 2.4 | 75 | 2.8$^{c}$ | 1.2 | 32.4 | 134 |
| 50 | 10 | 98.5$^{a}$ | 22.5 | 42.8 | 102 | 17.9$^{b}$ | 3.7 | -28.5 | 92 | 2.2$^{c}$ | 0.6 | 3.3 | 128 |
| 50 | 20 | 75.5$^{a}$ | 13.6 | 9.4 | 114 | 27.3$^{b}$ | 5.2 | 8.8 | 120 | 2.5$^{c}$ | 0.6 | 18.3 | 144 |
| 50 | 30 | 70.0$^{a}$ | 10.4 | 1.5 | 115 | 22.7$^{b}$ | 3.6 | -9.5 | 124 | 2.6$^{c}$ | 0.6 | 21.1 | 187 |
| 50 | 100 | 69.0$^{a}$ | 7.5 | 0.0 | 154 | 25.1$^{b}$ | 2.8 | 0.0 | 158 | 2.1$^{c}$ | 0.2 | 0.0 | 154 |
| 100 | 5 | 64.6$^{a}$ | 22.9 | -6.3 | 79 | 24.8$^{b}$ | 9.3 | -1.3 | 84 | 1.8$^{c}$ | 0.6 | -15.0 | 74 |
| 100 | 10 | 67.7$^{a}$ | 22.2 | -1.9 | 104 | 22.0$^{b}$ | 5.8 | -12.2 | 84 | 2.1$^{c}$ | 0.5 | -1.9 | 80 |
| 100 | 20 | 111.5$^{a}$ | 24.7 | 61.7 | 99 | 20.8$^{b}$ | 4.4 | -17.0 | 96 | 1.7$^{c}$ | 0.3 | -19.7 | 79 |
| 100 | 30 | 94.2$^{a}$ | 18.0 | 36.6 | 103 | 28.9$^{b}$ | 7.7 | 15.1 | 146 | 1.6$^{c}$ | 0.2 | -23.5 | 81 |
| 100 | 100 | 69.0$^{a}$ | 6.9 | 0.0 | 99 | 25.1$^{b}$ | 2.7 | 0.0 | 108 | 2.1$^{c}$ | 0.2 | 0.0 | 108 |
| 400 | 5 | 135.8$^{a}$ | NA | 96.9 | NA | 16.3$^{b}$ | NA | -34.9 | NA | 2.5$^{c}$ | NA | 15.0 | NA |
| 400 | 10 | 131.6$^{a}$ | 4.3 | 90.7 | 5 | 13.3$^{b}$ | 3.1 | -47.1 | 33 | 2.3$^{c}$ | 0.1 | 8.9 | 8 |
| 400 | 20 | 111.5$^{a}$ | 13.4 | 61.7 | 27 | 20.8$^{b}$ | 5.6 | -17.0 | 60 | 1.7$^{c}$ | 0.5 | -19.7 | 64 |
| 400 | 30 | 98.8$^{a}$ | 12.4 | 43.2 | 33.08 | 27.9$^{b}$ | 8.5 | 11.1 | 81 | 1.7$^{c}$ | 0.4 | -20.7 | 65 |
| 400 | 100 | 69.0$^{a}$ | 7.2 | 0.0 | 52 | 25.1$^{b}$ | 2.7 | 0.0 | 53 | 2.1$^{c}$ | 0.2 | 0.0 | 55 |

Mean values followed by same letter in a column for each forest typeare not significantly different ($p > 0.05$)
Smaller plots in TRF and MMF overestimate basal area.

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[i] Plot size (m$^2$): 25 →5m x 5m; 50 →10m x 5m; 100 →10m x 10m; 400 →20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

**Table 18: Systematic sampling along vertical transect (SSV) outputs for basal area per hectare ($m^2ha^{-1}$) forest unit**

| Plot size ($m^2$)[i] | S.I.% [ii] | Tropical rain forest | | | | Moist montane forest | | | | Dry woodland forest | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $m^2ha^{-1}$ | | | | $m^2ha^{-1}$ | | | | $m^2ha^{-1}$ | | | |
| | | Mean | SE | Dev.%[iii] | CV% | Mean | SE | Dev.% | CV% | Mean | SE | Dev.% | CV% |
| 25 | 5 | $102.6^{a}$ | 53.6 | 48.7 | 234 | $27.4^{b}$ | 7.3 | 9.2 | 119 | $1.4^{c}$ | 0.2 | -32.9 | 63 |
| 25 | 10 | $89.3^{a}$ | 30.1 | 29.5 | 213 | $28.1^{b}$ | 5.4 | 11.9 | 121 | $3.3^{c}$ | 1.5 | 56.3 | 288 |
| 25 | 20 | $73.9^{a}$ | 18.4 | 7.1 | 222 | $23.6^{b}$ | 3.3 | -5.9 | 126 | $2.9^{c}$ | 0.8 | 38.0 | 250 |
| 25 | 30 | $72.7^{a}$ | 15.5 | 5.4 | 234 | $22.8^{b}$ | 3.2 | -9.1 | 154 | $2.8^{c}$ | 0.6 | 31.0 | 235 |
| 25 | 100 | $69.0^{a}$ | 7.2 | 0.0 | 210 | $25.1^{b}$ | 2.7 | 0 | 215 | $2.1^{c}$ | 0.2 | 0.0 | 211 |
| 50 | 5 | $42.2^{a}$ | 20.3 | -38.9 | 152 | $16.8^{b}$ | 4.2 | -32.9 | 78 | $3.4^{c}$ | 1.3 | 60.1 | 117 |
| 50 | 10 | $72.4^{a}$ | 28.4 | 4.9 | 175 | $22.1^{b}$ | 4.9 | -11.8 | 100 | $2.4^{c}$ | 0.7 | 13.6 | 123 |
| 50 | 20 | $73.9^{a}$ | 18.4 | 7.1 | 158 | $23.6^{b}$ | 3.4 | -5.9 | 92 | $2.9^{c}$ | 0.8 | 38.0 | 174 |
| 50 | 30 | $71.7^{a}$ | 15.5 | 3.9 | 167 | $23.0^{b}$ | 3.1 | -8.5 | 106 | $2.7^{c}$ | 0.6 | 28.2 | 163 |
| 50 | 100 | $69.0^{a}$ | 7.5 | 0.0 | 154 | $25.1^{b}$ | 2.8 | 0 | 158 | $2.1^{c}$ | 0.2 | 0.0 | 154 |
| 100 | 5 | $52.9^{a}$ | 16.5 | -23.4 | 70 | $31.3^{b}$ | 9.2 | 24.9 | 66 | $3.3^{c}$ | 1.3 | 53.1 | 87 |
| 100 | 10 | $72.4^{a}$ | 35.7 | 4.9 | 156 | $22.1^{b}$ | 5.7 | -11.8 | 82 | $2.4^{c}$ | 0.7 | 13.6 | 89 |
| 100 | 20 | $73.9^{a}$ | 20.9 | 7.1 | 127 | $23.6^{b}$ | 3.9 | -5.9 | 74 | $2.9^{c}$ | 0.8 | 38.0 | 119 |
| 100 | 30 | $71.7^{a}$ | 16.4 | 3.9 | 125 | $23.0^{b}$ | 3.5 | -8.5 | 83 | $2.7^{c}$ | 0.6 | 28.2 | 112 |
| 100 | 100 | $69.0^{a}$ | 6.9 | 0.0 | 99 | $25.1^{b}$ | 2.7 | 0 | 108 | $2.1^{c}$ | 0.2 | 0.0 | 108 |
| 400 | 5 | $54.2^{a}$ | NA | -21.5 | NA | $11.8^{b}$ | NA | -52.8 | NA | $2.9^{c}$ | NA | 37.1 | NA |
| 400 | 10 | $52.4^{a}$ | 1.8 | -24.1 | 5 | $28.1^{b}$ | 7.2 | 11.9 | 36 | $1.9^{c}$ | 1.1 | -13.1 | 81 |
| 400 | 20 | $73.9^{a}$ | 22.8 | 7.1 | 69 | $23.6^{b}$ | 5.2 | -5.9 | 49 | $2.9^{c}$ | 0.6 | 38.0 | 48 |
| 400 | 30 | $68.9^{a}$ | 16.3 | -0.1 | 62 | $21.7^{b}$ | 3.9 | -13.5 | 48 | $2.7^{c}$ | 0.5 | 26.3 | 48 |
| 400 | 100 | $69.0^{a}$ | 6.6 | 0.0 | 48 | $25.1^{b}$ | 2.7 | 0 | 53 | $2.1^{c}$ | 0.2 | 0.0 | 55 |

Mean values followed by same letter in a column for each forest typeare not significantly different ($p > 0.05$)

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[i] Plot size ($m^2$): 25 → 5m x 5m; 50 → 10m x 5m; 100 → 10m x 10m; 400 → 20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

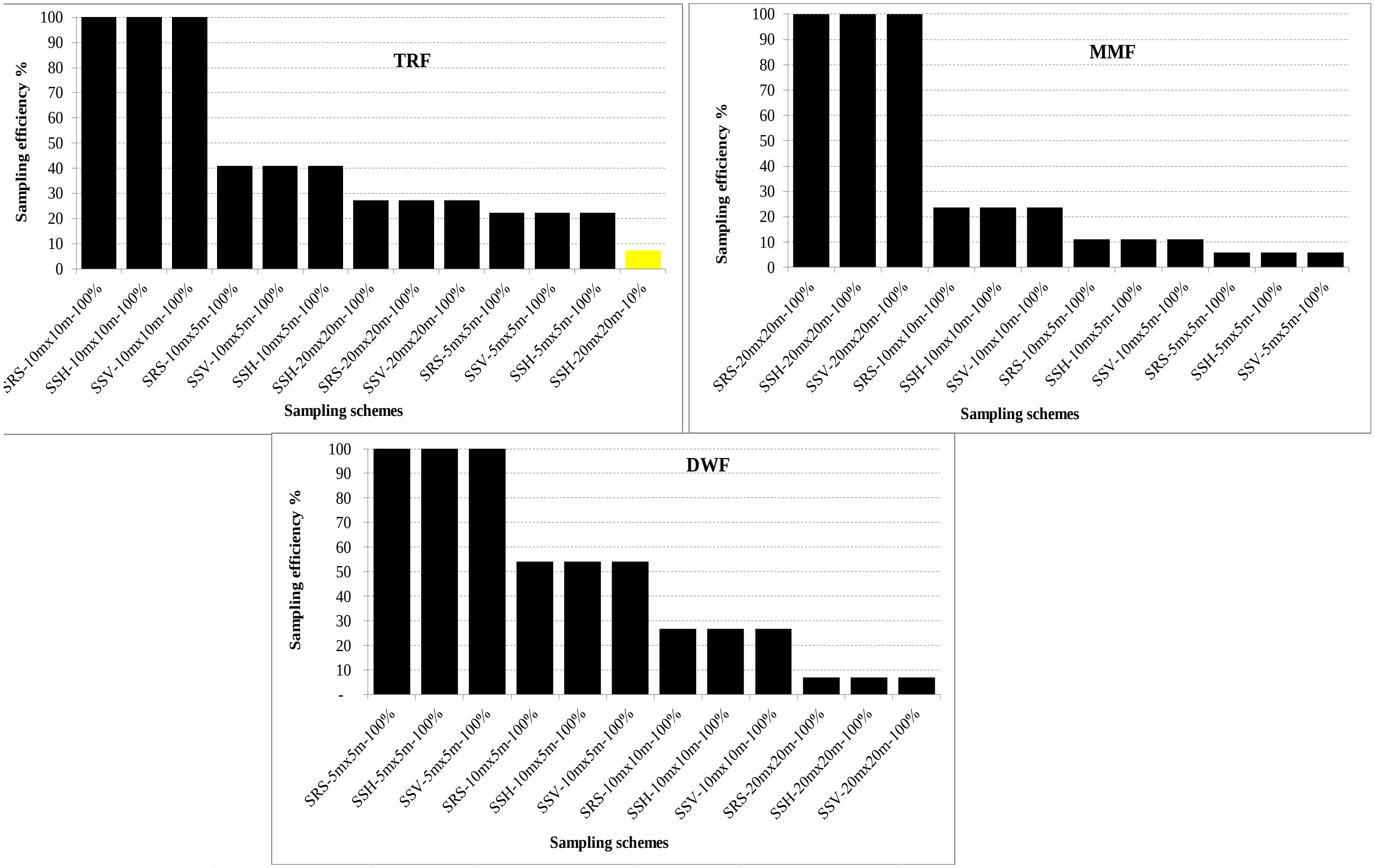

**Figure 26: Sampling schemes relative efficiency for forest basal area per hectare ($m^2ha^{-1}$) in tropical rain forest (TRF), moist montane forest (MMF) and Dry woodland (DWF), Kenya**

**Black bars** = complete inventory schemes (100% intensity);
**Yellow bar** = SSH sampling schemes with intensity < 100%;

**Table 19: Simple random sampling (SRS) outputs for quadratic mean diameter in different forest types**

| Plot size (m$^2$)[i] | S.I.% [ii] | Rainforest | | | | Moist forest | | | | Dry woodland | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Quadratic mean diameter (cm) | | | | Quadratic mean diameter (cm) | | | | Quadratic mean diameter (cm) | | | |
| | | Mean | SE | Dev.%[iii] | *CV%* | Mean | SE | Dev.% | *CV%* | Mean | SE | Dev.% | *CV%* |
| 25 | 5 | 15.5$^{a}$ | 2.7 | 11.7 | 77.1 | 13.5$^{a}$ | 2.6 | 3.8 | 87.4 | 4.0$^{a}$ | 0.4 | -1.7 | 50.5 |
| 25 | 10 | 13.0$^{a}$ | 1.9 | -6.2 | 93.3 | 13.6$^{a}$ | 1.9 | 4.0 | 87.3 | 5.2$^{a}$ | 0.5 | 29.2 | 59.8 |
| 25 | 20 | 15.5$^{a}$ | 2.1 | 11.7 | 118.5 | 12.1$^{a}$ | 1.0 | 7.6 | 76.3 | 4.9$^{a}$ | 0.5 | 22.1 | 96.4 |
| 25 | 30 | 15.9$^{a}$ | 1.6 | 14.5 | 109.9 | 12.9$^{a}$ | 1.0 | -1.3 | 88.1 | 4.2$^{a}$ | 0.3 | 2.9 | 76.4 |
| 25 | 100 | 13.9$^{a}$ | 0.7 | 0.0 | 101.9 | 13.0$^{a}$ | 0.6 | 0.0 | 88.6 | 4.0$^{a}$ | 0.1 | 0.0 | 70.0 |
| 50 | 5 | 15.7$^{ab}$ | 3.0 | 5.1 | 61.2 | 11.3$^{a}$ | 3.2 | -19.2 | 90.4 | 4.6$^{a}$ | 0.7 | 10.1 | 47.9 |
| 50 | 10 | 11.7$^{ab}$ | 1.6 | -21.7 | 61.9 | 14.5$^{a}$ | 2.3 | 4.1 | 69.5 | 3.5$^{a}$ | 0.2 | -16.2 | 28.1 |
| 50 | 20 | 15.1$^{ab}$ | 2.0 | 1.2 | 82.6 | 10.3$^{a}$ | 1.0 | -26.2 | 62.1 | 5.3$^{a}$ | 0.6 | 27.5 | 69.2 |
| 50 | 30 | 14.0$^{ab}$ | 1.1 | -5.8 | 61.2 | 13.4$^{a}$ | 1.0 | -4.1 | 59.4 | 4.6$^{a}$ | 0.3 | 9.4 | 57.1 |
| 50 | 100 | 14.9$^{ab}$ | 0.8 | 0.0 | 71.7 | 13.9$^{a}$ | 0.7 | 0.0 | 75.8 | 4.2$^{a}$ | 0.2 | 0.0 | 56.0 |
| 100 | 5 | 19.1$^{b}$ | 7.4 | 14.7 | 87.0 | 12.9$^{a}$ | 2.4 | -10.0 | 41.2 | 4.6$^{a}$ | 0.5 | 6.3 | 23.2 |
| 100 | 10 | 15.2$^{b}$ | 2.1 | -8.5 | 43.7 | 15.1$^{a}$ | 1.6 | 5.8 | 32.6 | 4.2$^{a}$ | 0.3 | -4.7 | 19.1 |
| 100 | 20 | 19.0$^{b}$ | 2.6 | 14.3 | 62.1 | 13.7$^{a}$ | 0.9 | -4.0 | 30.0 | 3.8$^{a}$ | 0.2 | -12.9 | 22.6 |
| 100 | 30 | 19.3$^{b}$ | 1.9 | 15.6 | 55.2 | 14.2$^{a}$ | 1.0 | -0.3 | 39.7 | 4.4$^{a}$ | 0.5 | 1.7 | 63.2 |
| 100 | 100 | 16.7$^{b}$ | 0.8 | 0.0 | 50.0 | 14.3$^{a}$ | 0.8 | 0.0 | 53.6 | 4.4$^{a}$ | 0.2 | 0.0 | 45.4 |
| 400 | 5 | 16.8$^{ab}$ | NA | -5.0 | NA | 22.3$^{a}$ | NA | 48.5 | NA | 6.5$^{a}$ | NA | 40.9 | NA |
| 400 | 10 | 16.2$^{ab}$ | 2.7 | -8.3 | 23.6 | 10.9$^{a}$ | 1.0 | -27.6 | 13.6 | 4.5$^{a}$ | 1.0 | -2.3 | 30.9 |
| 400 | 20 | 17.2$^{ab}$ | 2.5 | -2.6 | 32.4 | 12.4$^{a}$ | 0.6 | -17.2 | 11.6 | 5.6$^{a}$ | 0.9 | 21.0 | 34.4 |
| 400 | 30 | 20.4$^{ab}$ | 2.0 | 15.8 | 25.6 | 12.4$^{a}$ | 0.9 | -17.6 | 18.5 | 4.7$^{a}$ | 0.3 | 1.9 | 19.7 |
| 400 | 100 | 17.6$^{ab}$ | 0.8 | 0.0 | 23.7 | 15.0$^{a}$ | 1.0 | 0.0 | 33.9 | 4.6$^{a}$ | 0.3 | 0.0 | 30.2 |

Mean values followed by same letter in a column for each forest type are not significantly different ($p > 0.05$).

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[i] Plot size (m$^2$): 25 → 5m x 5m; 50 → 10m x 5m; 100 → 10m x 10m; 400 → 20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

**Table 20: Systematic sampling along horizontal transect (SSH) outputs for quadratic mean diameter in different forest types**

| Plot size $(m^2)$[i] | S.I.% [ii] | Rainforest | | | | Moist forest | | | | Dry woodland | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Quadratic mean diameter (cm) | | | | Quadratic mean diameter (cm) | | | | Quadratic mean diameter (cm) | | | |
| | | Mean | SE | Dev.%[iii] | *CV%* | Mean | SE | Dev.% | *CV%* | Mean | SE | Dev.% | *CV%* |
| 25 | 5 | $12.7^{a}$ | 2.8 | -8.8 | 100.6 | $9.1^{a}$ | 1.4 | -30.3 | 67.8 | $3.9^{a}$ | 0.5 | -3.4 | 51.6 |
| 25 | 10 | $16.4^{a}$ | 3.2 | 18.3 | 122.1 | $9.4^{a}$ | 1.1 | -27.9 | 75.6 | $3.5^{a}$ | 0.3 | -12.4 | 46.1 |
| 25 | 20 | $15.6^{a}$ | 2.0 | 12.0 | 112.2 | $11.0^{a}$ | 0.9 | -15.4 | 70.2 | $3.8^{a}$ | 0.2 | -5.6 | 48.3 |
| 25 | 30 | $14.6^{a}$ | 1.5 | 5.4 | 109.0 | $10.9^{a}$ | 0.7 | -16.6 | 67.6 | $3.9^{a}$ | 0.2 | -3.8 | 62.0 |
| 25 | 100 | $13.9^{a}$ | 0.7 | 0.0 | 101.9 | $13.0^{a}$ | 0.6 | 0.0 | 88.6 | $4.0^{a}$ | 0.1 | 0.0 | 70.0 |
| 50 | 5 | $16.6^{ab}$ | 3.0 | 11.4 | 56.6 | $16.6^{b}$ | 3.0 | 19.3 | 57.9 | $3.7^{a}$ | 0.6 | -11.3 | 53.5 |
| 50 | 10 | $17.8^{ab}$ | 2.3 | 19.5 | 56.7 | $13.6^{b}$ | 1.9 | -2.2 | 62.0 | $3.5^{a}$ | 0.4 | -15.7 | 47.2 |
| 50 | 20 | $17.7^{ab}$ | 2.8 | 18.9 | 98.6 | $14.3^{b}$ | 1.4 | 2.6 | 62.7 | $3.9^{a}$ | 0.3 | -6.6 | 54.1 |
| 50 | 30 | $16.3^{ab}$ | 1.9 | 9.4 | 91.3 | $13.0^{b}$ | 1.0 | -6.6 | 61.9 | $4.1^{a}$ | 0.4 | -1.5 | 74.5 |
| 50 | 100 | $14.9^{ab}$ | 0.8 | 0.0 | 71.7 | $13.9^{b}$ | 0.7 | 0.0 | 75.8 | $4.2^{a}$ | 0.2 | 0.0 | 56.0 |
| 100 | 5 | $16.2^{b}$ | 4.0 | -2.8 | 55.3 | $13.4^{ab}$ | 1.9 | -6.2 | 32.4 | $3.9^{a}$ | 0.4 | -9.5 | 25.5 |
| 100 | 10 | $15.5^{b}$ | 2.8 | -6.9 | 57.2 | $12.8^{ab}$ | 1.4 | -10.2 | 35.7 | $4.8^{a}$ | 0.5 | 9.8 | 35.8 |
| 100 | 20 | $20.6^{b}$ | 3.1 | 23.5 | 67.7 | $11.9^{ab}$ | 1.1 | -16.4 | 41.3 | $4.1^{a}$ | 0.3 | -4.8 | 36.6 |
| 100 | 30 | $19.4^{b}$ | 2.2 | 16.3 | 62.0 | $13.9^{ab}$ | 1.8 | -2.8 | 71.8 | $4.1^{a}$ | 0.3 | -6.8 | 34.2 |
| 100 | 100 | $16.7^{b}$ | 0.8 | 0.0 | 50.0 | $14.3^{ab}$ | 0.8 | 0.0 | 53.6 | $4.4^{a}$ | 0.2 | 0.0 | 45.4 |
| 400 | 5 | $22.6^{ab}$ | NA | 0.0 | NA | $12.4^{ab}$ | NA | -17.2 | NA | $3.2^{a}$ | NA | -30.0 | NA |
| 400 | 10 | $24.5^{ab}$ | 2.0 | 39.1 | 11.5 | $11.1^{ab}$ | 1.3 | -25.9 | 16.6 | $3.4^{a}$ | 0.1 | -26.8 | 6.1 |
| 400 | 20 | $22.6^{ab}$ | 2.1 | 28.0 | 21.1 | $12.6^{ab}$ | 1.2 | -16.1 | 21.3 | $4.1^{a}$ | 0.6 | -10.3 | 33.2 |
| 400 | 30 | $21.1^{ab}$ | 1.8 | 19.5 | 22.1 | $15.3^{ab}$ | 2.7 | 2.0 | 47.5 | $4.0^{a}$ | 0.4 | -12.4 | 29.3 |
| 400 | 100 | $17.6^{ab}$ | 0.8 | 0.0 | 23.7 | $15.0^{ab}$ | 1.0 | 0.0 | 58.0 | $4.6^{a}$ | 0.3 | 0.0 | 30.2 |

Mean values followed by same letter in a column for each forest typeare not significantly different ($p > 0.05$)

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[i] Plot size ($m^2$): 25 → 5m x 5m; 50 → 10m x 5m; 100 → 10m x 10m; 400 → 20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

**Table 21: Systematic sampling along vertical transect (SSV) outputs for quadratic mean diameter in different forest types**

| Plot size $(m^2)$[i] | S.I.% [ii] | Rainforest | | | | Moist forest | | | | Dry woodland | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Quadratic mean diameter (cm) | | | | Quadratic mean diameter (cm) | | | | Quadratic mean diameter (cm) | | | |
| | | Mean | SE | Dev.%[iii] | *CV%* | Mean | SE | Dev.% | *CV%* | Mean | SE | Dev.% | *CV%* |
| 25 | 5 | $14.5^{a}$ | 3.7 | 4.7 | 113.0 | $12.6^{a}$ | 2.2 | -3.3 | 76.3 | $3.9^{ab}$ | 0.3 | -4.2 | 34.2 |
| 25 | 10 | $13.4^{a}$ | 2.3 | -3.2 | 110.3 | $13.9^{a}$ | 1.7 | 6.4 | 78.4 | $5.0^{ab}$ | 0.8 | 22.8 | 96.9 |
| 25 | 20 | $12.6^{a}$ | 1.5 | -9.4 | 107.3 | $13.2^{a}$ | 1.1 | 1.5 | 75.6 | $4.9^{a}$ | 0.4 | 21.4 | 75.5 |
| 25 | 30 | $12.8^{a}$ | 1.2 | -8.1 | 106.4 | $12.4^{a}$ | 0.9 | -4.7 | 81.7 | $4.8^{a}$ | 0.3 | 19.6 | 72.7 |
| 25 | 100 | $13.9^{a}$ | 0.7 | 0.0 | 101.9 | $13.0^{a}$ | 0.6 | 0.0 | 88.6 | $4.0^{b}$ | 0.1 | 0.0 | 70.0 |
| 50 | 5 | $12.2^{ab}$ | 2.7 | -18.4 | 69.8 | $15.5^{a}$ | 2.9 | 11.4 | 59.6 | $5.4^{ab}$ | 0.7 | 29.4 | 43.9 |
| 50 | 10 | $14.3^{ab}$ | 2.5 | -4.1 | 77.1 | $14.3^{a}$ | 1.8 | 2.8 | 57.5 | $4.5^{ab}$ | 0.4 | 9.0 | 43.0 |
| 50 | 20 | $13.5^{ab}$ | 1.7 | -9.4 | 78.7 | $14.2^{a}$ | 1.3 | 1.6 | 58.1 | $5.0^{a}$ | 0.5 | 20.4 | 64.0 |
| 50 | 30 | $14.2^{ab}$ | 1.5 | -4.5 | 80.6 | $13.4^{a}$ | 1.1 | -3.9 | 60.8 | $5.0^{a}$ | 0.4 | 18.9 | 60.3 |
| 50 | 100 | $14.9^{ab}$ | 0.8 | 0.0 | 71.7 | $13.9^{a}$ | 0.7 | 0.0 | 75.8 | $4.2^{b}$ | 0.2 | 0.0 | 56.0 |
| 100 | 5 | $15.9^{b}$ | 3.2 | -4.7 | 44.5 | $15.9^{a}$ | 2.7 | 11.1 | 38.1 | $5.4^{ab}$ | 0.8 | 25.1 | 34.6 |
| 100 | 10 | $14.9^{b}$ | 3.3 | -10.3 | 69.1 | $13.8^{a}$ | 1.7 | -3.1 | 37.8 | $4.7^{ab}$ | 0.5 | 7.6 | 32.9 |
| 100 | 20 | $14.9^{b}$ | 2.0 | -10.6 | 60.3 | $13.7^{a}$ | 1.1 | -4.0 | 34.6 | $5.4^{a}$ | 0.7 | 23.3 | 55.9 |
| 100 | 30 | $15.7^{b}$ | 1.8 | -6.0 | 62.2 | $13.4^{a}$ | 1.1 | -6.3 | 43.3 | $5.3^{a}$ | 0.5 | 21.1 | 49.2 |
| 100 | 100 | $16.7^{b}$ | 0.8 | 0.0 | 50.0 | $14.3^{a}$ | 0.8 | 0.0 | 53.6 | $4.4^{b}$ | 0.2 | 0.0 | 45.4 |
| 400 | 5 | $17.3^{a}$ | NA | -1.9 | NA | $12.9^{a}$ | NA | -13.7 | NA | $4.8^{ab}$ | NA | 4.1 | NA |
| 400 | 10 | $16.5^{a}$ | 0.8 | -6.6 | 7.1 | $15.6^{a}$ | 3.5 | 4.4 | 31.6 | $5.6^{ab}$ | 0.8 | 21.9 | 20.7 |
| 400 | 20 | $17.0^{a}$ | 1.9 | -3.5 | 24.9 | $13.9^{a}$ | 1.5 | -7.0 | 24.7 | $5.8^{a}$ | 0.8 | 25.0 | 31.6 |
| 400 | 30 | $16.4^{a}$ | 1.4 | -6.9 | 22.5 | $13.2^{a}$ | 1.2 | -12.3 | 24.7 | $5.4^{a}$ | 0.6 | 17.8 | 29.8 |
| 400 | 100 | $17.6^{a}$ | 0.8 | 0.0 | 23.7 | $15.0^{a}$ | 1.0 | 0.0 | 33.9 | $4.6^{b}$ | 0.3 | 0.0 | 30.2 |

Mean values followed by same letter in a column for each forest type are not significantly different ($p > 0.05$)

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[i] Plot size $(m^2)$: 25 → 5m x 5m; 50 → 10m x 5m; 100 → 10m x 10m; 400 → 20 m x 20 m

[ii] S.I. %= Sampling Intensity in percentage = 100 x no, of plots making the sample / total number of such plots over the 1 hectare forest

[iii] Dev.% = 100 x (Sample statistic – Population parameter)/population parameter

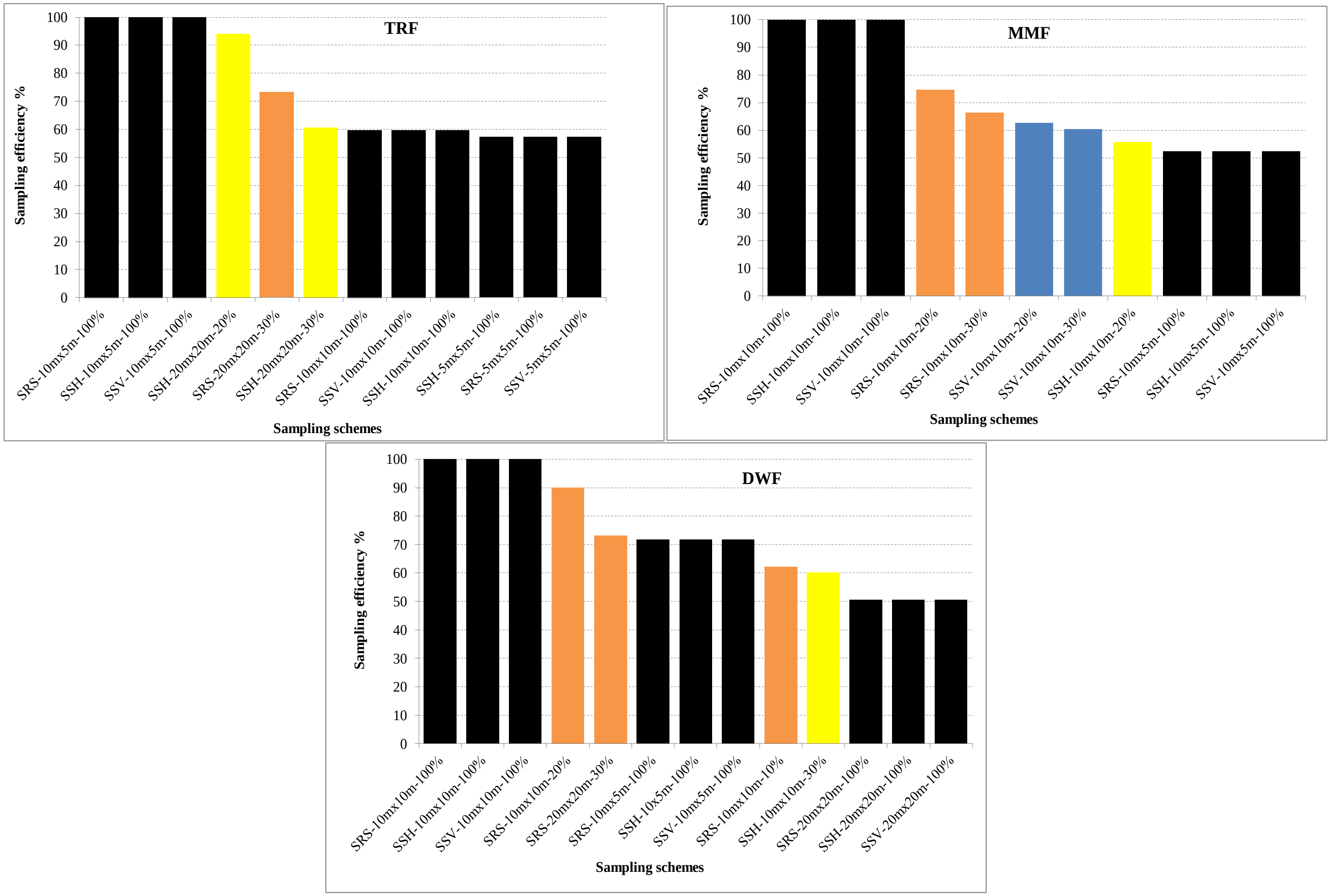

**Figure 27: Sampling schemes for quadratic mean diameter of trees in tropical rain forest (TRF), moist montane forest (MMF) and dry woodland (DWF)**

**Black bars** = complete inventory schemes (100% intensity);
**Orange bars** = SRS sampling schemes with intensity < 100%;
**Yellow bars** = SSH sampling schemes with intensity < 100%;
**Blue bars** = SSV sampling schemes with intensity < 100%.

### 4.3.6 Influence of Slope Gradient on Sampling Schemes' Efficiency for Forest Attributes

Slope gradient was pronounced in the Mt Elgon moist montane forest with an average of 9.5; and a range of 8 to 16 %. Data from this forest were organised following the slope gradient and used to test the effect of diagonal transects on the efficiency of forest sampling schemes for regeneration, density and basal area (Table 22). Among the three attributes, regeneration count was the most sensitive stage and attribute in the moist montane forest with reference to slope gradient.

***Sampling scheme for the number of seedlings per hectare***

For regeneration, diagonal sampling design (SSD) differed with horizontal sampling for tested intensities of 10% and 20% ($p < 0.05$) but did not significantly differ from other designs at 30% intensity, regardless of plot sizes. In this case, horizontal transect-based schemes underestimated the regeneration density for plot size of 5 m x 5 m, which is the optimal plot size for regeneration. It is prudent to use intensity of at least 30% when small plot sizes are applied along horizontal transect in the montane forest to assess regeneration. With larger plot sizes, a 10% intensity was adequate along transects facing any direction. Although many sampling schemes were found to give sufficiently accurate estimates of assessed quantities (Table 22), efficiency index was used to rank and filter out the most efficient inventory schemes. Both plot sizes and sampling intensities contributed to efficiency of each scheme. With lowest acceptable relative efficiency index value set at 50%, two sampling schemes (SSD-10mx10m-30% and SSD-10mx10m-20%) emerged useful, and both are made of plots arranged along the diagonal transect, where transect line intersects the slope gradient diagonally (Figure 7 & Figure 28).

**Table 22: Estimates for forest attributes through systematic sampling along diagonal transect in Mt Elgon forest**

|  |  |  | SSD |  | SSH |  | SSV |  |  |
|---|---|---|---|---|---|---|---|---|---|
| Attributes | Plot (m$^2$) | S.I.% | Mean | SE | Mean | SE | Mean | SE | 95% CI for μ |
| Regeneration | 25 | 10 | 8217$^{a}$ | 1765 | 3100$^{b}$ | 498 | 6650$^{ab}$ | 1392 | 5354 – 7204 |
|  |  | 20 | 7753$^{a}$ | 1280 | 4005$^{b}$ | 600 | 7100$^{ab}$ | 1087 |  |
|  |  | 30 | 7259$^{ab}$ | 1008 | 5590$^{b}$ | 940 | 8493$^{a}$ | 1167 |  |
|  | 50 | 10 | 8259$^{a}$ | 1556 | 5610$^{b}$ | 1075 | 6270$^{ab}$ | 1645 | 5299-7259 |
|  |  | 20 | 8463$^{a}$ | 1532 | 5855$^{b}$ | 969 | 7100$^{ab}$ | 1222 |  |
|  |  | 30 | 7280$^{ab}$ | 1198 | 6367$^{b}$ | 886 | 8833$^{a}$ | 1299 |  |
|  | 100 | 10 | 7322$^{a}$ | 2892 | 3670$^{b}$ | 942 | 6270$^{ab}$ | 1660 | 5158-7400 |
|  |  | 20 | 6767$^{a}$ | 1547 | 4005$^{b}$ | 665 | 7100$^{ab}$ | 1503 |  |
|  |  | 30 | 7633$^{ab}$ | 1287 | 4797$^{b}$ | 791 | 8833$^{a}$ | 1492 |  |
| Forest density | 25 | 10 | 1474$^{a}$ | 202 | 1610$^{a}$ | 198 | 1630$^{a}$ | 164 | 1328-1536 |
|  |  | 20 | 1367$^{a}$ | 146 | 1515$^{a}$ | 128 | 1490$^{a}$ | 106 |  |
|  |  | 30 | 1429$^{a}$ | 125 | 1537$^{a}$ | 103 | 1510$^{a}$ | 99 |  |
|  | 50 | 10 | 8259$^{a}$ | 1556 | 5610$^{a}$ | 1075 | 6270$^{a}$ | 1645 | 1324-1540 |
|  |  | 20 | 1566$^{a}$ | 128 | 1265$^{a}$ | 127 | 1490$^{a}$ | 109 |  |
|  |  | 30 | 1513$^{a}$ | 106 | 1353$^{a}$ | 98 | 1477$^{a}$ | 97 |  |
|  | 100 | 10 | 7322$^{a}$ | 2892 | 3670$^{a}$ | 942 | 6270$^{a}$ | 1660 | 1318-1546 |
|  |  | 20 | 1506$^{a}$ | 136 | 1515$^{a}$ | 115 | 1490$^{a}$ | 103 |  |
|  |  | 30 | 1463$^{a}$ | 105 | 1533$^{a}$ | 104 | 1477$^{a}$ | 103 |  |
| Basal area | 25 | 10 | 21.73$^{a}$ | 5.07 | 16.46$^{a}$ | 4.15 | 28.07$^{a}$ | 5.37 | 19.79-30.37 |
|  |  | 20 | 19.29$^{a}$ | 3.62 | 20.81$^{a}$ | 3.85 | 23.59$^{a}$ | 3.32 |  |
|  |  | 30 | 17.74$^{a}$ | 2.82 | 19.98$^{a}$ | 2.85 | 22.79$^{a}$ | 3.2 |  |
|  | 50 | 10 | 29.19$^{a}$ | 4.7 | 17.92$^{a}$ | 3.69 | 22.12$^{a}$ | 4.93 | 19.59-30.57 |
|  |  | 20 | 25.03$^{a}$ | 3.53 | 27.29$^{a}$ | 5.19 | 23.59$^{a}$ | 3.44 |  |
|  |  | 30 | 22.58$^{a}$ | 2.87 | 22.69$^{a}$ | 3.63 | 22.95$^{a}$ | 3.14 |  |
|  | 100 | 10 | 26.84$^{a}$ | 6.96 | 22.01$^{a}$ | 5.84 | 22.12$^{a}$ | 5.72 | 19.19-30.37 |
|  |  | 20 | 23.72$^{a}$ | 4.05 | 20.81$^{a}$ | 4.45 | 23.59$^{a}$ | 3.88 |  |
|  |  | 30 | 25.02$^{a}$ | 3.07 | 28.87$^{a}$ | 7.72 | 22.95$^{a}$ | 3.46 |  |

Mean values followed by same letter for each variable are not significantly different ($p > 0.05$)

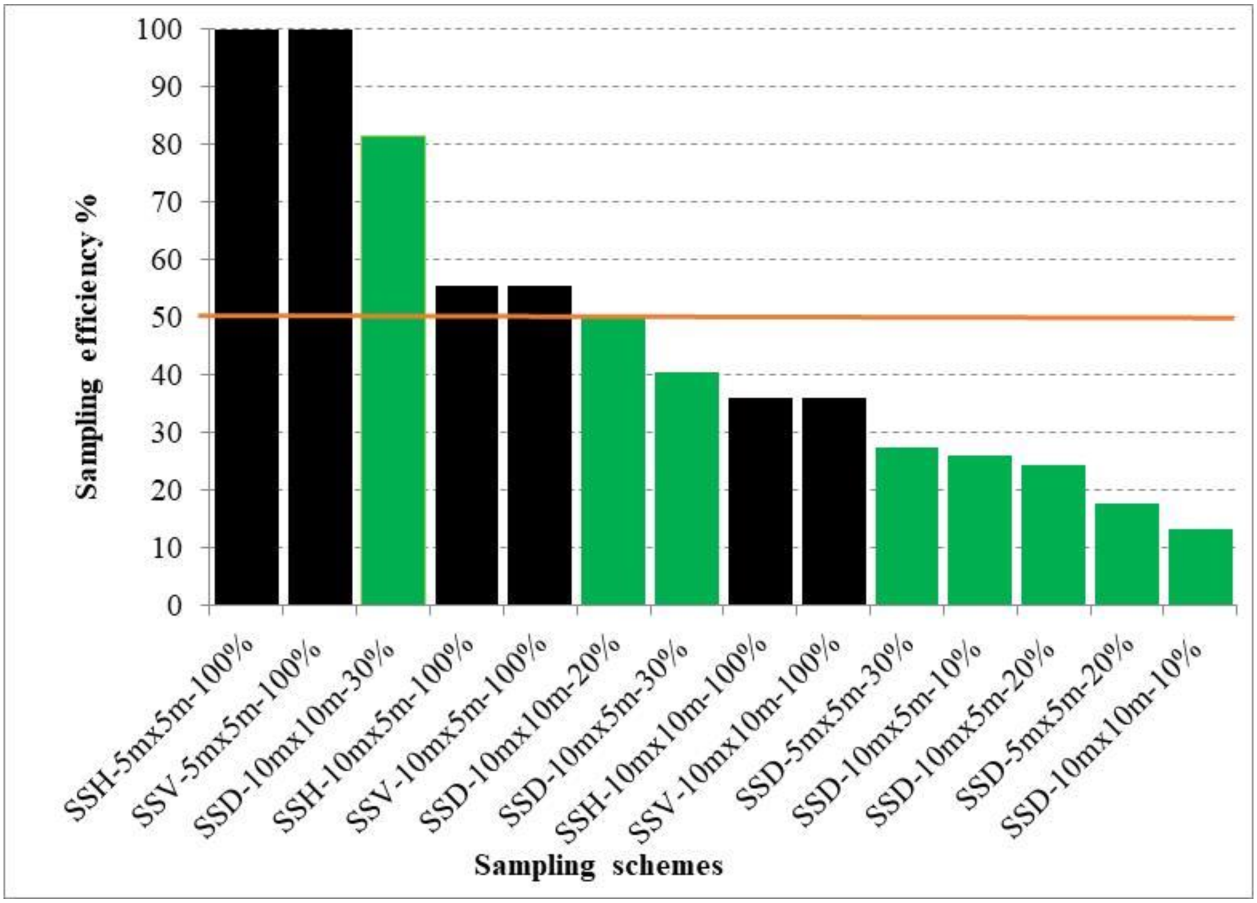

**Figure 28: Efficiency of sampling schemes for number of seedlings per hectare on slope**

**Black bars** = complete inventory schemes (100% intensity);
**Green bars** = SSD sampling schemes with intensity < 100%;

Optimum plot size was 10 m x 10 m along the diagonal transect, with a sampling intensity of ideally 30 % (but can be at least 20%), translating into a minimum sample size of 30 plots or at least 20 plots). The other sampling schemes reported in Figure 28 are accurate (and are all along diagonal transect) but not efficient. Where complete inventory of a hectare is undertaken, 5 m x 5 m small plot size should be adopted along belt transect facing any direction. This plot size minimizes sampling error and perhaps the magnitude of plot edge effect errors for seedlings.

In terms of choice of type of transect, it was observed that only sampling along diagonal was efficient as compared to vertically and horizontally oriented belt transects. Diagonal transect is the only effective sampling design on the sloping terrain in the moist montane forest (MMF); but it must be accompanied by careful selection of plot size and intensity.

### ***Sampling schemes for forest density in stems per hectare***

Findings in Table 22 indicate that neither forest density nor basal area estimates, was influenced by plot sizes in the moist montane forest. However, sampling intensity as small as 10% resulted in overestimation of tree density for all plot sizes; and should be avoided. Results in Figure 29 confirms the same by revealing a long list of accurate inventory schemes along the three transect types (horizontal – yellow colour; vertical – blue colour; diagonal – green colour; complete inventory – black colour). Based on relative efficiency index value and the critical level of 50%, all the four inventory schemes were represented. However, to optimize efficiency level, adequate adoption of sampling intensity and plot size must be realized. In terms of relative efficiency of inventory schemes, optimum plot size and sampling intensity for stem density per hectare, small plot sizes (5 m x 5 m or 10 m x 5 m) are most efficient along vertical or horizontal transects, up to a sample size of at least 1 ha. As plot size increases, efficiency (and reliability) of the design declines. There were more alternative efficient sampling schemes for inventory of stems per hectare than for regeneration (seedlings) (Figure 29).

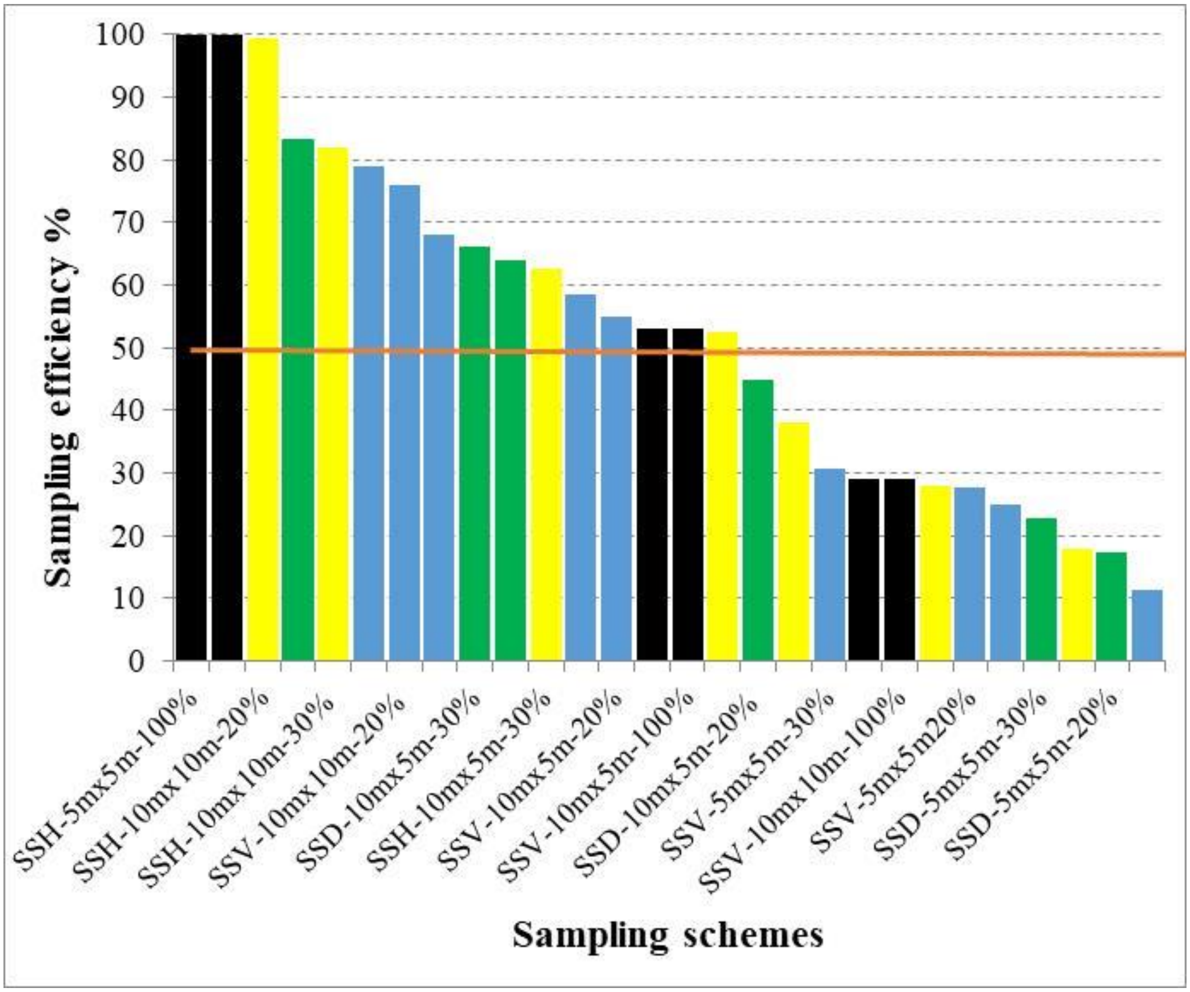

**Figure 29: Forest density (stems /ha) assessment on the gentle slope of montane forest**

**Black bars** = complete inventory schemes (100% intensity);
**Yellow bars** = SSH sampling schemes with intensity < 100%;
**Green bars** = SSD sampling schemes with intensity < 100%;
**Blue bars** = SSV sampling schemes with intensity < 100%

### *Basal area per hectare*

From Table 22, basal area estimates in moist montane forest were not significantly different among sampling designs, plot sizes and sampling intensities. Results in Figure 30, however, show that only complete inventory schemes per hectare are the only ones reliable based relative efficiency index values for different sampling schemes at a critical level of 50% relative efficiency. Large plot size of 20 m x 20 m along any transect direction was the most efficient in comparison with smaller ones that were tested. The smaller the plot size, the less efficient is the inventory design for basal area in the montane forest. This is the opposite requirement of plot size effect for assessment of regeneration. Complete inventory schemes with smaller plot sizes were associated with efficiency below 50%. Where complete inventory over one hectare is not practical, the best option is to adopt diagonally oriented transect with 30% sampling intensity of 10 m x 10 m plot size; however relative efficiency would be below 50%. No sampling intensity less than 100 % is reliable enough. This is an indication of high variability of basal area within the forest.

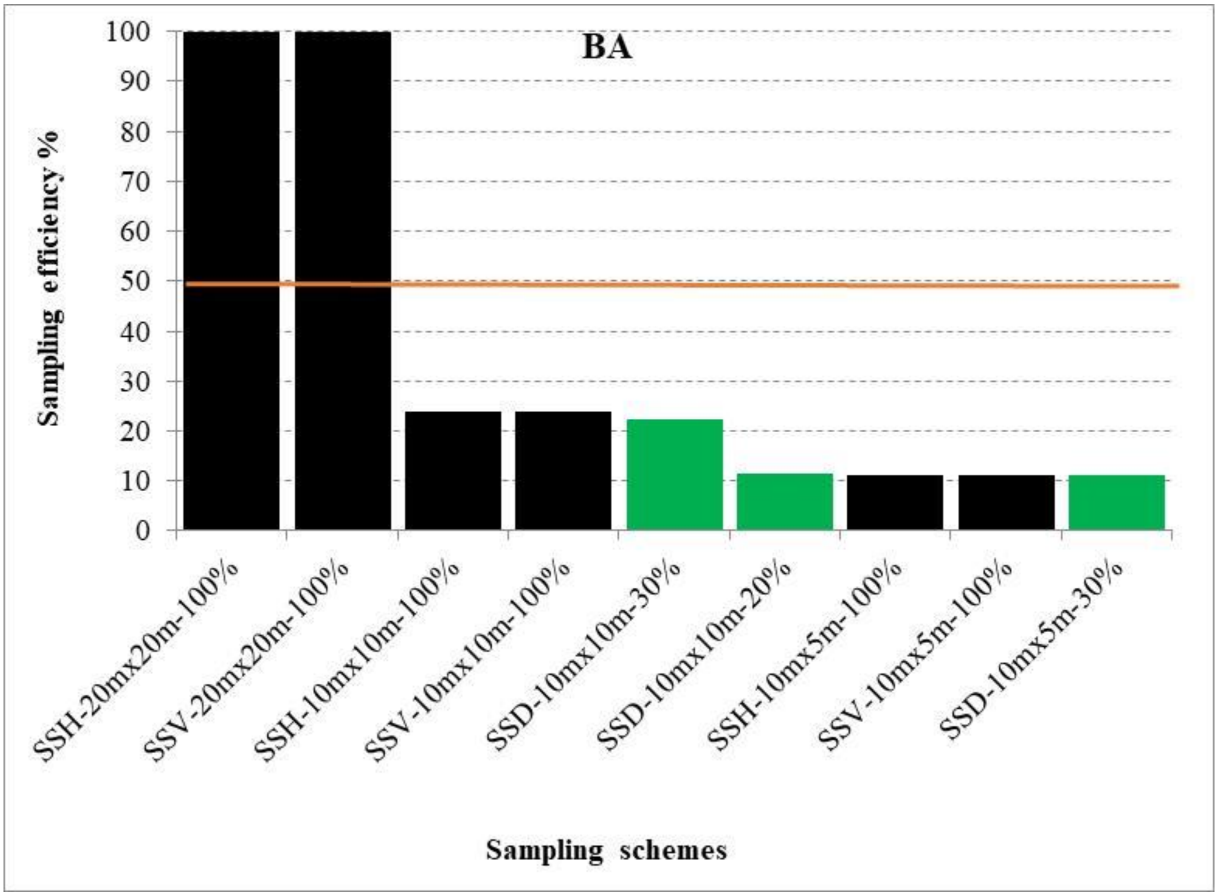

**Figure 30: Basal area assessment on slope in montane forest**

**Black bars** = complete inventory schemes (100% intensity);
**Green bars** = SSD sampling schemes with intensity < 100%;

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# CHAPTER FIVE

# DISCUSSION

## 5.1 General Context

Data used to test the performance of different sampling designs, intensities and plot sizes were collected from three distinct sites, that mimic a climate gradient from low rainfall dry zone (Loruk woodland, 629 mm yr$^{-1}$) to high rainfall humid zone (Kakamega rainforest; 1971 mm yr$^{-1}$) through the intermediate moist zone (Mt Elgon forest, 1541mm yr$^{-1}$). These forest sites also differed in altitude from 987 m a.s.l. at Loruk to 2000-2060 m at Mt. Elgon through 1580 m a.s.l. at Kakamega. Loruk is community-owned and under silvopastoral land use system. Kakamega snd Mt Elgon are protected state-owned forests adjacent to densely populated human settlements and farming activities. Communities around Mt Elgon forest practice mixed livestock rearing and crop farming system. The three sites represent different ecological, climatic and socio-economic complexity of natural forest resources in Kenya. Many factors, biotic or abiotic, affect the composition, structure and dynamics of the above forests and woodlands (Hitimana et al. 2004; Hitimana et al., 2010; Kiruki et al., 2017; Schwartz & Caro, 2003). Abiotic factors such as soil, topography, precipitation, temperature and drought not only influence plant species composition (Randriamalala, Radosy, Razanaka, Randriambanona & Harve, 2016), but also determine regeneration success including seeding, seed germination, tree seedling establishment and early sapling survival and growth (Principe et al., 2014).

Sampling effort was measured in time spent on making observations and measurements on a plot and influenced efficiency of sampling schemes. This surrogate of sampling cost is critical in measuring sampling efficiency in the tropics (Klauberg et al., 2016; Muchiri et al., 2016). The design of any plot network needs to balance cost with being representative of the conditions intended to be considered in the model (Weiskittel et al., 2011). The sampling effort was measured and determined for each sampling scheme (Appendix VI). Time spent in collecting data over one hectare compared well with findings from a recent pilot inventory study in Kenya (Nduati et al., 2016) but higher than the documented sampling effort per hectare in Amazon forest (Holmes et al., 2002; Klauberg et al., 2016).

## 5.2 Forest Vertical and Canopy Structure across Forest Types

Small plot size of 5 m x 5 m produced a more detail and realistic description of canopy height structure in all the three forest types than larger plots. The top canopy height structure was best described using data from 5 m x 5 m plots than the use of larger plots such as 20 m x 20 m. It was found that TRF and MMF were much similar in terms of height and percentage canopy gaps but not so for screening efficiency and number of canopy layers (Figure 16). Both the tropical rain forest and the moist montane forest were multi-layered almost in equal measure in contrast to the tropical dry woodland forest in which only 2 to 3 layers are distinguishable. TRF canopy layers were more differentiated and distinctly visible than in other forest types (Figures 13a-b). The characteristic of canopy stratification in the montane forest was typical of a forest ecosystem in the building phase, recovering form historical disturbances (Hitimana et al., 2004). This study confirmed that tropical rain forest trees were much taller than those in montane forest but percent Brokaw canopy gaps was small in both forests. Screening efficiency (i.e. shading conditions of the undergrowth by canopy foliage) was highest in tropical rainforest, perhaps due to different types of species and density levels. The undergrowth in montane forest potentially received more light than in the tropical rain forest. Dry woodland forest canopy was most porous to light penetration among the three forest types. Highest percentage gaps in Loruk woodland may be a result of harsh climatic conditions and/or animal disturbance through grazing in this pastoralism-dominated region. Grazing influences species composition and ecosystem functioning by removing species from important functional groups (Neil, Raymond & Philip, 1995). Grazing may also prevent young seedlings from reaching mature stages, changes morphology of individual trees by turning single stem into multi-stemmed individual and cause death through trampling and uprooting (Eshete, Sterck, Teketay & Bongers, 2009; Zida, Sawadogo, Tigabu, Tiveau & Odena, 2007). Continuous intensive grazing also accelerates soil compaction and erosion leading to site degradation (Eshete et al., 2009). Overall, the TRF was found to be more complex and diverse than the moist montane and dry woodland forest types; with DWF being the simplest and perhaps most vulnerable ecosystem among them.

## 5.3 Forest Composition and Taxonomic Balance

The type and number of tree species, genera and families varied among the three forest types (Figure 9; Appendix X). The balance in taxonomic composition for the various forest types was determined by family – genera – species ratios (Figure 10). In terms of species richness and number of genera per hectare, tropical rainforest was more diverse than moist lower montane forest; and dry woodland forest was the least diverse. Comparison based on tree families reflected less the differences in species diversity among the forest types. The similarity level between forest types varied with different taxa, for both Jaccard and Sorensen indices. However, for all cases, the dry woodland forest was the most dissimilar to other forest types. At DWF, the dominant species were *Acacia reficiens* and *A. mellifera* which, according to (Snelder, 1994), are positive indicators of intensive grazing. *A. reficiens* is known to be an indication of heavily grazed and exhausted woodland (Kiyiapi, 1994). Based on both Jaccard and Sorensen similarity indices, similarity in tree composition between Kakamega tropical rainforest and Mt Elgon moist montane forests is high at family level, moderate at genera level and low at species level (Figures 11a, b, c).

## 5.4 Species Dominance and Diversity

Species relative dominance structure was much similar across the forest types. Maximum richness was highest in TRF, intermediate in montane forest and lowest in dry woodland forest (Table 8). Species evenness was also highest in TRF, intermediate in MMF and lowest in DWF. The species diversity level was influenced more by the number of species in the forest than evenness. Based on Magurran (1988)'s expected Shannon species diversity index values (1.5 to 4.5), the diversity was above average at TRF, within average range at MMF and below average at DWF. Species diversity and species richness index relationship was found to be stronger in comparison with the influence of evenness. The number of species was therefore found to be a good indicator of species diversity across the three forest types; and can reliably be applied as a positive indicator of levels of tree species diversity in biodiversity studies [through species presence /absence records]. Rapid assessment of tree species diversity in studied forests can be achieved using species richness. The three forest types differed in number of species, types of species but were much similar in species evenness and species relative dominance.

Tree species diversity in DWF (Shannon index =1.69) compared well with other woodlands e.g. Kitui dry bushland and thickets (Shannon index between 1.33 and 1.65) (Kiruki et al., 2017). However, in Kitui, 10 species accounted for 84% of woody plants compared to only three species that make 75% of the recorded individuals per ha in DWF. The findings reveal that the dry woodland was equally important in supporting a number of tree species, and share some taxonomic groups (genera and families) with tropical rainforests and moist montane forests. Species diversity being significantly different among the studied forest types ($p < 0.05$; Table 8), it is also observed that species richness is a perfect mirror of overall species diversity. This is because equity (evenness) of individual among observed species varied relatively less between the forest types as compared to variation in species richness. Species richness being easiest to measure is subsequently adequate to compare and rank the forest types in terms of diversity of woody vegetation. This is also an indicatiion that tree species diversity in tropical natural forests can be approximated based on species presence / absence binary data records

## 5.5 Forest Regeneration, Recruitment And Structural Stability

### 5.5.1 Regeneration and Recruitment

Seedlings and saplings, respectively, contributed over 80% and 8% to overall forest density in both TRF and MMF (Figures 17a, b). The ratio was exceptionally different in the dry woodland forest where seedlings contributed 48% and saplings 40 % of total density. Apparently, the current seedling stage was very deficient. In terms of regeneration and recruitment process, TRF was the most prolific, populated and balanced than MMF and DWF. Within the dry woodland forest, large trees (≥5 cm dbh) contributed 12 % of total density; the highest percentage as compared to tropical rain forest (5 %) and moist montane forest (2 %).

The recruitment process of individuals into the different development stages was only regular (balanced) in TRF for trees sized up to about 110 cm dbh. MMF was extremely deficient in tree size categories between 50 and 70 cm DBH classes. Past heavy logging activities at Mt

Elgon site (Hitimana et al., 2004) might have mostly affected trees which distorted the structural balance of tree diameter size distribution for trees with DBH ≥50 cm; causing drastic departure from the balanced trend observed in Kakamega tropical rain forest site. A balanced diameter distribution (i.e. regular regeneration and recruitment) is characterised by constant “q” value across different diameter categories. Graphically, q values are drawn against diameter class midpoints, and regular recruitment patterns over time are expected to follow a straight line. The results on “q” ratio (Figure 18) reveal that recruitment process fluactuated and therefore not regular in all the forests. Historical selective logging in Kakamega rainforest (Mutiso et al., 2013) and Mt Elgon forest (Hitimana, 2000; Hitimana et al., 2004; Hitimana et al., 2010) are the likely factors that distorted recruitment patterns in these two ecosystems. Factors that affect seedlings and saplings in the dry woodland, e.g. sporadic rainfall, shaped the pattern of “q” ratio graph which characterizes cohorting in the regeneration process over time.

Narrower range of dbh classes were observed in the DWF which suggest, not withstanding environmental and ecological constraints to tree growth on this site, that this forest type was the simplest and perhaps the youngest in succession. To this extent, tropical rain forest is concluded to be more stable than the other forest types, and the woodland ecosystem is the least stable. Moist montane forest maintained the intermediate status due to human interference. Tree recruitment patterns within the selected forest types followed the reverse –J curve for all the forest types but the level of regeneration and diamter size distribution patterns revealed different degrees of structural stability of the forests. The stability was highest for the tropical rainforest, which was also characterised by highest proportion of seedling stage. Both tropical rainforest and moist montane forest had number of seedlings > number of saplings. The moist montane forest had higher proportion of large trees than saplings. Large trees: saplings ratio was 100:80 in MMF against 100:130 in TRF and 100:330 in DWF. The observed diameter size structure at MMF was the opposite of the norm in structurally stable mixed natural forests. The deficiency in saplings within MMF site is a reflection of the disturbed seedling establishment phase in the recent past. This forest site experienced heavy logging and charcoal production as documented in recent studies. Further monitoring of regeneration establishment and resilience is required at MMF and DWF where stocking levels in pole and sapling stages are also low in absolute terms.

Overall, there were concerns over low regeneration levels in the dry woodland forest that should be increased to ensure stand structure stability of the woodland. Therefore, rehabilitation work is required to uplift the stocking levels in MMF and DWF, either by protecting upcoming regeneration and/or planting more trees in degraded or open gaps. Seed germination and seedling establishment are known to be vulnerable stages, very much sensitive to variations in microsite conditions such as edaphic, droughts, fires, tramping and grazing, and majority of them do not transit into the next diameter size class (Hitimana et al., 2004; Kiruki et al., 2017). Generally, trees and forests are shaped by their history in addition to the present factors that act upon them; that is, the prior use or disturbance determines the existing state of development (Pretzsch, 2009).

### 5.5.2 Diameter Size Distribution Structure

Diameter structure analysis revealed three distinct development phases: individuals with DBH below 10 cm; DBH between 10 and 35 cm, and > 35 cm DBH tree category. Regeneration and recruitment levels were satisfactory in closed canopy forests (TRF and MMF) but regeneration was under-stocked in dry woodland site (DWF). Timber-sized trees (above 35 cm DBH) were understocked in all the three studied forests. Diameter size distribution patterns in the three forests revealed that the TRF and MMF had more balanced structures and therefore were more stable than DWF. The number of stems in various diameter classes was lower in MMF than in TRF and lowest in DWF. The woodland had most of its individuals below 20 cm dbh. The diameter size structure in DWF characterized a very simple forest system and thus less stable than tropical rainforest and moist montane forest. There is need to monitor the ecological stability and sustainability of the woodland forest and find ways of enhancing its conservation and management standing. Management interventions are required to promote a stable forest structure in the near future. For example, the woodland can be protected by adopting sustainable grazing systems. There may be need to research on suitable model for the woodland ecosystems as a unique context.

### 5.6 Forest Density Measures

Standing basal area distribution is a key component in volume, biomass and carbon sequestration computation in forestry. Stand basal area is a product of both tree sizes and their abundance. Basal area is a positive indicator of wood biomass production and is used as a measure of forest productivity in combination with height. The level of standing basal area was highest in TRF; more than double that of from MMF. All the three forests combined, tropical rainforest contributed over 70% of the standing basal area. The dry woodland forest contributed less than 5% and the moist montane forest contained around 25%. On average, trees from tropical rain and moist montane forests were of larger tree diameter sizes than in the dry woodland forest. Quadratic mean diameter was nearly the same in TRF and MMF. Small diameter trees were on average found in DWF. Quadratic diameter mean was less density-dependent than basal area.

Referring to height as an indicator of site quality, recorded mean top canopy height was highest in tropical rain forest (30.5 m), intermediate in moist montane forest (22.8m) and lowest in the dry woodland (5.1m). The differences in productivity across the study forests are a dictate of differences in site quality, species composition and disturbance history; TRF being perhaps the best protected and managed of all. The situation is however different with forest density (number of trees per hectare). The tropical rainforest maintained its dominance but with a decreased magnitude. In comparison to basal area, relative tree density declined to 50% in TRF and increased to 25% in DWF. TRF dominated all vegetation types in terms of forest tree density, basal area and quadratic mean diameter structures.

### 5.7 Efficiency of Sampling Schemes

#### 5.7.1 Sampling Schemes for Tree Species Richness and Diversity

By using percentage of species per sampling effort (Figures 19a-d), simple random sampling design and 30 % sampling intensity formed the best sampling scheme to be used to compare species diversity through richness. The second approach compared species-area curve models for 30% sampling intensity against100% sampling intensity to measure species richness over 1 ha. The use of 5 m x 5 m plot size (Figure 19a), was efficient with both SSV and SSH in

TRF. SSH was also adequate in DWF. Slight deviations were found from reference curve. They are therefore reliable in developing species-area curve model for the specified forests. They were found inadequate for MMF. Based on 10 m x 5 m plot size, SSH and SSV transect sampling were found efficient for TRF in development of species-area curve model; however deviation from reference curve was wider than with smaller plot size. The 10 m x 10 m plot size was inadequate for species-area curve modelling in all forest types and for all sampling designs. The 20 m x 20 m plot size along SSH transect was efficient scheme for species –area curve model development per hectare in MMF and in TRF despite some observed light deviation from reference curve. Sampling along the horizontal transect dominated the list of reliable designs in developing cumulative species-area curve models. Species-area curves (Figures 20a-d) are used to compare tree species richness among sites; effects of adopting different directions of belt transects and of sub-sampling 1-ha forest unit were investigated (Brower et al., 1990; Denslow, 1995; Gillison & Brewer, 1985; Hitimana, 2000; Schwarz et al., 1976) and their results are as presented here below.

### 5.7.2 Sampling Schemes for Natural Forest Regeneration

Sampling schemes for forest regeneration inventory refers to how to capture the number of seedlings (individuals <1 cm dbh and not taller than 150 cm) per hectare. SRS estimate of seedlings per hectare did not significantly differ from actual population values. However, with systematic sampling along east –west (SSH) oriented transect, the selection of sampling intensity (10% to 30% for TRF) had a significant effect depending on the forest type: For DWF, all sampling intensities and plot sizes were found adequate for regeneration inventory. Accuracy of the inventory outputs along the north – south oriented (SSV) transect was significantly affected by sampling intensity but with different levels: 5% - 10% for TRF and 5% - 20% for MMF. For DWF, all the sampling schemes were adequate for estimation of averages or totals (point estimates). Using measures of sampling efficiency, best schemes were identified: SSV-5mx5m-30% (83% efficiency) and SSH-10mx5m-5% (80%) for TRF. In DWF, best performing schemes were SRS-10mx10m-30% (91 % efficient), SSV-10mx10m-30% (75 %) and SSV-10m x5m-30%

(74%). For MMF, all evaluated sampling schemes were not efficient. Seedling surveys should be done over the entire 1 ha, subdivided into 5 mx 5 m sub-plots.

### 5.7.3 Sampling Schemes for Number of Trees per Unit Area

Evaluation of suitable sampling schemes for forest density (number of stems ≥5 cm DBH ha$^{-1}$) revealed that tested sampling intensities and plot sizes produced estimates of forest density which were accurate enough in tropical rain forest and moist montane forest. However, in DWF inventory, density estimate from 30% sample in SSV was significantly different from actual population value ($p < 0.05$). Based on the measure of sampling efficiency, many suitable schemes were recorded, with the best three or four per forest type being singled out: SRS-10mx10m-30%, SSV-20mx20m-20%, SSH-10mx10m-30% and SSV-10mx10m-30% in TRF; SSH-10mx10m-20%, SRS-10mx10m-20% and SSH-10mx10m-30% for MMF, and SSV-10mx5m-30%, SRS-10mx10m-30% and SSH-10mx10m-30% for DWF. All sampling designs (SRS, SSV and SSH) were found efficient when combined with the right plot size. Optimum plot size for forest density was 10 m x 10 m across all designs and forest types, with the sampling intensity varying between 20% and 30%.

### 5.7.4 Sampling Schemes for Natural Forest Basal Area and Quadratic Mean Diameter

Estimation of woody biomass in trees and dry woodlands is crucial for sustainable management (Henry et al., 2011; Schreuder et al., 1993). Evaluation of efficiency of sampling was done based on forest basal area per hectare (m$^2$ ha$^{-1}$) as one of the simplest measures of forest density. Graphically, different combinations of sampling intensity, plot size and designs produced different estimates for basal area and fluctuated around the population parameters. However, all the evaluated sampling schemes yielded good estimates of the population value ($p > 0.05$) in all the forest types. However, sampling efficiency analysis showed that no single sampling scheme was efficient enough based on the reference inventory for all forest types. In this case, only 100 % inventory per ha with 10 mx10 m plot size resulted in the smallest sampling error compared to other plot sizes. We recommended full-cover basal area inventory per ha. In contrast, efficient sampling schemes for quadratic mean diameter, a variable derived from mean basal area per hectare, were obtained. The accuracy of sampling for QMD in TRF was influenced by plot size but not by sampling intensity. Most efficient schemes, two per forest type, were SSH-20mx20m-20% and SRS-20mx20m-30% for TRF; SRS-10mx10m-20% and SRS-10mx10m-30% for MMF, and SRS-10mx10m-20% and SRS-20mx20m-30% for DWF. Sampling schemes for quadratic mean diameter could be used for basal area but estimates to be interpreted cautiously.

### 5.7.5 Sampling Schemes for Natural Forest Attributes along a Slope Gradient

Sampling schemes along slope gradient were influenced by the slope for regeneration (Figure 28), but not so much for stems per hectare (Figure 29) and basal area (Figure 30). Sampling schemes along the slope gradient may be stratified and place more units placed in the stratum with highest variability (Lackmann, 2011). Stratification is recommended to minimize the influence of variation between strata on estimated values. Plot sizes for various forest attributes would conform to the findings in previous sections. However, exact sampling intensities per stratum is a subject for further investigations.

## 5.8. Summary of Findings

### 5.8.1 Tree Composition, Diversity, Structure and Recruitment of the Three Natural Forest Types

***Forest composition, relative dominance and diversity***

Forest composition at family taxonomic level varied from one forest type to the other, with high similarity between TRF and MMF, good similarity between MMF and DWF. Some level of similarity, though still low, exists between TRF and DWF. All families at DWF were monogenic, implying a delicate taxonomic balance. At family level, TRF and MMF were 4.6 times richer than DWF. Equal number of families was found in TRF and MMF. Relative dominance of species (evenness) was low across the forest types; few species (25-30%) counted for majority of the individuals in each site (75-77%). Species diversity is therefore more influenced by the number of species rather than eveneness in all the forest types. Inventories on species diversity (biodiversity) can reliably be compared based on the species richness among the three types of forests.

### ***Forest vertical structure***

Forest vertical structure was simpler at DWF than at TRF and MMF. Top canopy height at TRF was 6 times that at DWF; 1.3 times that at MMF. MMF height was 4.5 times that of DWF. Forest gaps were negligible (< 1%) at TRF and MMF sites and < 5% at DWF. However, light screening efficiency was 2.8 times and 1.9 times higher than in DWF for TRF and MMF, respectively. Shading effect correlates posively with screening efficiency, and thus may have significant ecological implications in forest regeneration. TRF canopy layers were more differentiated and distinctly visible than in other forest types; making it more stable and richer in habitat diversity for host of flora and fauna species than the other ecosytems.

### ***Forest regeneration, recruitment and diameter size structure***

TRF dominated all vegetation types in terms of forest tree density, basal area and mean diameter attributes. In terms of forest horizontal structure, TRF and MMF are well balanced and well stocked. However, DWF was understocked with very low regeneration levels. Diameter size structures in TRF and MMF conform to the conventional reverse- J curve based on the UNO model for stable tropical natural forests in Eastern Africa but not so for tropical DWF. TRF was more complex and diverse than the moist montane and dry woodland forest types; with DWF being the simplest and perhaps most vulnerable ecosystem among them.

Overall, the characterisation of sampled forest types showed a gradient in biophysical features, from a more complex and stable TRF to a simplest and most vulnerable DWF

### 5.8.2 Efficiency of Sampling Schemes

***Sampling for species richness and diversity***

Species richness was found to mirror species diversity in all the studied forest types. Using percentage of maximum tree species captured from one hectare as a measure of sampling efficiency (percent species indicator), systematic sampling based schemes (SSV and SSH) with use of 5 mx 5 m plot size, produced mixed results for sampling intensities less than 30%. Most efficient sampling scheme using this small plot, is to apply simple random sampling with high sampling intensity (30%). However, doubling the plot size (10 m x 5 m) and maintaining the 30% sampling intensity, made both SSH and SRS efficient schemes in each of the studied forest types. Larger plot sizes of 10 mx10 m and 20 mx20 m produced good estimates of species richness in equal measure for both SSH and SRS, with 20%-30 % sampling intensities in all the studied forests. The choice is between the uses of few large plots or many smaller plots but maintain adequate sampling intensity. This would depend on other considerations in the planning of forest inventory. Where both SRS and systematic sampling give same quality of parameter estimates, the later design is more practical and in most cases preferable. There are fewer options of sampling schemes usefull for developing species – area curves for further use in estimating species richness (species accumulation rate indicator). This study established that with a fixed 30% sampling intensity, the optimum plot sizes of 5 mx 5 m or 10 m x 5 m were applicable only in tropical rain forest, and could be arranged along transects regardless of the orientation. Larger plot sizes were not efficient. In the other forest types, the efficient scheme is to collect data over the entire one hectare (complete inventory) but using optimum plot size of 5 mx 5 m along transect lines facing any direction in the montane forest, and horizontal (East – West) direction in the dry woodland. Overall, sub-sampling of 1 ha-forest unit is practical in TRF with 30% intensity (i.e. 0.3 ha sample area). For other forest types, minimum sample size would be a total of 1 ha, using 5 mx 5 m plots, distributed along horizontal transects (East-West direction).

Efficient sampling schemes for species diversity (number of species) are SRS or SSH in TRF and DWF; e.g. SSH- any plot size between 25 m2 and 400 m2 - 30% with high efficiency (89-94%). Complete enumeration of 1 ha plot is inevitable in MMF.

Cumulative species-area curve models are applicable using 30% intensity per hectare, with varying sampling designs and plot sizes among forest types. However, 10 m x 10 m plot size was found to be inadequate.

### *Sampling for natural forest regeneration density*

Adequacy and efficiency of sampling schemes for forest regeneration inventory based on sampling error and cost of operations per sampling unit established that systematic sampling along transects, with 10% sampling intensity was in general adequate for each of the tested plot sizes. SRS was also accurate for all the studied forest types. Plot sizes did not influence the outcome of the regeneration sampling. For the dry woodland forest in particular, both simple random sampling and systematic sampling designs were found practical and adequate for all tested sampling intensities for regeneration abundance. For both the tropical rainforest and the moist montane forest sites, SSH with 30% sampling intensity was adequate, and smaller sampling intensities (5% and 10%) were compatible with SSV. However, beside adequacy, efficient schemes (accurate and cost-effective) varied from one forest type to the other. In TRF, systematic sampling –based schemes (SSV-30%- 5 mx 5 m and SSH-5%-10 m x 5 m) performed better than random sampling. In MMF, the minimal sample size should be one hectare, with 5 mx 5 m plot size being used as the optimal size. For DWF, there were more options of efficient sampling schemes from both SRS and SSV. However, the smallest plot size of 5 mx 5 m was not adequate and optimal plot sizes were 10 m x 5 m and 10 mx10 m with 100% intensity. Sampling for regeneration density can based on the following established efficient sampling schemes for tree regeneration: SSH- 5 m x 10 m-5% (e=80%) for tropical rain forest; SSV/SSH- 5 m x 5 m-100% for moist montane forest; and SSV-10 m x 10 m-30% (e=75%) and SSV- 5 m x 10 m-30% (e=74%) for dry woodland forest in Kenya.

### *Sampling for forest density in number of stems per ha*

For inventory of forest density, SRS and SSH are both efficiently applicable with each of the tested plot sizes and sampling intensities in all forest types, with optimum plot size of 10 mx10 m, and adequate sampling intensity varying between 20% and 30%. SSV is also applicable in TRF and MMF with any sampling intensity but it can only be applicable in DWF for a sample size of at least 1 ha. Forest density attribute had the highest number of efficient sampling schemes across the three forest types. The most efficient sampling schemes are:

i) SRS-10mx10m-30% (e= 99%), SRS-10mx10m-20% (e= 81%), SSV-20mx20m-20% (e= 98%) and SSH-10mx10m-30% (e= 94%) for tropical rain forest;
ii) SSH-10 mx10m-20% (e= 99%), SRS-10mx10m-20% (e= 86%), SSH-10mx10m-30% (e=82%) and SSV-10mx10m-30% (e= 79%) for moist montane forest;
iii) SSV-10m x5m-30% (e= 92%), SRS-10mx10m-30% (e= 89%) and SSH-10mx10m-30% (e= 88%) for dry woodland forest in Kenya.

***Sampling for forest basal area***

For basal area, efficient inventory strategy is to measure trees over the entire 1 ha-area but using 10 m x 10 m subdivision units in TRF and MMF or 5 m x 5 m subdivisions in DWF. Sampling for standing basal area did not show any promising sub-sampling scheme of 1 ha forest unit; none was found efficient enough to assess basal area, across studied forest types. However, the following data compilation units minimized sampling error within 1ha-complete inventory:

i) 10 m x 10 m for tropical rain forest,
ii) 20 m x 20 m for moist montane forest and
iii) 5 m x 5 m for dry woodland forest in Kenya.

***Sampling for quadratic mean diameter***

Sampling for QMD had mixed results. In MMF and DWF all tested schemes produced reliable results. However, in TRF, the systematic sampling should be vertical with 10 m x 10 m plot size with any sampling intensity. Quadratic mean diameter, unlike basal area, had efficient sampling schemes within the 1 ha-forest unit and for the different forest types. They were:

i) SSH-20mx20m-20% (e=94%), SSH-20mx20m-30% (e= 61%) and SRS-20mx20m-30% (e= 73%) for TRF;
ii) SRS-10mx10m-20% (e= 75%), SSV-10mx10m-20% (e= 63%), SSV-10mx10m-30% (e= 60%), SRS-10mx10m-30% (e= 66%) and SSH-10mx10m-20% (e= 56%) for MMF;
iii) SRS-10mx10m-20% (e= 90%), SRS-10mx10m-10% (e= 62%), SRS-20mx20m-30% (e= 73%) and SSH-10mx10 m-30% (e= 60%) for DWF in Kenya.

***Efficient sampling schemes with respect to slope gradient in a tropical montane forest***

Where gradient slope is apparent, regeneration sampling schemes with small plot sizes e.g. 5 mx 5 m should apply 30 % intensity for SSH. For plots larger than 5 m x 5 m, 10% intensity was optimum for any transect design (SSD = SSH = SSV). Analysis of relative efficiency of the many candidate schemes revealed that many options exist for regeneration assessment on the slope gradient and accommodate all transect designs. However, the most efficient were SSD-30%-10mx10 m and SSD-20%-10mx10m. SSD was found superior to SSH and SSV on average. Optimum plot size was found to be 10mx10 m in sampling (less than 100 % intensity). But where entire 1 ha is assessed, smaller plots were most effective along any transect. For forest density measured by number of stems per ha, effective sampling intensity should be higher than 10%. SSD, SSH and SSV – based sampling schemes are applicable but with small plot sizes ( 5 m x 5 m and 10 m x 5 m) being most effective where 100% inventory is performed in one hectare. As plot sizes increase, the efficiency of sampling schemes declines. For basal area assessments, larger plot size of 20 m x 20 m was the most effective for any transect design. The choice of a transect direction would depend on the convenience of field work. Sampling schemes along the slope gradient /diagonal transect improved assessment of regeneration and basal area. However, efficiency of sampling schemes for basal area along the slope gradient was still below 50%. It remains imperative to invoque complete inventory of 1 ha forest unit but which should be subdivided into 20 m x 20 m compilation units. Efficient sub-sampling of one hectare was found justified along diagonal transects on sloppy terrains. Most efficient schemes are the following:

i) SSD-10mx10m-30% (e= 81%), SSD-10mx10m-20% (e= 50%) for number of seedlings per hectare. It implies that levels of seedling establishment vary along the slope gradient.
ii) For density (no. stems ha$^{-1}$) inventory in the montane forest: SSD-10mx10m-20% (e= 83%), SSH-10mx10m-20% (e= 99%) and SSV- and SRS-based schemes (e $\leq$ 79%).

### 5.8.3 Optimum Schemes, Plot Sizes and/or Sampling Intensities

Different sampling schemes are associated with different optimum plot sizes and optimum sampling intensities. Different forest attributes often require different sampling schemes. Table 23 summarizes, case by case, inventory schemes found in this study as efficient for indicated attributes and per speficied forest type. Optimisation of inventories with multiple objectives can be achieved by integrating suitable plot size, sampling intensity and /or sampling design.

**Table 23: Examples of Sampling Schemes's Optimum Plot Sizes, Intensities And Designs For Different Forest Types**

| **Studied forest attribute** | **Measured indicator** | **Optimum plot size (m x m)** | **Adequate sampling intensity (%)** | **Required Sampling design** | **Forest type where applied** |
|---|---|---|---|---|---|
| Species diversity or richness | Percent species in a sample | 5X5 | 30 | SRS | TRF or MMF or DWF |
| | | 10x5 | 30 | SSH or SSV | TRF or MMF or DWF |
| | | 10X10 or 20X20 | 20 or 30 | SSH or SSV | TRF or MMF or DWF |
| | Species accumulation rate (species - area curve) | 5X5 or 10x5 | 30 | SSH or SSV | TRF |
| | | 5X5 | 100 | SSH or SSV | MMF |
| | | 5X5 | 100 | SSH | MMF or DWF |
| | | 5X5 | 30 | SSH | TRF |
| Regeneration density | seedlings /ha | 5X5 | 30 | SSV | TRF |
| | | 5X5 | 100 | | MMF |
| | | 10x5 | 5 | SSH | TRF |
| | | 10x5 or 10X10 | 100 | SSV | DWF |
| Forest density | Stems /ha | 10 x 10 | 20 or 30 | SRS or SSH | TRF or MMF or DWF |
| | | 10 x 10 | 20 or 30 | SSV | TRF or MMF |
| | | 10 x 10 | 100 | SSV | DWF |
| | Basal area/ha | 5 x 5 | 100 | Total inventory | DWF |
| | | 10 x 10 | 100 | Total inventory | TRF or MMF |
| | QMD | 5X5, 10x5 or 10X10 | 10, 20 or 30 | | MMF or DWF |
| | | 10X10 | 10, 20 or 30 | SSV | TRF |
| Slope gradient effect | Seedlings /ha | 5X5 | 30 | SSH | Slope: 8-16% (MMF) |
| | | 5X5 or 10x5 | 100 | SSD or SSH or SSV | |
| | | 10x5 or 10X10 | 10 | SSD or SSH or SSV | |
| | | 10x10 | 20 or 30 | SSD | |
| | Stems /ha | 5x5 or 10x5 | 100 | | MMF |
| | Basal area/ha | 20x20 | 100 | | MMF |

# CHAPTER SIX

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1. Conclusions

Tropical rainforest was more diverse, complex and structurally stable than the tropical montane and dry woodland forests in terms of species composition, vertical and horizontal structure, regeneration and recruitment. Many small plots e.g 5 mx 5 m in size gave more accurate description of vertical structure in all the three forest types than fewer large plots e.g. 20 mx20 m in size. Sampling for comparative purposes of tree species diversity (e.g. beta and gamma diversity) is achievable through use of species richness alone. Both random and systematic sampling designs supported efficient and applicable sampling schemes for forest regeneration, density and diversity indicators, based on different combinations of optimum plot sizes and sampling intensities. The study identified and documented optimum plot sizes, adequate sampling intensities, required sampling designs applicable in tropical rainforest, tropical moist montane forest and tropical dry woodland forest to assess species diversity/richness, regeneration density and forest density indicators including sampling along slope gradient. Subdividing one-hectare forest unit into sub-plots for data collection increased accuracy and effectiveness of forest inventory schemes even where sampling intensity should be 100%; and optimum plot sizes vary depending on forest type or forest attribute, e.g. basal area $ha^{-1}$ in general; and seedlings $ha^{-1}$, stems $ha^{-1}$ along slope gradient in montane forest. Systematic sampling was superior to simple random sampling even in some situations where complete inventory is the option; for example, systematic data collection along transects to fit species – area curve models in dry woodland and montane forests. Diagonal transect –based sampling schemes were superior to sampling methods along vertical and horizontal transects for regeneration (but not for stems and basal area $ha^{-1}$) in the montane forest where slope gradient exists, but require selection of optimum plot size (e.g.10 m x10 m) and adequate sampling intensity (e.g. 20% –30%)

Characterisation of sampled forest types showed a gradient in biophysical features, from more complex and stable TRF to simplest and most vulnerable DWF

SRS and SSH-based sampling schemes were both efficient for species richness assessment in TRF and DWF; e.g. SSH- any plot size between 25 $m^2$ and 400 $m^2$ - 30% are associated with relative efficiency levels betwwn 89 % and 94%. Assessment of species richness on slopes such as in montane forests requires a minimum plot size of 1 ha.

Cumulative species-area curve models that estimate the number of species per hectare can efficiently be fitted by data from 0.3 ha (30% sampling intensity in a hectare) using random sampling or systematic sampling along belt transects, and plot sizes as small as 25 $m^2$ and as large as 400 $m^2$ in tropical rain forests, moist montane forest and dry woodland forest. Relative efficiency levels were 80% and above. However, 10 m x 10 m plot size was an outlying plot size.

Well-designed systematic sampling schemes along transects were found superior to random sampling for assessment of number of seedlings (individuals < 1 cm dbh) per hectare, with high efficiency levels e.g. 80% for SSH- 5 m x 10 m-5% in tropical rain forest; 75 % for SSV-10 m x 10 m-30% in dry woodland forest. No sub-sampling scheme of 1 ha forest plot was found efficient enough in montane forest where local topograpghy is characterised by a slope gradient (1% to 16%). One hectare forest unit is the lowest data compilation unit, with field data gathered systematically along belt transects and using 5 m x 5 m subplots.

Forest density measured by the number of stems per hectare (for individuals ≥ 1 cm dbh) was found to be the most cost-effective measure of overall forest density across all the forest types we investigated. This attribute had the highest number of efficient sampling schemes in each forest type: two SRS schemes and two SS schemes in for tropical rain forest with efficiency level above 80%; one SRS and two SS schemes in moist montane forest and dry woodland forest, with efficiency level over 80%. Systematic sampling – based schemes in a hectare were generally as efficient as random sampling; SS was even superior to SRS in montane and dry woodland forests.

Basal area as a stand parameter was the least sensitive to sampling in studied forest types. No sub-sampling scheme of 1 ha forest unit was efficient enough to assess basal area. However accuracy of estimates per hectare [as a compilation unit] was found to be influenced by the applied sub-plot size e.g. sampling error within 1ha complete inventory was lowest by subdividing the area into 10 m x 10 m units in tropical rain forest, 20 m x 20 m units in moist montane forest and 5 m x 5 m units in dry woodland forest.

Quadratic mean diameter, unlike basal area, had efficient sampling schemes within the 1 ha forest unit and for the different forest types. Systematic sampling-based scheme was more effiecient than random sampling scheme in tropical rain forest with relaive effiency above 90%; random and systematic sampling-based schemes were effiencient in moist montane and dry woodland forests. However, in both forests, systematic sampling had lower efficiency levels than random sampling based schemes.

Finally, sampling schemes along the slope gradient (diagonal transect) was much superior than vertical and horizontal transects in the montane forest and raised sampling efficiency for regeneration to over 80%. Assessment of forest density (no. stems ha$^{-1}$) along diagonal transect was among most efficient, with efficiency level above 80%.

The sampling scheme along diagonal transect was superior to using vertical or horizontal transect. However, efficiency level was below the 50% minimum mark. Complete enumeration over one hectare remains the ideal plot size, with 20 m x 20 m sub-units.

## 6.2 Recommendations

Practically, in multiple resource assessment, a blended approach should be applied. For example, the inventory unit should be 100mx100m for basal area but subdivided into 20 mx20 m subplots. Smaller units of 5 mx 5 m each should be nested in the 20 mx20 m plots for regeneration assessment. If the transect is diagonal, nested plots should be increased to 10 mx10 m plots and use at least 30% sampling intensity along a diagonal transect. The same 10 mx10 m would be adequate and used for capturing forest density data with 20% or 30 % sampling intensity along any transect direction. Efficiency measured by sampling error and sampling effort enabled identification and ranking different sampling schemes for each attribute and forest type.

There is need to replicate this study in other tropical forest types in order to provide comprehensive and exhaustive applicable inventory protocols. There is need to measure and monitor the ecological stability and sustainability of natural forests including woodlands based on availed schemes to enhance knowledge creation and informed-decision making in forest resource conservation and management.

i) Multiple purpose forest inventory covering different development stages requires careful integration of different plot sizes, sampling intensities and transect orientations.
ii) Efficient sampling schemes along transects (SSH, SSV, SSD) are practically more convenient and recommended over simple random sampling (SRS) based schemes in mixed tropical natural forests.
iii) Diagonal transect improved efficiency of sampling seedlings and, to a limited extent, basal area
iv) Choice of plot size and sampling intensity must be balanced with the implied cost and desired reliability of the results.
v) Where sampling schemes for quadratic mean diameter are used, basal area estimates should be used and interpreted with caution.

### 6.3 Suggestions for Future Research

UNO model was found to be less applicable outside closed canopy forests. There is need to investigate and develop structural stability model for tropical woodlands as an important tool for measuring and monitoring management standards for these ecosystems. To scale up the test of efficiency and application of identified efficient inventory schemes to minimize sampling errors (the measures of precision) which include, but not limited to, stratified sampling, cluster sampling and /or multistage sampling in tropical forests. There is need to carry out research on regeneration establishment and resilience of the montane and woodlands forests. Similar research done in other forest strata of Kenya would support decisions regarding establishment of an accurate and cost-effective National Forest Inventory. There is need to investigate factors contributing to inefficiency of 10 m x 10 m plot size in developing reliable cumulative species-area curves for the tropical natural forests; efficiency of various plot shapes applied in forest inventory including circular and rectangular plots; and efficiency of other sampling designs including stratified, cluster, multistage and multiphase sampling designs. Further research is required for efficient sampling methods to estimate basal area

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# APPENDICES

## APPENDIX I: LOCATION, ELEVATION AND CLIMATE FEATURES OF THE FOREST STUDY SITES, KENYA

| | | | | **Experimental sites for sampling designs** | | |
|---|---|---|---|---|---|---|
| Sites | Elevation (m a.s.l) | Climate type & Kenya Agro-ecological zone | Disturbance history | Monthly temperature (°C ) | Annual rainfall (mm) | Georeferenced location (GPS coordinates in decimal degrees) |
| Kakamega Tropical Rain Forest (Isecheno) | 1580 | Humid and warm Tropical (Af)<br>Upper Midland (AEZ UM0) | Moderate logging | 20.4 | 1971 | Lat.: 0.269624 - 0.270523<br>Long.: 34.900855 - 34.901755 |
| Mt Elgon Moist Montane Forest (Kaberwa) | 1976 | Moist and warm temperate (Cfb)<br>Upper Highland (AEZ UH0) | Extensive Logging | 17.9 | 1577 | Lat.: 0.867403 - 0.868302<br>Long.:34.692033 - 34.692932 |
| Loruk Tropical dry woodland Forest (Loruk) | 987 | Dry Tropical (Aw)<br>Lower Midland (AEZ LM5) | Livestock grazing | 23.7 | 629 | Lat.: 0.71024565 - 0.71114497<br>Long.: 36.000983 - 36.001882 |

Weather data are averages between 1982 and 2012.
(Hitimana et al., 2004; Hitimana et al., 2010; Fashing et al., 2003; Joetzoald & Schmidt, 1983; Kokwaro, 1988; Mutiso et al., 2013).

# APPENDIX II: R CODES FOR CREATING VARIOUS PLOT SIZES

## 1. Introduction

This process is the same in R studio for all the three forests. We use Mt. Elgon site to illustrate it. We just update the name of the forest in the function and run to get output.

## 2. Merging 5 m by 5 m plots to create 10 m by 5 m plots

Field data collection from the forest was done and organized in 400 plots of equal size of 5 m x 5 m (Smallest plot size tested in the study).
*Display of grid for four hundred 5 m by 5 m plots is available (Appendix III. 1.)*

Reorganising field data from same forest in 10 m x 5 m plot size was done in R as described below. It required having 1 ha forest divided it into 200 plots of 10 m x 5 m each. Each plot here is going to be twice as large as the the plots in the previous part.
We create the 200 plots here by merging every two consecutive plots (vertically) from the initial grid of 400 plots.

First, let us identify the unique plots in order

```
plots = unique(mt_elgon$plot.no.)
plots = as.character(plots)
```

We take the *odd* plot number eg *1111* to represent the new plot that is created by merging the two plots *1111* and *1112*. The unique plots are arranged in ascending order from 1 through 400. The position of the plot in this arrangement (between 1 and 400) can be separated as either *even eg 2* or *odd eg 1*. The first and second lines of the code below checks if the position is even or odd and creates a list with the values *TRUE* if the position is even and *FALSE* if the position is odd.

```
is.even = function(x) x%%2 == 0
even = is.even(1:length(plots))
```

Finally, the two lists *plots* and *even* are merged together to create a table with two rows, one for plot number and another indicating whether the position is odd or even, and 400 rows, one for each unique plot number.

```
mytable= cbind(plots,even)
mytable= as.data.frame(mytable)
```

Our new table is named *mytable*

Unique number for the new created plot of 10 m x 5 m is the *odd* plot number from each pair of small plots that were merged. In R, we create another column in *mytable*. This column will contain the unique plot number.The first line of code below creates another column and calls it *newplots*. The second part of the code adds the values of plot number that we want.

```
mytable= mutate(mytable, newplots = plots )
mytable[mytable$even == T,][3] = mytable[mytable$even == F,][3]
```

We use this table to check for all values of *plot number* in our *mt_elgon* data set that match the values of *plots* in *mytable* and we replace them with the values of *newplots* in *mytable*. We also ensure the values in these three columns are of the same "data type".

```
mytable$plots = as.character(mytable$plots)
mytable$newplots = as.character(mytable$newplots)
mt_elgon$plot.no. = as.character(mt_elgon$plot.no.)
```

```
for (i in 1:nrow(mt_elgon)) {
  for (j in 1:nrow(mytable)) {
    if (mt_elgon$plot.no.[i] == mytable$plots[j]) {
      mt_elgon$plot.no.[i] = mytable$newplots [j]
    }
  }
}
length(unique(mt_elgon$plot.no.))
## [1] 200
```

We now have 200 unique plots from initial 400. We can now go ahead with our analysis just in the same way as it is done in the 400 plots.

```
uniq_plots = as.character(unique(mt_elgon$PLOT.NO.))
length(uniq_plots)
## [1] 200
```

Arranging the plots appropriately;

```
uniq_plots = cbind(uniq_plots[1:20], uniq_plots[21:40], uniq_plots[41:60], uniq_plots[61:80],
uniq_plots[81:100], uniq_plots[101:120], uniq_plots[121:140], uniq_plots[141:160],
uniq_plots[161:180], uniq_plots[181:200])
```

```
uniq_plots = as.data.frame(uniq_plots)
```

*Display of grid for two hundred 10 m by 5 m plots is available (Appendix III.2)*

### 3. Merging 10 m by 5 m plots to create 10 m by 10 m plots

The 200 plots grid is made of 20 columns and 10 rows. We need to merge two consecutive plots (horizontally) to create 10 columns, and obtain a grid of 10 columns by 10 rows as follows.

```
x = unique(mt_elgon$plot.no.)
x = as.data.frame(x)
```

```
y = x

y[11:20,] = y[1:10,]
y[31:40,] = y[21:30,]
y[51:60,] = y[41:50,]
y[71:80,] = y[61:70,]
y[91:100,] = y[81:90,]
y[111:120,] = y[101:110,]
y[131:140,] = y[121:130,]
y[151:160,] = y[141:150,]
y[171:180,] = y[161:170,]
y[191:200,] = y[181:190,]

mytable= cbind(x,y)
names(mytable) = c("plots", "newplots")

mytable$plots = as.character(mytable$plots)
mytable$newplots = as.character(mytable$newplots)
mt_elgon$plot.no. = as.character(mt_elgon$plot.no.)

for (i in 1:nrow(mt_elgon)) {
  for (j in 1:nrow(mytable)) {
    if (mt_elgon$plot.no.[i] == mytable$plots[j]) {
      mt_elgon$plot.no.[i] = mytable$newplots [j]
    }
  }
}

length(unique(mt_elgon$plot.no.))
## [1] 100
```

We now have 100 unique plots from initial 200 plots. We can now go ahead with our analysis just like in the 400 plots.

```
uniq_plots = as.character(unique(mt_elgon$PLOT.NO.))
length(uniq_plots)
## [1] 100
```

Then we arrange the plots appropriately.

```
uniq_plots = cbind(uniq_plots[1:10], uniq_plots[11:20], uniq_plots[21:30], uniq_plots[31:40],
uniq_plots[41:50], uniq_plots[51:60], uniq_plots[61:70], uniq_plots[71:80],
uniq_plots[81:90], uniq_plots[91:100])

uniq_plots = as.data.frame(uniq_plots)
```

*Display of grid for one hundred 10 m by 10 m plots is available (Appendix III.3)*

## 4. Merging 10 m by 10 m plots to create 20 m by 20 m plots

### 4..1. Merging pairs of consecutive plots vertically  to create 20 m by 10 m plots

First, let us identify the unique plots from the list of 10mx10m-plots

```
plots = unique(mt_elgon$plot.no.)
plots = as.character(plots)
```

The unique plots are arranged in order from 1 through 100. The position of the plot in this arrangement (between 1 and 100) can be separated as either *even eg 2* or *odd eg 1*. The first and second lines of the code below check if the position is even or odd and create a list with the values *TRUE* if the position is even and *FALSE* if the position is odd.

Finally, the two lists *plots* and *even* are merged together to create a table with two rows: one for plot number and another indicating whether the position is odd or even. and 100 rows, one for each unique plot number.

```
is.even = function(x) x%%2 == 0
even = is.even(1:length(plots))
mytable= cbind(plots,even)
mytable= as.data.frame(mytable)
```

Our new table is named *mytable*

Unique number for the new created plot of 20 m x 10 m is the *odd* plot number from each pair of 10mx10m-plots that were merged. In R, we create another column in *mytable*. This column will contain the unique plot number for 20 m x 10 m plot.The first line of code below creates another column and calls it *newplots*. The second part of the code adds the values of plot number that we want.

```
mytable= mutate(mytable, newplots = plots )
mytable[mytable$even == T,][3] = mytable[mytable$even == F,][3]

mytable$plots = as.character(mytable$plots)
mytable$newplots = as.character(mytable$newplots)
mt_elgon$plot.no. = as.character(mt_elgon$plot.no.)

for (i in 1:nrow(mt_elgon)) {
  for (j in 1:nrow(mytable)) {
    if (mt_elgon$plot.no.[i] == mytable$plots[j]) {
      mt_elgon$plot.no.[i] = mytable$newplots [j]
    }
  }
}

length(unique(mt_elgon$plot.no.))
## [1] 50
```

We now have 50 unique plots from initial 100 plots

### 4.2. Merging consecutive 20 m by 10 m plots horizontally to form 20 m by 20 m plots

The fifty **20 m x 10 m** plots are arranged in 5 rows and 10 columns. In R, we need to reduce the 10 columns with 10 m length each to 5 columns with 20 m length each.

```
x = unique(mt_elgon$plot.no.)
x = as.data.frame(x)
y = x

y[6:10,] = y[1:5,]
y[16:20,] = y[11:15,]
y[26:30,] = y[21:25,]
y[36:40,] = y[31:35,]
y[46:50,] = y[41:45,]

mytable= cbind(x,y)
names(mytable) = c("plots", "newplots")

mytable$plots = as.character(mytable$plots)
mytable$newplots = as.character(mytable$newplots)
mt_elgon$plot.no. = as.character(mt_elgon$plot.no.)

for (i in 1:nrow(mt_elgon)) {
  for (j in 1:nrow(mytable)) {
    if (mt_elgon$plot.no.[i] == mytable$plots[j]) {
      mt_elgon$plot.no.[i] = mytable$newplots [j]
    }
  }
}
length(unique(mt_elgon$plot.no.))
## [1] 25
```

We now have 25 unique plots from initial 50 and can go ahead with our data analysis from them.

```
uniq_plots = as.character(unique(mt_elgon$PLOT.NO.))
length(uniq_plots)
## [1] 25
```

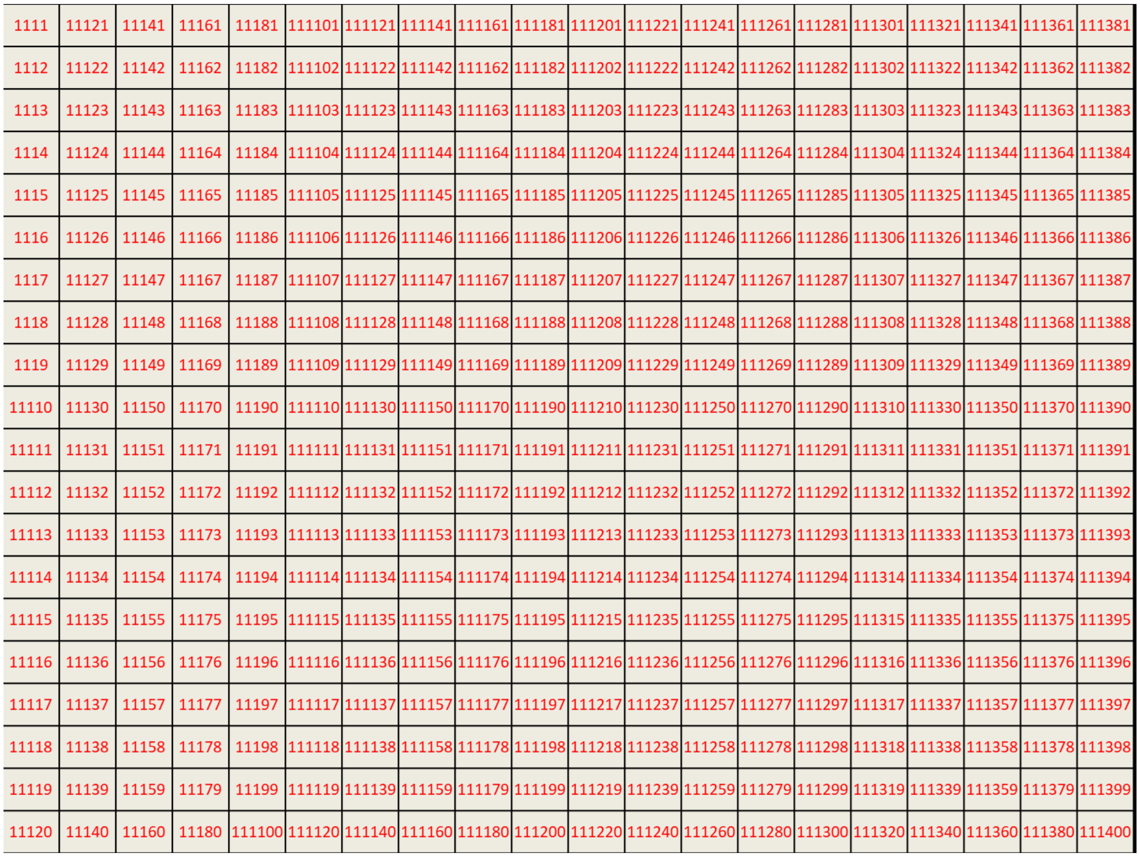
Appropriate arrangement of the plots through are codes:

```
uniq_plots = cbind(uniq_plots[1:5], uniq_plots[6:10], uniq_plots[11:15], uniq_plots[16:20],
uniq_plots[21:25])
uniq_plots = as.data.frame(uniq_plots)
```

*Display of grid for twenty-five 20 m by 20 m plots is available (Appendix III.4)*

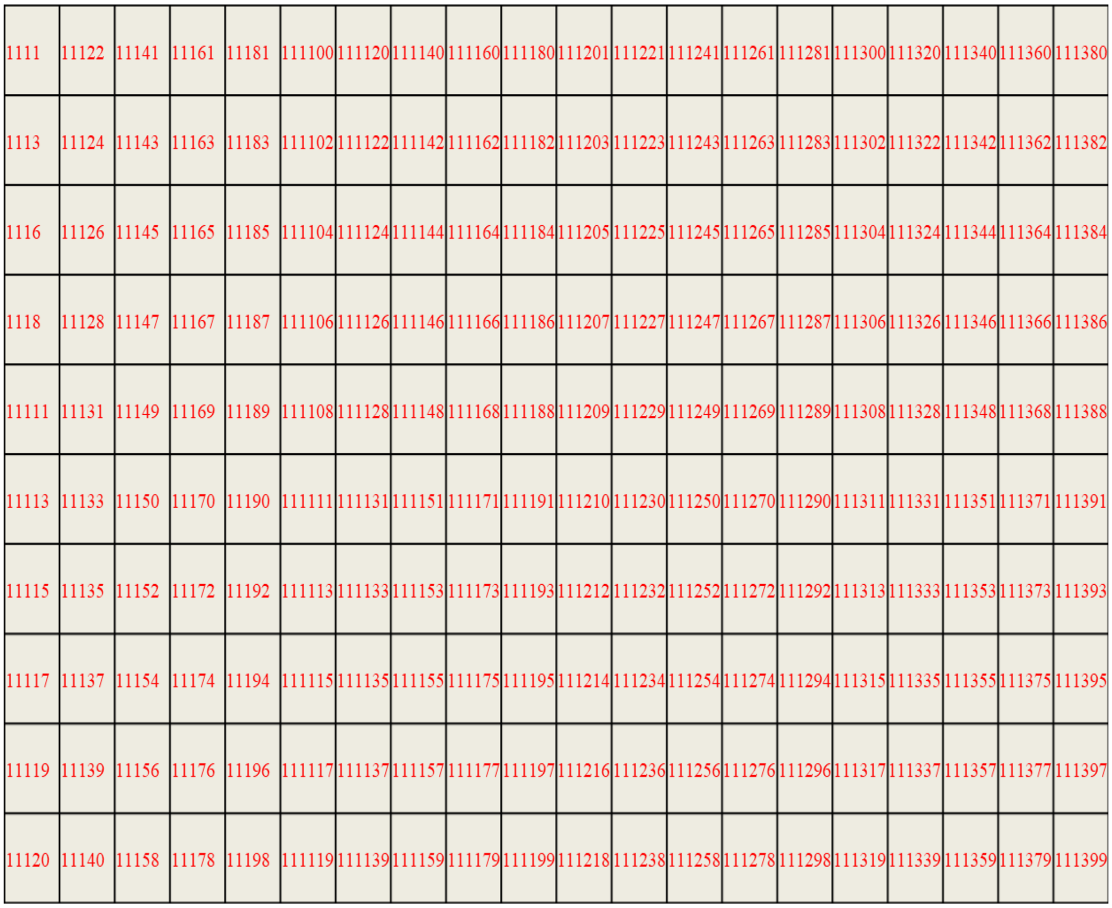
# APPENDIX III: SAMPLING FRAMES FOR DIFFERENT PLOT SIZES

## 1. Grid of the 400 5 m x 5 m-plots: case in Mt Elgon 100 mx100m-Forest Unit



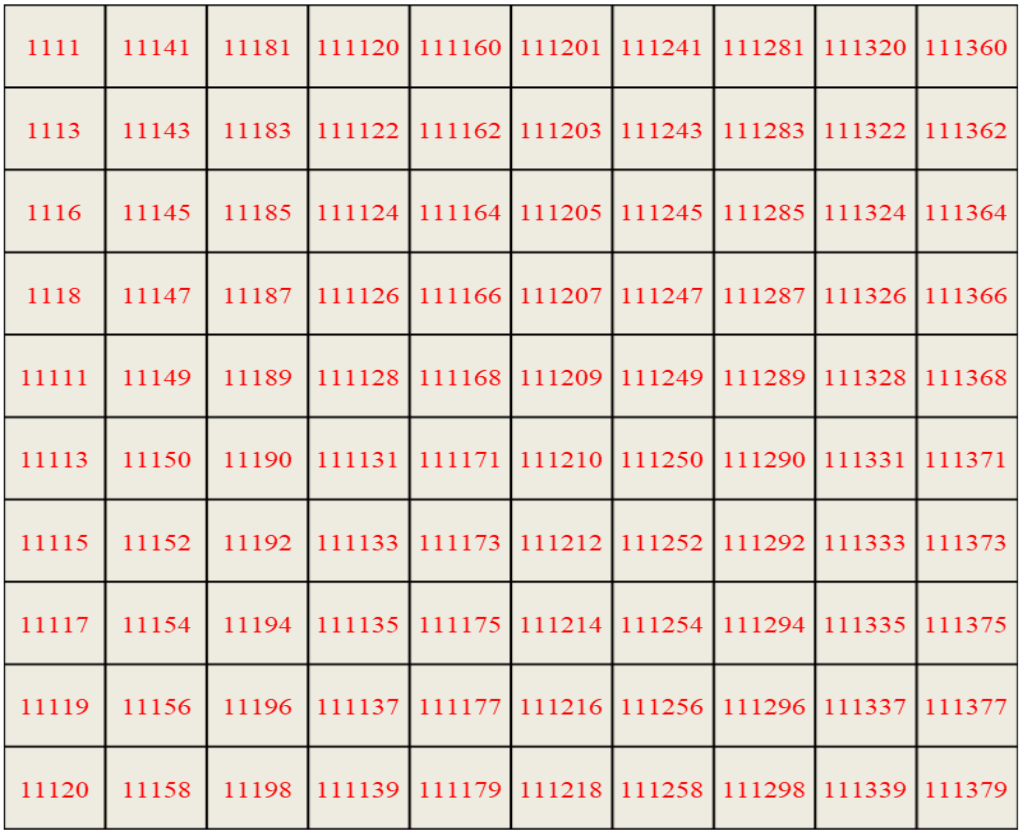
| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1111 | 11121 | 11141 | 11161 | 11181 | 111101 | 111121 | 111141 | 111161 | 111181 | 111201 | 111221 | 111241 | 111261 | 111281 | 111301 | 111321 | 111341 | 111361 | 111381 |
| 1112 | 11122 | 11142 | 11162 | 11182 | 111102 | 111122 | 111142 | 111162 | 111182 | 111202 | 111222 | 111242 | 111262 | 111282 | 111302 | 111322 | 111342 | 111362 | 111382 |
| 1113 | 11123 | 11143 | 11163 | 11183 | 111103 | 111123 | 111143 | 111163 | 111183 | 111203 | 111223 | 111243 | 111263 | 111283 | 111303 | 111323 | 111343 | 111363 | 111383 |
| 1114 | 11124 | 11144 | 11164 | 11184 | 111104 | 111124 | 111144 | 111164 | 111184 | 111204 | 111224 | 111244 | 111264 | 111284 | 111304 | 111324 | 111344 | 111364 | 111384 |
| 1115 | 11125 | 11145 | 11165 | 11185 | 111105 | 111125 | 111145 | 111165 | 111185 | 111205 | 111225 | 111245 | 111265 | 111285 | 111305 | 111325 | 111345 | 111365 | 111385 |
| 1116 | 11126 | 11146 | 11166 | 11186 | 111106 | 111126 | 111146 | 111166 | 111186 | 111206 | 111226 | 111246 | 111266 | 111286 | 111306 | 111326 | 111346 | 111366 | 111386 |
| 1117 | 11127 | 11147 | 11167 | 11187 | 111107 | 111127 | 111147 | 111167 | 111187 | 111207 | 111227 | 111247 | 111267 | 111287 | 111307 | 111327 | 111347 | 111367 | 111387 |
| 1118 | 11128 | 11148 | 11168 | 11188 | 111108 | 111128 | 111148 | 111168 | 111188 | 111208 | 111228 | 111248 | 111268 | 111288 | 111308 | 111328 | 111348 | 111368 | 111388 |
| 1119 | 11129 | 11149 | 11169 | 11189 | 111109 | 111129 | 111149 | 111169 | 111189 | 111209 | 111229 | 111249 | 111269 | 111289 | 111309 | 111329 | 111349 | 111369 | 111389 |
| 11110 | 11130 | 11150 | 11170 | 11190 | 111110 | 111130 | 111150 | 111170 | 111190 | 111210 | 111230 | 111250 | 111270 | 111290 | 111310 | 111330 | 111350 | 111370 | 111390 |
| 11111 | 11131 | 11151 | 11171 | 11191 | 111111 | 111131 | 111151 | 111171 | 111191 | 111211 | 111231 | 111251 | 111271 | 111291 | 111311 | 111331 | 111351 | 111371 | 111391 |
| 11112 | 11132 | 11152 | 11172 | 11192 | 111112 | 111132 | 111152 | 111172 | 111192 | 111212 | 111232 | 111252 | 111272 | 111292 | 111312 | 111332 | 111352 | 111372 | 111392 |
| 11113 | 11133 | 11153 | 11173 | 11193 | 111113 | 111133 | 111153 | 111173 | 111193 | 111213 | 111233 | 111253 | 111273 | 111293 | 111313 | 111333 | 111353 | 111373 | 111393 |
| 11114 | 11134 | 11154 | 11174 | 11194 | 111114 | 111134 | 111154 | 111174 | 111194 | 111214 | 111234 | 111254 | 111274 | 111294 | 111314 | 111334 | 111354 | 111374 | 111394 |
| 11115 | 11135 | 11155 | 11175 | 11195 | 111115 | 111135 | 111155 | 111175 | 111195 | 111215 | 111235 | 111255 | 111275 | 111295 | 111315 | 111335 | 111355 | 111375 | 111395 |
| 11116 | 11136 | 11156 | 11176 | 11196 | 111116 | 111136 | 111156 | 111176 | 111196 | 111216 | 111236 | 111256 | 111276 | 111296 | 111316 | 111336 | 111356 | 111376 | 111396 |
| 11117 | 11137 | 11157 | 11177 | 11197 | 111117 | 111137 | 111157 | 111177 | 111197 | 111217 | 111237 | 111257 | 111277 | 111297 | 111317 | 111337 | 111357 | 111377 | 111397 |
| 11118 | 11138 | 11158 | 11178 | 11198 | 111118 | 111138 | 111158 | 111178 | 111198 | 111218 | 111238 | 111258 | 111278 | 111298 | 111318 | 111338 | 111358 | 111378 | 111398 |
| 11119 | 11139 | 11159 | 11179 | 11199 | 111119 | 111139 | 111159 | 111179 | 111199 | 111219 | 111239 | 111259 | 111279 | 111299 | 111319 | 111339 | 111359 | 111379 | 111399 |
| 11120 | 11140 | 11160 | 11180 | 111100 | 111120 | 111140 | 111160 | 111180 | 111200 | 111220 | 111240 | 111260 | 111280 | 111300 | 111320 | 111340 | 111360 | 111380 | 111400 |

## 2. Grid of the 200 10 m x 5 m-plots: case in Mt Elgon 100 mx100m-Forest Unit



| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1111 | 11122 | 11141 | 11161 | 11181 | 111100 | 111120 | 111140 | 111160 | 111180 | 111201 | 111221 | 111241 | 111261 | 111281 | 111300 | 111320 | 111340 | 111360 | 111380 |
| 1113 | 11124 | 11143 | 11163 | 11183 | 111102 | 111122 | 111142 | 111162 | 111182 | 111203 | 111223 | 111243 | 111263 | 111283 | 111302 | 111322 | 111342 | 111362 | 111382 |
| 1116 | 11126 | 11145 | 11165 | 11185 | 111104 | 111124 | 111144 | 111164 | 111184 | 111205 | 111225 | 111245 | 111265 | 111285 | 111304 | 111324 | 111344 | 111364 | 111384 |
| 1118 | 11128 | 11147 | 11167 | 11187 | 111106 | 111126 | 111146 | 111166 | 111186 | 111207 | 111227 | 111247 | 111267 | 111287 | 111306 | 111326 | 111346 | 111366 | 111386 |
| 11111 | 11131 | 11149 | 11169 | 11189 | 111108 | 111128 | 111148 | 111168 | 111188 | 111209 | 111229 | 111249 | 111269 | 111289 | 111308 | 111328 | 111348 | 111368 | 111388 |
| 11113 | 11133 | 11150 | 11170 | 11190 | 111111 | 111131 | 111151 | 111171 | 111191 | 111210 | 111230 | 111250 | 111270 | 111290 | 111311 | 111331 | 111351 | 111371 | 111391 |
| 11115 | 11135 | 11152 | 11172 | 11192 | 111113 | 111133 | 111153 | 111173 | 111193 | 111212 | 111232 | 111252 | 111272 | 111292 | 111313 | 111333 | 111353 | 111373 | 111393 |
| 11117 | 11137 | 11154 | 11174 | 11194 | 111115 | 111135 | 111155 | 111175 | 111195 | 111214 | 111234 | 111254 | 111274 | 111294 | 111315 | 111335 | 111355 | 111375 | 111395 |
| 11119 | 11139 | 11156 | 11176 | 11196 | 111117 | 111137 | 111157 | 111177 | 111197 | 111216 | 111236 | 111256 | 111276 | 111296 | 111317 | 111337 | 111357 | 111377 | 111397 |
| 11120 | 11140 | 11158 | 11178 | 11198 | 111119 | 111139 | 111159 | 111179 | 111199 | 111218 | 111238 | 111258 | 111278 | 111298 | 111319 | 111339 | 111359 | 111379 | 111399 |

### 3. Grid of the 100 10 m x 10 m-plots: case in Mt Elgon 100 mx100m-Forest Unit



| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1111 | 11141 | 11181 | 111120 | 111160 | 111201 | 111241 | 111281 | 111320 | 111360 |
| 1113 | 11143 | 11183 | 111122 | 111162 | 111203 | 111243 | 111283 | 111322 | 111362 |
| 1116 | 11145 | 11185 | 111124 | 111164 | 111205 | 111245 | 111285 | 111324 | 111364 |
| 1118 | 11147 | 11187 | 111126 | 111166 | 111207 | 111247 | 111287 | 111326 | 111366 |
| 11111 | 11149 | 11189 | 111128 | 111168 | 111209 | 111249 | 111289 | 111328 | 111368 |
| 11113 | 11150 | 11190 | 111131 | 111171 | 111210 | 111250 | 111290 | 111331 | 111371 |
| 11115 | 11152 | 11192 | 111133 | 111173 | 111212 | 111252 | 111292 | 111333 | 111373 |
| 11117 | 11154 | 11194 | 111135 | 111175 | 111214 | 111254 | 111294 | 111335 | 111375 |
| 11119 | 11156 | 11196 | 111137 | 111177 | 111216 | 111256 | 111296 | 111337 | 111377 |
| 11120 | 11158 | 11198 | 111139 | 111179 | 111218 | 111258 | 111298 | 111339 | 111379 |

### 4. Grid of the 25 20 m x 20 m-plots: case in Mt Elgon 100 mx100m-Forest Unit

| | | | | |
|---|---|---|---|---|
| 1111 | 11181 | 111160 | 111241 | 111320 |
| 1116 | 11185 | 111164 | 111245 | 111324 |
| 11111 | 11189 | 111168 | 111249 | 111328 |
| 11115 | 11192 | 111173 | 111252 | 111333 |
| 11119 | 11196 | 111177 | 111256 | 111337 |

# APPENDIX IV: SIMPLE RANDOM SAMPLING PROCESS IN R FOR DIFFERENT PLOT SIZES AND SAMPLING INTENSITIES

The processes reported about mt. Elgon are the same across all the other forests

## SIMPLE RANDOM SAMPLING (SRS)

### a. 5 m by 5 m plot size

#### i. 30% intensity (SRS-5mx5m-30% sampling scheme)

We take a sample from 400 plots e.g. 30% (equivalent to 120 plots) by first accessing the list of all the 400 plots (sampling frame) as follows:

```
uniq_plots = unique(mt_elgon$PLOT.NO.)
length(uniq_plots)
## [1] 400
```

Now that we have 400 plots, we can pick SRS samples of different sizes ie for different intensities 30%, 20%, 10%, 5%. For reproducibility, let us set our seed to 100

```
set.seed(100)
# 30% sample
size_30 = sample(uniq_plots, 0.3*400)
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]

length(unique(mt_elgon_0.3$PLOT.NO.))
## [1] 120
```

List of the one hundred and twenty 5mx5m-plots for SRS- 5 m x 5 m-30% sampling scheme in Mt Elgon forest is thus generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).

*Display of samples for all the three forests are indicated in Appendix VI.1.*

#### ii. 20% intensity (SRS-5mx5m-20% sampling scheme)

```
# 20% sample
size_20 = sample(uniq_plots, 0.2*400)
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]

length(unique(mt_elgon_0.2$PLOT.NO.))
## [1] 80
```

List of the eighty 5mx5m-plots for SRS- 5 m x 5 m-20% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).

*Display of samples for all the three forests are indicated in Appendix VI.2.*

#### iii. 10% intensity (SRS-5mx5m-10% sampling scheme)

```
# 10% sample
size_10 = sample(uniq_plots, 0.1*400)
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]

length(unique(mt_elgon_0.1$PLOT.NO.))
## [1] 40
```

List of the fourty 5mx5m-plots for SRS- 5 m x 5 m-10% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk). *Display of samples for all the three forests are indicated in Appendix VI.3.*

### iv. 5% intensity (SRS-5mx5m-5% sampling scheme)

```
# 5% sample
size_5 = sample(uniq_plots, 0.05*400)
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]

length(unique(mt_elgon_0.05$PLOT.NO.))
## [1] 20
```

List of the twenty 5mx5m-plots for SRS-5 mx5m-5% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk). *Display of samples for all the three forests are indicated in Appendix VI.4.*

## b. 10 m by 5 m plot size

### i. 30% intensity (SRS-10mx5m-30% sampling scheme)

We take a sample from 200 plots e.g. 30% (equivalent to 60 plots) by first accessing the list of all the 200 plots (sampling frame) as follows:

```
uniq_plots = unique(mt_elgon$PLOT.NO.)
length(uniq_plots)
## [1] 200
```

Now that we have our 200 plots, we can pick SRS samples of different sizes ie for different intensities 30%, 20%, 10%, 5%. For reproducibility, let us set our seed to 100

```
set.seed(100)
# 30% sample
size_30 = sample(uniq_plots, 0.3*nrow(mt_elgon))
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]

length(unique(mt_elgon_0.3$PLOT.NO.))
## [1] 60
```

List of the sixty 0mx 5 m plots for SRS-10 m x 5 m-30% sampling scheme in Mt Elgon forest is thus generated. Similar procedure was applied on other forests by replacing the

name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).
*Display of samples for all the three forests are indicated in Appendix VI.5.*

### ii. 20% intensity (SRS-10mx5m-20% sampling scheme)

```
# 20% sample
size_20 = sample(uniq_plots, 0.2*nrow(mt_elgon))
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]

length(unique(mt_elgon_0.2$PLOT.NO.))
## [1] 40
```

List of the fourty 10mx5m-plots for SRS-10 m x 5 m-20% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).
*Display of samples for all the three forests are indicated in Appendix VI.6.*

### iii. 10% intensity (SRS-10mx5m-10% sampling scheme)

```
# 10% sample
size_10 = sample(uniq_plots, 0.1*nrow(mt_elgon))
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]

length(unique(mt_elgon_0.1$PLOT.NO.))
## [1] 20
```

List of the twenty 10mx5m-plots for SRS-10 m x 5 m-10% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).
*Display of samples for all the three forests are indicated in Appendix VI.7.*

### iv. 5% intensity (SRS-10mx5m-5% sampling scheme)

```
# 5% sample
size_5 = sample(uniq_plots, 0.05*nrow(mt_elgon))
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]

length(unique(mt_elgon_0.05$PLOT.NO.))
## [1] 10
```

List of the ten 10mx5m-plots for SRS-10mx5m-5% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).
*Display of samples for all the three forests are indicated in Appendix VI.8.*

## c. 10 m by 10 m plot size

### i. 30% intensity (SRS-10mx10m-30% sampling scheme)

We take a sample from 100 plots e.g. 30% (equivalent to 30 plots) by first accessing the list of all the 100 plots (sampling frame) as follows:

```
uniq_plots = unique(mt_elgon$PLOT.NO.)
length(uniq_plots)
## [1] 100
```

Now that we have our 100 plots, we can pick SRS samples of different sizes ie for different intensities 30%, 20%, 10%, 5%. For reproducibility, let us set our seed to 100

```
set.seed(100)
# 30% sample
size_30 = sample(uniq_plots, 0.3*nrow(mt_elgon))
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]

length(unique(mt_elgon_0.3$PLOT.NO.))
## [1] 30
```

List of the thirty 10mx10m-plots for SRS-10mx10m-30% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk). *Display of samples for all the three forests are indicated in Appendix VI.9.*

### ii. 20% intensity (SRS-10mx10m-20% sampling scheme)

```
# 20% sample
size_20 = sample(uniq_plots, 0.2*nrow(mt_elgon))
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]

length(unique(mt_elgon_0.2$PLOT.NO.))
## [1] 20
```

List of the twenty 10mx10m-plots for SRS-10mx10m-20% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk). *Display of samples for all the three forests are indicated in Appendix VI.10.*

### iii. 10% intensity (SRS-10mx10m-10% sampling scheme)

```
# 10% sample
size_10 = sample(uniq_plots, 0.1*nrow(mt_elgon))
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]

length(unique(mt_elgon_0.1$PLOT.NO.))
## [1] 10
```

List of the ten 10mx10m-plots for SRS-10mx10m-10% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk). *Display of samples for all the three forests are indicated in Appendix VI.11.*

#### iv. 5% intensity (SRS-10mx10m-5% sampling scheme)

```
# 5% sample
size_5 = sample(uniq_plots, 0.05*nrow(mt_elgon))
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]

length(unique(mt_elgon_0.05$PLOT.NO.))
## [1] 5
```

List of the five 10mx10m-plots for SRS-10mx10m-5% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).
*Display of samples for all the three forests are indicated in Appendix VI.12.*

### d. 20 m by 20 m plot size

#### i. 30% intensity (SRS-20mx20m-30% sampling scheme)

We take a sample from 25 plots e.g. 30% (equivalent to 7 plots) by first accessing the list of all the 25 plots (sampling frame) as follows:

```
uniq_plots = unique(mt_elgon$PLOT.NO.)
length(uniq_plots)
## [1] 25
```

Now that we have our 25 plots, we can pick SRS samples of different sizes ie for different intensities 30%, 20%, 10%, 5%. For reproducibility, let us set our seed to 100

```
set.seed(100)
# 30% sample
size_30 = sample(uniq_plots, 0.3*nrow(mt_elgon))
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]

length(unique(mt_elgon_0.3$PLOT.NO.))
## [1] 7
```

List of the seven 20mx20m-plots for SRS-20mx20m-30% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).
*Display of samples for all the three forests are indicated in Appendix VI.13.*

#### ii. 20% intensity (SRS-20mx20m-20% sampling scheme)

```
# 20% sample
size_20 = sample(uniq_plots, 0.2*nrow(mt_elgon))
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]

length(unique(mt_elgon_0.2$PLOT.NO.))
## [1] 5
```

List of the five 20mx20m-plots for SRS-20mx20m-20% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).
*Display of samples for all the three forests are indicated in Appendix VI.14.*

### iii. 10% intensity (SRS-20mx20m-10% sampling scheme)

```
# 10% sample
size_10 = sample(uniq_plots, 0.1*nrow(mt_elgon))
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]

length(unique(mt_elgon_0.1$PLOT.NO.))
## [1] 2
```

List of the two 20mx20m-plots for SRS-20mx20m-10% sampling scheme in Mt Elgon forest is generated. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).
*Display of samples for all the three forests are indicated in Appendix VI.15.*

### iv. 5% intensity (SRS-20mx20m-5% sampling scheme)

```
# 5% sample
size_5 = sample(uniq_plots, 0.05*nrow(mt_elgon))
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]

length(unique(mt_elgon_0.05$PLOT.NO.))
## [1] 1
```

Identity of the one 20mx20m-plot for SRS-20mx20m-5% sampling scheme in Mt Elgon forest is given. Similar procedure was applied on other forests by replacing the name of forest (mt_elgon) in R codes by that of the forest of interest (Kakamega or Loruk).
*Display of samples for all the three forests are indicated in Appendix VI.16.*

# APPENDIX V: SYSTEMATIC SAMPLING PROCESS IN R FOR DIFFERENT PLOT SIZES AND SAMPLING INTENSITIES

## V.1. SYSTEMATIC SAMPLING ALONG HORIZONTAL BELT TRANSECT (SSH) – EXAMPLE FROM MT. ELGON MONTANE FOREST

Horizontal transect faced East-West direction within the 100 m x 100 m forest unit. We sampled rows up to specified intensities.

a. 5 m by 5 m plot size

   i. 30% intensity

```
library(reshape2)
# 30% sample
size_30 = nrow(uniq_plots) * ncol(uniq_plots) * 0.3
## since each row has 20 plots, we get the number of rows to pick as
size_30  = size_30/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_30  = uniq_plots [8:13,]
size_30 = melt(size_30, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]
```

*Display of list of 5 m by 5 m plots with 30% SSH samples Appendix IX*

   ii. 20% intensity

```
# 20% sample
size_20 = nrow(uniq_plots) * ncol(uniq_plots) * 0.2
## since each row has 20 plots, we get the number of rows to pick as
size_20  = size_20/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_20  = uniq_plots [9:12,]
size_20 = melt(size_20, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]
```

*Display of list of 5 m by 5 m plots with 20% SSH samples Appendix VIII.*

   iii. 10% intensity

```
# 10% sample
size_10 = nrow(uniq_plots) * ncol(uniq_plots) * 0.1
## since each row has 20 plots, we get the number of rows to pick as
size_10  = size_10/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_10  = uniq_plots [8:13,]
size_10 = melt(size_10, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
```

```
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]
```

*Display of list of 5 m by 5 m plots with 10% SSH samples in Appendices VII.*

iv. 5% intensity

```
# 5% sample
size_5 = nrow(uniq_plots) * ncol(uniq_plots) * 0.05
## since each row has 20 plots, we get the number of rows to pick as
size_5  = size_5/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_5  = uniq_plots [8:13,]
size_5 = melt(size_5, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]
```

*Display of list of 5 m by 5 m plots with 5% SSH samples Appendix VI.*

b. 10 m by 5 m plot size

i. 30% intensity

```
library(reshape2)
# 30% sample
size_30 = nrow(uniq_plots) * ncol(uniq_plots) * 0.3
## since each row has 10 plots, we get the number of rows to pick as
size_30  = size_30/10
## we will therefore pick the 6 middle rows ie 8 to 13
size_30  = uniq_plots [8:13,]
size_30 = melt(size_30, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]
```

*Display of list of 10 m by 5 m plots with 30% SSH samples in Appendix IX.*

ii. 20% intensity

```
# 20% sample
size_20 = nrow(uniq_plots) * ncol(uniq_plots) * 0.2
## since each row has 20 plots, we get the number of rows to pick as
size_20  = size_20/10
## we will therefore pick the 6 middle rows ie 8 to 13
size_20  = uniq_plots [9:12,]
size_20 = melt(size_20, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]
```

*Display of list of 10 m by 5 m plots with 20% SSH samples in Appendix VIII.*

iii. 10% intensity

```
size_10 = nrow(uniq_plots) * ncol(uniq_plots) * 0.1
## since each row has 20 plots, we get the number of rows to pick as
```

```
size_10  = size_10/10
## we will therefore pick the 6 middle rows ie 8 to 13
size_10  = uniq_plots [10:11,]
size_10 = melt(size_10, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will  be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]
```

*Display of list of 10 m by 5 m plots with 10% SSH samples in Appendix VII.*

iv. 5% intensity

```
# 5% sample
size_5 = nrow(uniq_plots) * ncol(uniq_plots) * 0.05
## since each row has 20 plots, we get the number of rows to pick as
size_5  = size_5/10
## we will therefore pick the 6 middle rows ie 8 to 13
size_5  = uniq_plots [11,]
size_5 = melt(size_5, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]
```

*Display of list of 10 m by 5 m plots with 5% SSH samples in Appendix VI*

c. 10 m by 10 m plot size

i. 30% intensity

```
# 30% sample
size_30 = nrow(uniq_plots) * ncol(uniq_plots) * 0.3
## since each row has 10 plots, we get the number of rows to pick as
size_30  = size_30/10
## we will therefore pick the 6 middle rows ie 8 to 13
size_30  = uniq_plots [5:7,]
size_30 = melt(size_30, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]
```

*Display of list of 10m by 10m plots with 30% SSH samples in Appendix IX*

ii. 20% intensity

```
# 20% sample
size_20 = nrow(uniq_plots) * ncol(uniq_plots) * 0.2
## since each row has 20 plots, we get the number of rows to pick as
size_20  = size_20/10
## we will therefore pick the 6 middle rows ie 8 to 13
size_20  = uniq_plots [5:6,]
size_20 = melt(size_20, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
```

```
## now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]
```

*Display of list of 10m by 10m plots with 20% SSH samples in Appendix VIII.*

iii. 10% intensity

```
# 10% sample
size_10 = nrow(uniq_plots) * ncol(uniq_plots) * 0.1
## since each row has 20 plots, we get the number of rows to pick as
size_10  = size_10/10
## we will therefore pick the 6 middle rows ie 8 to 13
size_10  = uniq_plots [5,]
size_10 = melt(size_10, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]
```

*Display of list of 10m by 10m plots with 10% SSH samples in Appendix VII*

iv. 5% intensity

```
# 5% sample
size_5 = nrow(uniq_plots) * ncol(uniq_plots) * 0.05
## since each row has 20 plots, we get the number of rows to pick as
size_5  = size_5/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_5  = uniq_plots [5, 1:5]
size_5 = melt(size_5, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]
```

*Display of list of 10m by 10m plots with 5% SSH samples in Appendix VI.*

### d. 20 m by 20 m plot size

i. 30% intensity

```
# 30% sample
size_30 = nrow(uniq_plots) * ncol(uniq_plots) * 0.3
## since each row has 5 plots, we get the number of rows to pick as
size_30  = size_30/5
## we will therefore pick the 6 middle rows ie 8 to 13
size_30  = c(uniq_plots [3,], uniq_plots [4, 1:3])
size_30 = melt(size_30, id.var = NULL, variable.name= "v1")
## now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30$value ),]
```

*Display of list of 20 m by 20 m plots with 30% SSH samples in Appendix IX*

ii. 20% intensity

```
# 20% sample
size_20 = nrow(uniq_plots) * ncol(uniq_plots) * 0.2
## since each row has 5 plots, we get the number of rows to pick as
```

```
size_20  = size_20/5
## we will therefore pick the 6 middle rows ie 8 to 13
size_20  = uniq_plots [3,]
size_20 = melt(size_20, id.var = NULL, variable.name= "v1")
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20$value),]
```

*Display of list of 20 m by 20 m plots with 20% SSH samples in Appendix VIII*

iii. 10% intensity

```
# 10% sample
size_10 = nrow(uniq_plots) * ncol(uniq_plots) * 0.1
## since each row has 5 plots, we get the number of rows to pick as
size_10  = size_10/5
## we will therefore pick the 6 middle rows ie 8 to 13
size_10  = uniq_plots [5,1:3]
size_10 = melt(size_10, id.var = NULL, variable.name= "v1")
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10$value),]
```

*Display of list of 20 m by 20 m plots with 10% SSH samples* ***in VII***

iv. 5% intensity

```
# 5% sample
size_5 = nrow(uniq_plots) * ncol(uniq_plots) * 0.05
## since each row has 5 plots, we get the number of rows to pick as
size_5  = size_5/5
## we will therefore pick the 6 middle rows ie 8 to 13
size_5  = uniq_plots [5, 1:2]
size_5 = melt(size_5, id.var = NULL, variable.name= "v1")
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5$value),]
```

*Display of list of 20 m by 20 m plots with 5% SSH samples in Appendix VI.*

## V.2. SYSTEMATIC SAMPLING ALONG VERTICAL BELT TRANSECT (SSV) – EXAMPLE FROM MT. ELGON MONTANE FOREST

Vertical transect faced North-South direction within the 100 m x 100 m forest unit. We sampled columns up to specified intensities.

a. 5 m by 5 m plot

i. 30%

```
# 30% sample
size_30 = nrow(uniq_plots) * ncol(uniq_plots) * 0.3
## since each row has 20 plots, we get the number of rows to pick as
size_30  = size_30/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_30  = uniq_plots [,8:13]
size_30 = melt(size_30, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]
```

*Display of list of 5 m by 5 m plots with 30% SSV samples in Appendix IX.*

ii. 20% intensity

```
# 20% sample
size_20 = nrow(uniq_plots) * ncol(uniq_plots) * 0.2
## since each row has 20 plots, we get the number of rows to pick as
size_20  = size_20/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_20  = uniq_plots [,9:12]
size_20 = melt(size_20, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]
```

*Display of list of 5 m by 5 m plots with 20% SSV samples in Appendix VIII.*

iii. 10% intensity

```
# 10% sample
size_10 = nrow(uniq_plots) * ncol(uniq_plots) * 0.1
## since each row has 20 plots, we get the number of rows to pick as
size_10  = size_10/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_10  = uniq_plots [,8:13]
size_10 = melt(size_10, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]
```

*Display of list of 5 m by 5 m plots with 10% SSV samples in Appendix VII.*

### iv. 5% intensity

```
# 5% sample
size_5 = nrow(uniq_plots) * ncol(uniq_plots) * 0.05
## since each row has 20 plots, we get the number of rows to pick as
size_5  = size_5/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_5  = uniq_plots [,8:13]
size_5 = melt(size_5, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]
```

*Display of list of 5 m by 5 m plots with 5% SSV samples in Appendix VI.*

## b. 10 m by 5 m plot size

### i. 30% intensity

```
# 30% sample
size_30 = nrow(uniq_plots) * ncol(uniq_plots) * 0.3
## since each column has 20 plots, we get the number of rows to pick as
size_30  = size_30/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_30  = uniq_plots [,5:7]
size_30 = melt(size_30, id.var = NULL, variable.name= "v5")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]
```

*Display of list of 10 m by 5 m plots with 30% SSV samples in Appendix IX.*

### ii. 20% intensity

```
# 20% sample
size_20 = nrow(uniq_plots) * ncol(uniq_plots) * 0.2
## since each row has 20 plots, we get the number of rows to pick as
size_20  = size_20/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_20  = uniq_plots [,5:6]
size_20 = melt(size_20, id.var = NULL, variable.name= "v5")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]
```

*Display of list of 10 m by 5 m plots with 20% SSV samples in Appendix VIII.*

### iii. 10% intensity

```
# 10% sample
size_10 = nrow(uniq_plots) * ncol(uniq_plots) * 0.1
## since each row has 20 plots, we get the number of rows to pick as
size_10  = size_10/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_10  = uniq_plots [,5]
```

```
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]
```

*Display of list of 10 m by 5 m plots with 10% SSV samples in Appendix VII.*

iv. 5% intensity

```
# 5% sample
size_5 = nrow(uniq_plots) * ncol(uniq_plots) * 0.05
## since each row has 20 plots, we get the number of rows to pick as
size_5  = size_5/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_5  = uniq_plots [1:10,5]
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]
```

*Display of list of 10 m by 5 m plots with 5% SSV samples in Appendix VI.*

c. 10 m by 10 m plot

i. 30% intensity

```
# 30% sample
size_30 = nrow(uniq_plots) * ncol(uniq_plots) * 0.3
## since each column has 10 plots, we get the number of rows to pick as
size_30  = size_30/10
## we will therefore pick the 6 middle rows ie 8 to 13
size_30  = uniq_plots [,5:7]
size_30 = melt(size_30, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30),]
```

*Display of list of 10 m by 10 m plots with 30% SSV samples in Appendix IX.*

ii. 20% intensity

```
# 20% sample
size_20 = nrow(uniq_plots) * ncol(uniq_plots) * 0.2
## since each row has 20 plots, we get the number of rows to pick as
size_20  = size_20/10
## we will therefore pick the 6 middle rows ie 8 to 13
size_20  = uniq_plots [,5:6]
size_20 = melt(size_20, id.var = NULL, variable.name= "v1")[,2]
## Warning: attributes are not identical across measure variables; they will be dropped
## Now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]
```

*Display of list of 10 m by 10 m plots with 20% SSV samples in Appendix VIII.*

iii. 10% intensity

```
# 10% sample
size_10 = nrow(uniq_plots) * ncol(uniq_plots) * 0.1
## since each row has 20 plots, we get the number of rows to pick as
size_10  = size_10/10
```

```
## we will therefore pick the 6 middle rows ie 8 to 13
size_10  = uniq_plots [,5]
## now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]
```

*Display of list of 10 m by 10 m plots with 10% SSV samples in Appendix VII.*

#### iv. 5% intensity

```
size_5 = nrow(uniq_plots) * ncol(uniq_plots) * 0.05
## since each row has 20 plots, we get the number of rows to pick as
size_5  = size_5/20
## we will therefore pick the 6 middle rows ie 8 to 13
size_5  = uniq_plots [ 1:5, 5]
## now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]
```

*Display of list of 10 m by 10 m plots with 5% SSV samples in Appendix VI.*

### d. 20 m by 20 m plot size

#### i. 30% intensity

```
# 30% sample
size_30 = nrow(uniq_plots) * ncol(uniq_plots) * 0.3
## since each row has 5 plots, we get the number of rows to pick as
size_30  = size_30/5
## we will therefore pick the 6 middle rows ie 8 to 13
size_30a = uniq_plots [,3]
size_30b = uniq_plots [ 1:3,4]
size_30 = c(melt(size_30a, id.var = NULL, variable.name= "v1"), melt(size_30b, id.var =
NULL, variable.name= "v1"))
size_30 = melt(size_30, id.var = NULL, variable.name= NULL)
## now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.3 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_30$value ),]
```

*Display of list of 20 m by 20 m plots  with 30% SSV samples in Appendix IX.*

#### ii. 20% intensity

```
# 20% sample
size_20 = nrow(uniq_plots) * ncol(uniq_plots) * 0.2
## since each row has 5 plots, we get the number of rows to pick as
size_20  = size_20/5
## we will therefore pick the 6 middle rows ie 8 to 13
size_20  = uniq_plots [,3]
## now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.2 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_20),]
```

*Display of list of 20 m by 20 m plots  with 20% SSV samples in Appendix VIII.*

#### iii. 10% intensity

```
# 10% sample
size_10 = nrow(uniq_plots) * ncol(uniq_plots) * 0.1
## since each row has 5 plots, we get the number of rows to pick as
```

```
size_10  = size_10/5
## we will therefore pick the 6 middle rows ie 8 to 13
size_10  = uniq_plots [1:3,5]
## now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.1 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_10),]
```

*Display of list of 20 m by 20 m plots with 10% SSV samples in Appendix VII.*

iv. 5% intensity

```
# 5% sample
size_5 = nrow(uniq_plots) * ncol(uniq_plots) * 0.05
## since each row has 5 plots, we get the number of rows to pick as
size_5  = size_5/5
## we will therefore pick the 6 middle rows ie 8 to 13
size_5  = uniq_plots [ 1:2,5]
## now subset the plots in mt_elgon whose plot numbers are among the selected regions.
mt_elgon_0.05 = mt_elgon [which(mt_elgon$PLOT.NO. %in% size_5),]
```

*Display of list of 20 m by 20 m plots  with 5% SSV samples in Appendix VI.*

# APPENDIX VI: SAMPLES DRAWN FROM EACH FOREST TYPE USING DIFFERENT SAMPLING DESIGNS, PLOT SIZES AND 5% INTENSITY

## VI.1. 5mx5m-5% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 12217 | 12210 | 122181 | 11117 | 11110 | 111181 | 13117 | 13110 | 131181 |
| 2 | 12224 | 12230 | 122182 | 11124 | 11130 | 111182 | 13124 | 13130 | 131182 |
| 3 | 12251 | 12250 | 122183 | 11151 | 11150 | 111183 | 13151 | 13150 | 131183 |
| 4 | 12288 | 12270 | 122184 | 11188 | 11170 | 111184 | 13188 | 13170 | 131184 |
| 5 | 122110 | 12290 | 122185 | 111110 | 11190 | 111185 | 131110 | 13190 | 131185 |
| 6 | 122111 | 122110 | 122186 | 111111 | 111110 | 111186 | 131111 | 131110 | 131186 |
| 7 | 122118 | 122130 | 122187 | 111118 | 111130 | 111187 | 131118 | 131130 | 131187 |
| 8 | 122123 | 122150 | 122188 | 111123 | 111150 | 111188 | 131123 | 131150 | 131188 |
| 9 | 122144 | 122170 | 122189 | 111144 | 111170 | 111189 | 131144 | 131170 | 131189 |
| 10 | 122152 | 122190 | 122190 | 111152 | 111190 | 111190 | 131152 | 131190 | 131190 |
| 11 | 122236 | 122210 | 122191 | 111236 | 111210 | 111191 | 131236 | 131210 | 131191 |
| 12 | 122261 | 122230 | 122192 | 111261 | 111230 | 111192 | 131261 | 131230 | 131192 |
| 13 | 122265 | 122250 | 122193 | 111265 | 111250 | 111193 | 131265 | 131250 | 131193 |
| 14 | 122281 | 122270 | 122194 | 111281 | 111270 | 111194 | 131281 | 131270 | 131194 |
| 15 | 122282 | 122290 | 122195 | 111282 | 111290 | 111195 | 131282 | 131290 | 131195 |
| 16 | 122286 | 122310 | 122196 | 111286 | 111310 | 111196 | 131286 | 131310 | 131196 |
| 17 | 122302 | 122330 | 122197 | 111302 | 111330 | 111197 | 131302 | 131330 | 131197 |
| 18 | 122326 | 122350 | 122198 | 111326 | 111350 | 111198 | 131326 | 131350 | 131198 |
| 19 | 122327 | 122370 | 122199 | 111327 | 111370 | 111199 | 131327 | 131370 | 131199 |
| 20 | 122373 | 122390 | 122200 | 111373 | 111390 | 111200 | 131373 | 131390 | 131200 |

## VI.2. 10mx5m-5% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 12211 | 12221 | 122161 | 11111 | 11121 | 111161 | 13111 | 13121 | 131161 |
| 2 | 12239 | 12261 | 122163 | 11139 | 11161 | 111163 | 13139 | 13161 | 131163 |
| 3 | 122139 | 122101 | 122165 | 111139 | 111101 | 111165 | 131139 | 131101 | 131165 |
| 4 | 122157 | 122141 | 122167 | 111157 | 111141 | 111167 | 131157 | 131141 | 131167 |
| 5 | 122159 | 122181 | 122169 | 111159 | 111181 | 111169 | 131159 | 131181 | 131169 |
| 6 | 122187 | 122221 | 122171 | 111187 | 111221 | 111171 | 131187 | 131221 | 131171 |
| 7 | 122211 | 122261 | 122173 | 111211 | 111261 | 111173 | 131211 | 131261 | 131173 |
| 8 | 122229 | 122301 | 122175 | 111229 | 111301 | 111175 | 131229 | 131301 | 131175 |
| 9 | 122369 | 122341 | 122177 | 111369 | 111341 | 111177 | 131369 | 131341 | 131177 |
| 10 | 122387 | 122381 | 122179 | 111387 | 111381 | 111179 | 131387 | 131381 | 131179 |

### VI.3. 10mx10m-5% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 122165 | 1229 | 122161 | 111165 | 1119 | 111161 | 131165 | 1319 | 131161 |
| 2 | 122173 | 12249 | 122163 | 111173 | 11149 | 111163 | 131173 | 13149 | 131163 |
| 3 | 122249 | 12289 | 122165 | 111249 | 11189 | 111165 | 131249 | 13189 | 131165 |
| 4 | 122251 | 122129 | 122167 | 111251 | 111129 | 111167 | 131251 | 131129 | 131167 |
| 5 | 122369 | 122169 | 122169 | 111369 | 111169 | 111169 | 131369 | 131169 | 131169 |

### VI.4. 20mx20m-5% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 122321 | 1229 | 122161 | 111257 | 11117 | 111321 | 131257 | 1319 | 131161 |

## APPENDIX VII: SAMPLES DRAWN FROM EACH FOREST TYPE USING DIFFERENT SAMPLING DESIGNS, PLOT SIZES AND 10% INTENSITY

### VII.1 5mx5m-10% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 12214 | 12210 | 122181 | 11114 | 11110 | 111181 | 13114 | 13110 | 131181 |
| 2 | 12227 | 12211 | 122182 | 11127 | 11111 | 111182 | 13127 | 13111 | 131182 |
| 3 | 12229 | 12230 | 122183 | 11129 | 11130 | 111183 | 13129 | 13130 | 131183 |
| 4 | 12285 | 12231 | 122184 | 11185 | 11131 | 111184 | 13185 | 13131 | 131184 |
| 5 | 122102 | 12250 | 122185 | 111102 | 11150 | 111185 | 131102 | 13150 | 131185 |
| 6 | 122110 | 12251 | 122186 | 111110 | 11151 | 111186 | 131110 | 13151 | 131186 |
| 7 | 122111 | 12270 | 122187 | 111111 | 11170 | 111187 | 131111 | 13170 | 131187 |
| 8 | 122114 | 12271 | 122188 | 111114 | 11171 | 111188 | 131114 | 13171 | 131188 |
| 9 | 122127 | 12290 | 122189 | 111127 | 11190 | 111189 | 131127 | 13190 | 131189 |
| 10 | 122135 | 12291 | 122190 | 111135 | 11191 | 111190 | 131135 | 13191 | 131190 |
| 11 | 122137 | 122110 | 122191 | 111137 | 111110 | 111191 | 131137 | 131110 | 131191 |
| 12 | 122138 | 122111 | 122192 | 111138 | 111111 | 111192 | 131138 | 131111 | 131192 |
| 13 | 122139 | 122130 | 122193 | 111139 | 111130 | 111193 | 131139 | 131130 | 131193 |
| 14 | 122147 | 122131 | 122194 | 111147 | 111131 | 111194 | 131147 | 131131 | 131194 |
| 15 | 122148 | 122150 | 122195 | 111148 | 111150 | 111195 | 131148 | 131150 | 131195 |
| 16 | 122165 | 122151 | 122196 | 111165 | 111151 | 111196 | 131165 | 131151 | 131196 |
| 17 | 122167 | 122170 | 122197 | 111167 | 111170 | 111197 | 131167 | 131170 | 131197 |
| 18 | 122175 | 122171 | 122198 | 111175 | 111171 | 111198 | 131175 | 131171 | 131198 |
| 19 | 122204 | 122190 | 122199 | 111204 | 111190 | 111199 | 131204 | 131190 | 131199 |
| 20 | 122217 | 122191 | 122200 | 111217 | 111191 | 111200 | 131217 | 131191 | 131200 |
| 21 | 122227 | 122210 | 122201 | 111227 | 111210 | 111201 | 131227 | 131210 | 131201 |
| 22 | 122228 | 122211 | 122202 | 111228 | 111211 | 111202 | 131228 | 131211 | 131202 |
| 23 | 122241 | 122230 | 122203 | 111241 | 111230 | 111203 | 131241 | 131230 | 131203 |
| 24 | 122244 | 122231 | 122204 | 111244 | 111231 | 111204 | 131244 | 131231 | 131204 |
| 25 | 122248 | 122250 | 122205 | 111248 | 111250 | 111205 | 131248 | 131250 | 131205 |
| 26 | 122255 | 122251 | 122206 | 111255 | 111251 | 111206 | 131255 | 131251 | 131206 |
| 27 | 122279 | 122270 | 122207 | 111279 | 111270 | 111207 | 131279 | 131270 | 131207 |
| 28 | 122285 | 122271 | 122208 | 111285 | 111271 | 111208 | 131285 | 131271 | 131208 |
| 29 | 122293 | 122290 | 122209 | 111293 | 111290 | 111209 | 131293 | 131290 | 131209 |
| 30 | 122312 | 122291 | 122210 | 111312 | 111291 | 111210 | 131312 | 131291 | 131210 |
| 31 | 122316 | 122310 | 122211 | 111316 | 111310 | 111211 | 131316 | 131310 | 131211 |
| 32 | 122327 | 122311 | 122212 | 111327 | 111311 | 111212 | 131327 | 131311 | 131212 |
| 33 | 122343 | 122330 | 122213 | 111343 | 111330 | 111213 | 131343 | 131330 | 131213 |
| 34 | 122347 | 122331 | 122214 | 111347 | 111331 | 111214 | 131347 | 131331 | 131214 |
| 35 | 122359 | 122350 | 122215 | 111359 | 111350 | 111215 | 131359 | 131350 | 131215 |
| 36 | 122364 | 122351 | 122216 | 111364 | 111351 | 111216 | 131364 | 131351 | 131216 |
| 37 | 122382 | 122370 | 122217 | 111382 | 111370 | 111217 | 131382 | 131370 | 131217 |
| 38 | 122384 | 122371 | 122218 | 111384 | 111371 | 111218 | 131384 | 131371 | 131218 |
| 39 | 122386 | 122390 | 122219 | 111386 | 111390 | 111219 | 131386 | 131390 | 131219 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 40 | 122392 | 122391 | 122220 | 111392 | 111391 | 111220 | 131392 | 131391 | 131220 |

### VII.2. 10mx5m-10% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 1225 | 12219 | 122161 | 1115 | 11119 | 111161 | 1315 | 13119 | 131161 |
| 2 | 12213 | 12221 | 122163 | 11113 | 11121 | 111163 | 13113 | 13121 | 131163 |
| 3 | 12217 | 12259 | 122165 | 11117 | 11159 | 111165 | 13117 | 13159 | 131165 |
| 4 | 12231 | 12261 | 122167 | 11131 | 11161 | 111167 | 13131 | 13161 | 131167 |
| 5 | 12273 | 12299 | 122169 | 11173 | 11199 | 111169 | 13173 | 13199 | 131169 |
| 6 | 12289 | 122101 | 122171 | 11189 | 111101 | 111171 | 13189 | 131101 | 131171 |
| 7 | 122131 | 122139 | 122173 | 111131 | 111139 | 111173 | 131131 | 131139 | 131173 |
| 8 | 122143 | 122141 | 122175 | 111143 | 111141 | 111175 | 131143 | 131141 | 131175 |
| 9 | 122155 | 122179 | 122177 | 111155 | 111179 | 111177 | 131155 | 131179 | 131177 |
| 10 | 122205 | 122181 | 122179 | 111205 | 111181 | 111179 | 131205 | 131181 | 131179 |
| 11 | 122223 | 122219 | 122181 | 111223 | 111219 | 111181 | 131223 | 131219 | 131181 |
| 12 | 122265 | 122221 | 122183 | 111265 | 111221 | 111183 | 131265 | 131221 | 131183 |
| 13 | 122267 | 122259 | 122185 | 111267 | 111259 | 111185 | 131267 | 131259 | 131185 |
| 14 | 122271 | 122261 | 122187 | 111271 | 111261 | 111187 | 131271 | 131261 | 131187 |
| 15 | 122305 | 122299 | 122189 | 111305 | 111299 | 111189 | 131305 | 131299 | 131189 |
| 16 | 122317 | 122301 | 122191 | 111317 | 111301 | 111191 | 131317 | 131301 | 131191 |
| 17 | 122337 | 122339 | 122193 | 111337 | 111339 | 111193 | 131337 | 131339 | 131193 |
| 18 | 122359 | 122341 | 122195 | 111359 | 111341 | 111195 | 131359 | 131341 | 131195 |
| 19 | 122377 | 122379 | 122197 | 111377 | 111379 | 111197 | 131377 | 131379 | 131197 |
| 20 | 122387 | 122381 | 122199 | 111387 | 111381 | 111199 | 131387 | 131381 | 131199 |

### VII.3. 10mx10m-10% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 12243 | 1229 | 122161 | 11143 | 1119 | 111161 | 13143 | 1319 | 131161 |
| 2 | 12259 | 12249 | 122163 | 11159 | 11149 | 111163 | 13159 | 13149 | 131163 |
| 3 | 12283 | 12289 | 122165 | 11183 | 11189 | 111165 | 13183 | 13189 | 131165 |
| 4 | 12287 | 122129 | 122167 | 11187 | 111129 | 111167 | 13187 | 131129 | 131167 |
| 5 | 12289 | 122169 | 122169 | 11189 | 111169 | 111169 | 13189 | 131169 | 131169 |
| 6 | 12293 | 122209 | 122171 | 11193 | 111209 | 111171 | 13193 | 131209 | 131171 |
| 7 | 122127 | 122249 | 122173 | 111127 | 111249 | 111173 | 131127 | 131249 | 131173 |
| 8 | 122209 | 122289 | 122175 | 111209 | 111289 | 111175 | 131209 | 131289 | 131175 |
| 9 | 122213 | 122329 | 122177 | 111213 | 111329 | 111177 | 131213 | 131329 | 131177 |
| 10 | 122377 | 122369 | 122179 | 111377 | 111369 | 111179 | 131377 | 131369 | 131179 |

### VII.4. 20mx20m-10% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 12297 | 1229 | 122161 | 11189 | 11117 | 111321 | 13189 | 131161 | 131161 |
| 2 | 122245 | 12289 | 122165 | 11197 | 11197 | 111325 | 13197 | 131165 | 131161 |

# APPENDIX VIII: SAMPLES DRAWN FROM EACH FOREST TYPE USING DIFFERENT SAMPLING DESIGNS, PLOT SIZES AND 20% INTENSITY

### VIII.1.5mx5m-20% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 1227 | 1229 | 122161 | 1117 | 1119 | 111161 | 1317 | 1319 | 131161 |
| 2 | 1228 | 12210 | 122162 | 1118 | 11110 | 111162 | 1318 | 13110 | 131162 |
| 3 | 12210 | 12211 | 122163 | 11110 | 11111 | 111163 | 13110 | 13111 | 131163 |
| 4 | 12212 | 12212 | 122164 | 11112 | 11112 | 111164 | 13112 | 13112 | 131164 |
| 5 | 12217 | 12229 | 122165 | 11117 | 11129 | 111165 | 13117 | 13129 | 131165 |
| 6 | 12232 | 12230 | 122166 | 11132 | 11130 | 111166 | 13132 | 13130 | 131166 |
| 7 | 12233 | 12231 | 122167 | 11133 | 11131 | 111167 | 13133 | 13131 | 131167 |
| 8 | 12237 | 12232 | 122168 | 11137 | 11132 | 111168 | 13137 | 13132 | 131168 |
| 9 | 12239 | 12249 | 122169 | 11139 | 11149 | 111169 | 13139 | 13149 | 131169 |
| 10 | 12240 | 12250 | 122170 | 11140 | 11150 | 111170 | 13140 | 13150 | 131170 |
| 11 | 12242 | 12251 | 122171 | 11142 | 11151 | 111171 | 13142 | 13151 | 131171 |
| 12 | 12247 | 12252 | 122172 | 11147 | 11152 | 111172 | 13147 | 13152 | 131172 |
| 13 | 12251 | 12269 | 122173 | 11151 | 11169 | 111173 | 13151 | 13169 | 131173 |
| 14 | 12255 | 12270 | 122174 | 11155 | 11170 | 111174 | 13155 | 13170 | 131174 |
| 15 | 12258 | 12271 | 122175 | 11158 | 11171 | 111175 | 13158 | 13171 | 131175 |
| 16 | 12263 | 12272 | 122176 | 11163 | 11172 | 111176 | 13163 | 13172 | 131176 |
| 17 | 12267 | 12289 | 122177 | 11167 | 11189 | 111177 | 13167 | 13189 | 131177 |
| 18 | 12274 | 12290 | 122178 | 11174 | 11190 | 111178 | 13174 | 13190 | 131178 |
| 19 | 12293 | 12291 | 122179 | 11193 | 11191 | 111179 | 13193 | 13191 | 131179 |
| 20 | 12297 | 12292 | 122180 | 11197 | 11192 | 111180 | 13197 | 13192 | 131180 |
| 21 | 12299 | 122109 | 122181 | 11199 | 111109 | 111181 | 13199 | 131109 | 131181 |
| 22 | 122113 | 122110 | 122182 | 111113 | 111110 | 111182 | 131113 | 131110 | 131182 |
| 23 | 122117 | 122111 | 122183 | 111117 | 111111 | 111183 | 131117 | 131111 | 131183 |
| 24 | 122140 | 122112 | 122184 | 111140 | 111112 | 111184 | 131140 | 131112 | 131184 |
| 25 | 122144 | 122129 | 122185 | 111144 | 111129 | 111185 | 131144 | 131129 | 131185 |
| 26 | 122146 | 122130 | 122186 | 111146 | 111130 | 111186 | 131146 | 131130 | 131186 |
| 27 | 122154 | 122131 | 122187 | 111154 | 111131 | 111187 | 131154 | 131131 | 131187 |
| 28 | 122157 | 122132 | 122188 | 111157 | 111132 | 111188 | 131157 | 131132 | 131188 |
| 29 | 122159 | 122149 | 122189 | 111159 | 111149 | 111189 | 131159 | 131149 | 131189 |
| 30 | 122172 | 122150 | 122190 | 111172 | 111150 | 111190 | 131172 | 131150 | 131190 |
| 31 | 122177 | 122151 | 122191 | 111177 | 111151 | 111191 | 131177 | 131151 | 131191 |
| 32 | 122182 | 122152 | 122192 | 111182 | 111152 | 111192 | 131182 | 131152 | 131192 |
| 33 | 122187 | 122169 | 122193 | 111187 | 111169 | 111193 | 131187 | 131169 | 131193 |
| 34 | 122189 | 122170 | 122194 | 111189 | 111170 | 111194 | 131189 | 131170 | 131194 |
| 35 | 122193 | 122171 | 122195 | 111193 | 111171 | 111195 | 131193 | 131171 | 131195 |
| 36 | 122194 | 122172 | 122196 | 111194 | 111172 | 111196 | 131194 | 131172 | 131196 |
| 37 | 122204 | 122189 | 122197 | 111204 | 111189 | 111197 | 131204 | 131189 | 131197 |
| 38 | 122205 | 122190 | 122198 | 111205 | 111190 | 111198 | 131205 | 131190 | 131198 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 39 | 122207 | 122191 | 122199 | 111207 | 111191 | 111199 | 131207 | 131191 | 131199 |
| 40 | 122216 | 122192 | 122200 | 111216 | 111192 | 111200 | 131216 | 131192 | 131200 |
| 41 | 122217 | 122209 | 122201 | 111217 | 111209 | 111201 | 131217 | 131209 | 131201 |
| 42 | 122223 | 122210 | 122202 | 111223 | 111210 | 111202 | 131223 | 131210 | 131202 |
| 43 | 122224 | 122211 | 122203 | 111224 | 111211 | 111203 | 131224 | 131211 | 131203 |
| 44 | 122228 | 122212 | 122204 | 111228 | 111212 | 111204 | 131228 | 131212 | 131204 |
| 45 | 122232 | 122229 | 122205 | 111232 | 111229 | 111205 | 131232 | 131229 | 131205 |
| 46 | 122241 | 122230 | 122206 | 111241 | 111230 | 111206 | 131241 | 131230 | 131206 |
| 47 | 122244 | 122231 | 122207 | 111244 | 111231 | 111207 | 131244 | 131231 | 131207 |
| 48 | 122251 | 122232 | 122208 | 111251 | 111232 | 111208 | 131251 | 131232 | 131208 |
| 49 | 122253 | 122249 | 122209 | 111253 | 111249 | 111209 | 131253 | 131249 | 131209 |
| 50 | 122254 | 122250 | 122210 | 111254 | 111250 | 111210 | 131254 | 131250 | 131210 |
| 51 | 122256 | 122251 | 122211 | 111256 | 111251 | 111211 | 131256 | 131251 | 131211 |
| 52 | 122268 | 122252 | 122212 | 111268 | 111252 | 111212 | 131268 | 131252 | 131212 |
| 53 | 122274 | 122269 | 122213 | 111274 | 111269 | 111213 | 131274 | 131269 | 131213 |
| 54 | 122275 | 122270 | 122214 | 111275 | 111270 | 111214 | 131275 | 131270 | 131214 |
| 55 | 122278 | 122271 | 122215 | 111278 | 111271 | 111215 | 131278 | 131271 | 131215 |
| 56 | 122287 | 122272 | 122216 | 111287 | 111272 | 111216 | 131287 | 131272 | 131216 |
| 57 | 122294 | 122289 | 122217 | 111294 | 111289 | 111217 | 131294 | 131289 | 131217 |
| 58 | 122298 | 122290 | 122218 | 111298 | 111290 | 111218 | 131298 | 131290 | 131218 |
| 59 | 122301 | 122291 | 122219 | 111301 | 111291 | 111219 | 131301 | 131291 | 131219 |
| 60 | 122307 | 122292 | 122220 | 111307 | 111292 | 111220 | 131307 | 131292 | 131220 |
| 61 | 122313 | 122309 | 122221 | 111313 | 111309 | 111221 | 131313 | 131309 | 131221 |
| 62 | 122316 | 122310 | 122222 | 111316 | 111310 | 111222 | 131316 | 131310 | 131222 |
| 63 | 122324 | 122311 | 122223 | 111324 | 111311 | 111223 | 131324 | 131311 | 131223 |
| 64 | 122328 | 122312 | 122224 | 111328 | 111312 | 111224 | 131328 | 131312 | 131224 |
| 65 | 122330 | 122329 | 122225 | 111330 | 111329 | 111225 | 131330 | 131329 | 131225 |
| 66 | 122335 | 122330 | 122226 | 111335 | 111330 | 111226 | 131335 | 131330 | 131226 |
| 67 | 122340 | 122331 | 122227 | 111340 | 111331 | 111227 | 131340 | 131331 | 131227 |
| 68 | 122342 | 122332 | 122228 | 111342 | 111332 | 111228 | 131342 | 131332 | 131228 |
| 69 | 122343 | 122349 | 122229 | 111343 | 111349 | 111229 | 131343 | 131349 | 131229 |
| 70 | 122356 | 122350 | 122230 | 111356 | 111350 | 111230 | 131356 | 131350 | 131230 |
| 71 | 122357 | 122351 | 122231 | 111357 | 111351 | 111231 | 131357 | 131351 | 131231 |
| 72 | 122363 | 122352 | 122232 | 111363 | 111352 | 111232 | 131363 | 131352 | 131232 |
| 73 | 122367 | 122369 | 122233 | 111367 | 111369 | 111233 | 131367 | 131369 | 131233 |
| 74 | 122377 | 122370 | 122234 | 111377 | 111370 | 111234 | 131377 | 131370 | 131234 |
| 75 | 122383 | 122371 | 122235 | 111383 | 111371 | 111235 | 131383 | 131371 | 131235 |
| 76 | 122385 | 122372 | 122236 | 111385 | 111372 | 111236 | 131385 | 131372 | 131236 |
| 77 | 122386 | 122389 | 122237 | 111386 | 111389 | 111237 | 131386 | 131389 | 131237 |
| 78 | 122388 | 122390 | 122238 | 111388 | 111390 | 111238 | 131388 | 131390 | 131238 |
| 79 | 122393 | 122391 | 122239 | 111393 | 111391 | 111239 | 131393 | 131391 | 131239 |
| 80 | 122399 | 122392 | 122240 | 111399 | 111392 | 111240 | 131399 | 131392 | 131240 |

### VIII.2. 10mx5m-20% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 1229 | 12217 | 122161 | 1119 | 11117 | 111161 | 1319 | 13117 | 131161 |
| 2 | 12213 | 12219 | 122163 | 11113 | 11119 | 111163 | 13113 | 13119 | 131163 |
| 3 | 12233 | 12221 | 122165 | 11133 | 11121 | 111165 | 13133 | 13121 | 131165 |
| 4 | 12241 | 12223 | 122167 | 11141 | 11123 | 111167 | 13141 | 13123 | 131167 |
| 5 | 12271 | 12257 | 122169 | 11171 | 11157 | 111169 | 13171 | 13157 | 131169 |
| 6 | 12287 | 12259 | 122171 | 11187 | 11159 | 111171 | 13187 | 13159 | 131171 |
| 7 | 12295 | 12261 | 122173 | 11195 | 11161 | 111173 | 13195 | 13161 | 131173 |
| 8 | 122103 | 12263 | 122175 | 111103 | 11163 | 111175 | 131103 | 13163 | 131175 |
| 9 | 122121 | 12297 | 122177 | 111121 | 11197 | 111177 | 131121 | 13197 | 131177 |
| 10 | 122123 | 12299 | 122179 | 111123 | 11199 | 111179 | 131123 | 13199 | 131179 |
| 11 | 122129 | 122101 | 122181 | 111129 | 111101 | 111181 | 131129 | 131101 | 131181 |
| 12 | 122139 | 122103 | 122183 | 111139 | 111103 | 111183 | 131139 | 131103 | 131183 |
| 13 | 122149 | 122137 | 122185 | 111149 | 111137 | 111185 | 131149 | 131137 | 131185 |
| 14 | 122157 | 122139 | 122187 | 111157 | 111139 | 111187 | 131157 | 131139 | 131187 |
| 15 | 122165 | 122141 | 122189 | 111165 | 111141 | 111189 | 131165 | 131141 | 131189 |
| 16 | 122169 | 122143 | 122191 | 111169 | 111143 | 111191 | 131169 | 131143 | 131191 |
| 17 | 122171 | 122177 | 122193 | 111171 | 111177 | 111193 | 131171 | 131177 | 131193 |
| 18 | 122175 | 122179 | 122195 | 111175 | 111179 | 111195 | 131175 | 131179 | 131195 |
| 19 | 122177 | 122181 | 122197 | 111177 | 111181 | 111197 | 131177 | 131181 | 131197 |
| 20 | 122185 | 122183 | 122199 | 111185 | 111183 | 111199 | 131185 | 131183 | 131199 |
| 21 | 122203 | 122217 | 122201 | 111203 | 111217 | 111201 | 131203 | 131217 | 131201 |
| 22 | 122215 | 122219 | 122203 | 111215 | 111219 | 111203 | 131215 | 131219 | 131203 |
| 23 | 122231 | 122221 | 122205 | 111231 | 111221 | 111205 | 131231 | 131221 | 131205 |
| 24 | 122247 | 122223 | 122207 | 111247 | 111223 | 111207 | 131247 | 131223 | 131207 |
| 25 | 122249 | 122257 | 122209 | 111249 | 111257 | 111209 | 131249 | 131257 | 131209 |
| 26 | 122251 | 122259 | 122211 | 111251 | 111259 | 111211 | 131251 | 131259 | 131211 |
| 27 | 122255 | 122261 | 122213 | 111255 | 111261 | 111213 | 131255 | 131261 | 131213 |
| 28 | 122257 | 122263 | 122215 | 111257 | 111263 | 111215 | 131257 | 131263 | 131215 |
| 29 | 122265 | 122297 | 122217 | 111265 | 111297 | 111217 | 131265 | 131297 | 131217 |
| 30 | 122267 | 122299 | 122219 | 111267 | 111299 | 111219 | 131267 | 131299 | 131219 |
| 31 | 122283 | 122301 | 122221 | 111283 | 111301 | 111221 | 131283 | 131301 | 131221 |
| 32 | 122301 | 122303 | 122223 | 111301 | 111303 | 111223 | 131301 | 131303 | 131223 |
| 33 | 122303 | 122337 | 122225 | 111303 | 111337 | 111225 | 131303 | 131337 | 131225 |
| 34 | 122309 | 122339 | 122227 | 111309 | 111339 | 111227 | 131309 | 131339 | 131227 |
| 35 | 122315 | 122341 | 122229 | 111315 | 111341 | 111229 | 131315 | 131341 | 131229 |
| 36 | 122327 | 122343 | 122231 | 111327 | 111343 | 111231 | 131327 | 131343 | 131231 |
| 37 | 122347 | 122377 | 122233 | 111347 | 111377 | 111233 | 131347 | 131377 | 131233 |
| 38 | 122361 | 122379 | 122235 | 111361 | 111379 | 111235 | 131361 | 131379 | 131235 |
| 39 | 122375 | 122381 | 122237 | 111375 | 111381 | 111237 | 131375 | 131381 | 131237 |
| 40 | 122381 | 122383 | 122239 | 111381 | 111383 | 111239 | 131381 | 131383 | 131239 |

### VIII.3. 10mx10m-20% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 12243 | 1229 | 122161 | 11143 | 1119 | 111161 | 13143 | 1319 | 131161 |
| 2 | 12253 | 12211 | 122163 | 11153 | 11111 | 111163 | 13153 | 13111 | 131163 |
| 3 | 12255 | 12249 | 122165 | 11155 | 11149 | 111165 | 13155 | 13149 | 131165 |
| 4 | 12289 | 12251 | 122167 | 11189 | 11151 | 111167 | 13189 | 13151 | 131167 |
| 5 | 12299 | 12289 | 122169 | 11199 | 11189 | 111169 | 13199 | 13189 | 131169 |
| 6 | 122129 | 12291 | 122171 | 111129 | 11191 | 111171 | 131129 | 13191 | 131171 |
| 7 | 122163 | 122129 | 122173 | 111163 | 111129 | 111173 | 131163 | 131129 | 131173 |
| 8 | 122177 | 122131 | 122175 | 111177 | 111131 | 111175 | 131177 | 131131 | 131175 |
| 9 | 122203 | 122169 | 122177 | 111203 | 111169 | 111177 | 131203 | 131169 | 131177 |
| 10 | 122217 | 122171 | 122179 | 111217 | 111171 | 111179 | 131217 | 131171 | 131179 |
| 11 | 122251 | 122209 | 122201 | 111251 | 111209 | 111201 | 131251 | 131209 | 131201 |
| 12 | 122253 | 122211 | 122203 | 111253 | 111211 | 111203 | 131253 | 131211 | 131203 |
| 13 | 122257 | 122249 | 122205 | 111257 | 111249 | 111205 | 131257 | 131249 | 131205 |
| 14 | 122283 | 122251 | 122207 | 111283 | 111251 | 111207 | 131283 | 131251 | 131207 |
| 15 | 122287 | 122289 | 122209 | 111287 | 111289 | 111209 | 131287 | 131289 | 131209 |
| 16 | 122293 | 122291 | 122211 | 111293 | 111291 | 111211 | 131293 | 131291 | 131211 |
| 17 | 122329 | 122329 | 122213 | 111329 | 111329 | 111213 | 131329 | 131329 | 131213 |
| 18 | 122363 | 122331 | 122215 | 111363 | 111331 | 111215 | 131363 | 131331 | 131215 |
| 19 | 122365 | 122369 | 122217 | 111365 | 111369 | 111217 | 131365 | 131369 | 131217 |
| 20 | 122377 | 122371 | 122219 | 111377 | 111371 | 111219 | 131377 | 131371 | 131219 |

### VIII.4. 20mx20m-20% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 1225 | 1229 | 122161 | 11113 | 1119 | 111161 | 13113 | 131161 | 131161 |
| 2 | 12289 | 12289 | 122165 | 11197 | 11189 | 111165 | 13197 | 131165 | 131161 |
| 3 | 122161 | 122169 | 122169 | 111173 | 111169 | 111169 | 131173 | 131169 | 131161 |
| 4 | 122169 | 122249 | 122173 | 111253 | 111249 | 111173 | 131253 | 131173 | 131161 |
| 5 | 122325 | 122329 | 122177 | 111333 | 111329 | 111177 | 131333 | 131177 | 131161 |

# APPENDIX IX: SAMPLES DRAWN FROM EACH FOREST TYPE USING DIFFERENT SAMPLING DESIGNS, PLOT SIZES AND 30% INTENSITY

## IX.1. 5mx5m-30% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 1224 | 1228 | 122141 | 1114 | 1118 | 111141 | 1314 | 1318 | 131141 |
| 2 | 12210 | 1229 | 122142 | 11110 | 1119 | 111142 | 13110 | 1319 | 131142 |
| 3 | 12211 | 12210 | 122143 | 11111 | 11110 | 111143 | 13111 | 13110 | 131143 |
| 4 | 12212 | 12211 | 122144 | 11112 | 11111 | 111144 | 13112 | 13111 | 131144 |
| 5 | 12213 | 12212 | 122145 | 11113 | 11112 | 111145 | 13113 | 13112 | 131145 |
| 6 | 12223 | 12213 | 122146 | 11123 | 11113 | 111146 | 13123 | 13113 | 131146 |
| 7 | 12224 | 12228 | 122147 | 11124 | 11128 | 111147 | 13124 | 13128 | 131147 |
| 8 | 12230 | 12229 | 122148 | 11130 | 11129 | 111148 | 13130 | 13129 | 131148 |
| 9 | 12238 | 12230 | 122149 | 11138 | 11130 | 111149 | 13138 | 13130 | 131149 |
| 10 | 12243 | 12231 | 122150 | 11143 | 11131 | 111150 | 13143 | 13131 | 131150 |
| 11 | 12248 | 12232 | 122151 | 11148 | 11132 | 111151 | 13148 | 13132 | 131151 |
| 12 | 12257 | 12233 | 122152 | 11157 | 11133 | 111152 | 13157 | 13133 | 131152 |
| 13 | 12265 | 12248 | 122153 | 11165 | 11148 | 111153 | 13165 | 13148 | 131153 |
| 14 | 12266 | 12249 | 122154 | 11166 | 11149 | 111154 | 13166 | 13149 | 131154 |
| 15 | 12267 | 12250 | 122155 | 11167 | 11150 | 111155 | 13167 | 13150 | 131155 |
| 16 | 12269 | 12251 | 122156 | 11169 | 11151 | 111156 | 13169 | 13151 | 131156 |
| 17 | 12270 | 12252 | 122157 | 11170 | 11152 | 111157 | 13170 | 13152 | 131157 |
| 18 | 12273 | 12253 | 122158 | 11173 | 11153 | 111158 | 13173 | 13153 | 131158 |
| 19 | 12274 | 12268 | 122159 | 11174 | 11168 | 111159 | 13174 | 13168 | 131159 |
| 20 | 12278 | 12269 | 122160 | 11178 | 11169 | 111160 | 13178 | 13169 | 131160 |
| 21 | 12279 | 12270 | 122161 | 11179 | 11170 | 111161 | 13179 | 13170 | 131161 |
| 22 | 12282 | 12271 | 122162 | 11182 | 11171 | 111162 | 13182 | 13171 | 131162 |
| 23 | 12283 | 12272 | 122163 | 11183 | 11172 | 111163 | 13183 | 13172 | 131163 |
| 24 | 12288 | 12273 | 122164 | 11188 | 11173 | 111164 | 13188 | 13173 | 131164 |
| 25 | 12294 | 12288 | 122165 | 11194 | 11188 | 111165 | 13194 | 13188 | 131165 |
| 26 | 12296 | 12289 | 122166 | 11196 | 11189 | 111166 | 13196 | 13189 | 131166 |
| 27 | 12299 | 12290 | 122167 | 11199 | 11190 | 111167 | 13199 | 13190 | 131167 |
| 28 | 122103 | 12291 | 122168 | 111103 | 11191 | 111168 | 131103 | 13191 | 131168 |
| 29 | 122104 | 12292 | 122169 | 111104 | 11192 | 111169 | 131104 | 13192 | 131169 |
| 30 | 122108 | 12293 | 122170 | 111108 | 11193 | 111170 | 131108 | 13193 | 131170 |
| 31 | 122109 | 122108 | 122171 | 111109 | 111108 | 111171 | 131109 | 131108 | 131171 |
| 32 | 122111 | 122109 | 122172 | 111111 | 111109 | 111172 | 131111 | 131109 | 131172 |
| 33 | 122116 | 122110 | 122173 | 111116 | 111110 | 111173 | 131116 | 131110 | 131173 |
| 34 | 122117 | 122111 | 122174 | 111117 | 111111 | 111174 | 131117 | 131111 | 131174 |
| 35 | 122119 | 122112 | 122175 | 111119 | 111112 | 111175 | 131119 | 131112 | 131175 |
| 36 | 122120 | 122113 | 122176 | 111120 | 111113 | 111176 | 131120 | 131113 | 131176 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 37 | 122124 | 122128 | 122177 | 111124 | 111128 | 111177 | 131124 | 131128 | 131177 |
| 38 | 122129 | 122129 | 122178 | 111129 | 111129 | 111178 | 131129 | 131129 | 131178 |
| 39 | 122137 | 122130 | 122179 | 111137 | 111130 | 111179 | 131137 | 131130 | 131179 |
| 40 | 122138 | 122131 | 122180 | 111138 | 111131 | 111180 | 131138 | 131131 | 131180 |
| 41 | 122146 | 122132 | 122181 | 111146 | 111132 | 111181 | 131146 | 131132 | 131181 |
| 42 | 122148 | 122133 | 122182 | 111148 | 111133 | 111182 | 131148 | 131133 | 131182 |
| 43 | 122149 | 122148 | 122183 | 111149 | 111148 | 111183 | 131149 | 131148 | 131183 |
| 44 | 122150 | 122149 | 122184 | 111150 | 111149 | 111184 | 131150 | 131149 | 131184 |
| 45 | 122153 | 122150 | 122185 | 111153 | 111150 | 111185 | 131153 | 131150 | 131185 |
| 46 | 122155 | 122151 | 122186 | 111155 | 111151 | 111186 | 131155 | 131151 | 131186 |
| 47 | 122156 | 122152 | 122187 | 111156 | 111152 | 111187 | 131156 | 131152 | 131187 |
| 48 | 122158 | 122153 | 122188 | 111158 | 111153 | 111188 | 131158 | 131153 | 131188 |
| 49 | 122170 | 122168 | 122189 | 111170 | 111168 | 111189 | 131170 | 131168 | 131189 |
| 50 | 122175 | 122169 | 122190 | 111175 | 111169 | 111190 | 131175 | 131169 | 131190 |
| 51 | 122181 | 122170 | 122191 | 111181 | 111170 | 111191 | 131181 | 131170 | 131191 |
| 52 | 122183 | 122171 | 122192 | 111183 | 111171 | 111192 | 131183 | 131171 | 131192 |
| 53 | 122186 | 122172 | 122193 | 111186 | 111172 | 111193 | 131186 | 131172 | 131193 |
| 54 | 122188 | 122173 | 122194 | 111188 | 111173 | 111194 | 131188 | 131173 | 131194 |
| 55 | 122192 | 122188 | 122195 | 111192 | 111188 | 111195 | 131192 | 131188 | 131195 |
| 56 | 122203 | 122189 | 122196 | 111203 | 111189 | 111196 | 131203 | 131189 | 131196 |
| 57 | 122204 | 122190 | 122197 | 111204 | 111190 | 111197 | 131204 | 131190 | 131197 |
| 58 | 122205 | 122191 | 122198 | 111205 | 111191 | 111198 | 131205 | 131191 | 131198 |
| 59 | 122206 | 122192 | 122199 | 111206 | 111192 | 111199 | 131206 | 131192 | 131199 |
| 60 | 122215 | 122193 | 122200 | 111215 | 111193 | 111200 | 131215 | 131193 | 131200 |
| 61 | 122216 | 122208 | 122201 | 111216 | 111208 | 111201 | 131216 | 131208 | 131201 |
| 62 | 122220 | 122209 | 122202 | 111220 | 111209 | 111202 | 131220 | 131209 | 131202 |
| 63 | 122228 | 122210 | 122203 | 111228 | 111210 | 111203 | 131228 | 131210 | 131203 |
| 64 | 122229 | 122211 | 122204 | 111229 | 111211 | 111204 | 131229 | 131211 | 131204 |
| 65 | 122230 | 122212 | 122205 | 111230 | 111212 | 111205 | 131230 | 131212 | 131205 |
| 66 | 122231 | 122213 | 122206 | 111231 | 111213 | 111206 | 131231 | 131213 | 131206 |
| 67 | 122233 | 122228 | 122207 | 111233 | 111228 | 111207 | 131233 | 131228 | 131207 |
| 68 | 122234 | 122229 | 122208 | 111234 | 111229 | 111208 | 131234 | 131229 | 131208 |
| 69 | 122237 | 122230 | 122209 | 111237 | 111230 | 111209 | 131237 | 131230 | 131209 |
| 70 | 122243 | 122231 | 122210 | 111243 | 111231 | 111210 | 131243 | 131231 | 131210 |
| 71 | 122244 | 122232 | 122211 | 111244 | 111232 | 111211 | 131244 | 131232 | 131211 |
| 72 | 122251 | 122233 | 122212 | 111251 | 111233 | 111212 | 131251 | 131233 | 131212 |
| 73 | 122255 | 122248 | 122213 | 111255 | 111248 | 111213 | 131255 | 131248 | 131213 |
| 74 | 122258 | 122249 | 122214 | 111258 | 111249 | 111214 | 131258 | 131249 | 131214 |
| 75 | 122261 | 122250 | 122215 | 111261 | 111250 | 111215 | 131261 | 131250 | 131215 |
| 76 | 122264 | 122251 | 122216 | 111264 | 111251 | 111216 | 131264 | 131251 | 131216 |
| 77 | 122269 | 122252 | 122217 | 111269 | 111252 | 111217 | 131269 | 131252 | 131217 |
| 78 | 122270 | 122253 | 122218 | 111270 | 111253 | 111218 | 131270 | 131253 | 131218 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 79 | 122277 | 122268 | 122219 | 111277 | 111268 | 111219 | 131277 | 131268 | 131219 |
| 80 | 122278 | 122269 | 122220 | 111278 | 111269 | 111220 | 131278 | 131269 | 131220 |
| 81 | 122279 | 122270 | 122221 | 111279 | 111270 | 111221 | 131279 | 131270 | 131221 |
| 82 | 122282 | 122271 | 122222 | 111282 | 111271 | 111222 | 131282 | 131271 | 131222 |
| 83 | 122283 | 122272 | 122223 | 111283 | 111272 | 111223 | 131283 | 131272 | 131223 |
| 84 | 122286 | 122273 | 122224 | 111286 | 111273 | 111224 | 131286 | 131273 | 131224 |
| 85 | 122289 | 122288 | 122225 | 111289 | 111288 | 111225 | 131289 | 131288 | 131225 |
| 86 | 122293 | 122289 | 122226 | 111293 | 111289 | 111226 | 131293 | 131289 | 131226 |
| 87 | 122295 | 122290 | 122227 | 111295 | 111290 | 111227 | 131295 | 131290 | 131227 |
| 88 | 122296 | 122291 | 122228 | 111296 | 111291 | 111228 | 131296 | 131291 | 131228 |
| 89 | 122311 | 122292 | 122229 | 111311 | 111292 | 111229 | 131311 | 131292 | 131229 |
| 90 | 122312 | 122293 | 122230 | 111312 | 111293 | 111230 | 131312 | 131293 | 131230 |
| 91 | 122313 | 122308 | 122231 | 111313 | 111308 | 111231 | 131313 | 131308 | 131231 |
| 92 | 122317 | 122309 | 122232 | 111317 | 111309 | 111232 | 131317 | 131309 | 131232 |
| 93 | 122318 | 122310 | 122233 | 111318 | 111310 | 111233 | 131318 | 131310 | 131233 |
| 94 | 122321 | 122311 | 122234 | 111321 | 111311 | 111234 | 131321 | 131311 | 131234 |
| 95 | 122324 | 122312 | 122235 | 111324 | 111312 | 111235 | 131324 | 131312 | 131235 |
| 96 | 122325 | 122313 | 122236 | 111325 | 111313 | 111236 | 131325 | 131313 | 131236 |
| 97 | 122329 | 122328 | 122237 | 111329 | 111328 | 111237 | 131329 | 131328 | 131237 |
| 98 | 122340 | 122329 | 122238 | 111340 | 111329 | 111238 | 131340 | 131329 | 131238 |
| 99 | 122343 | 122330 | 122239 | 111343 | 111330 | 111239 | 131343 | 131330 | 131239 |
| 100 | 122344 | 122331 | 122240 | 111344 | 111331 | 111240 | 131344 | 131331 | 131240 |
| 101 | 122346 | 122332 | 122241 | 111346 | 111332 | 111241 | 131346 | 131332 | 131241 |
| 102 | 122351 | 122333 | 122242 | 111351 | 111333 | 111242 | 131351 | 131333 | 131242 |
| 103 | 122354 | 122348 | 122243 | 111354 | 111348 | 111243 | 131354 | 131348 | 131243 |
| 104 | 122359 | 122349 | 122244 | 111359 | 111349 | 111244 | 131359 | 131349 | 131244 |
| 105 | 122360 | 122350 | 122245 | 111360 | 111350 | 111245 | 131360 | 131350 | 131245 |
| 106 | 122363 | 122351 | 122246 | 111363 | 111351 | 111246 | 131363 | 131351 | 131246 |
| 107 | 122365 | 122352 | 122247 | 111365 | 111352 | 111247 | 131365 | 131352 | 131247 |
| 108 | 122367 | 122353 | 122248 | 111367 | 111353 | 111248 | 131367 | 131353 | 131248 |
| 109 | 122372 | 122368 | 122249 | 111372 | 111368 | 111249 | 131372 | 131368 | 131249 |
| 110 | 122373 | 122369 | 122250 | 111373 | 111369 | 111250 | 131373 | 131369 | 131250 |
| 111 | 122375 | 122370 | 122251 | 111375 | 111370 | 111251 | 131375 | 131370 | 131251 |
| 112 | 122376 | 122371 | 122252 | 111376 | 111371 | 111252 | 131376 | 131371 | 131252 |
| 113 | 122378 | 122372 | 122253 | 111378 | 111372 | 111253 | 131378 | 131372 | 131253 |
| 114 | 122380 | 122373 | 122254 | 111380 | 111373 | 111254 | 131380 | 131373 | 131254 |
| 115 | 122382 | 122388 | 122255 | 111382 | 111388 | 111255 | 131382 | 131388 | 131255 |
| 116 | 122383 | 122389 | 122256 | 111383 | 111389 | 111256 | 131383 | 131389 | 131256 |
| 117 | 122384 | 122390 | 122257 | 111384 | 111390 | 111257 | 131384 | 131390 | 131257 |
| 118 | 122392 | 122391 | 122258 | 111392 | 111391 | 111258 | 131392 | 131391 | 131258 |
| 119 | 122395 | 122392 | 122259 | 111395 | 111392 | 111259 | 131395 | 131392 | 131259 |
| 120 | 122398 | 122393 | 122260 | 111398 | 111393 | 111260 | 131398 | 131393 | 131260 |

### IX.2. 10mx5m-30% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 12223 | 12215 | 122161 | 11123 | 11115 | 111161 | 13123 | 13115 | 131161 |
| 2 | 12235 | 12217 | 122163 | 11135 | 11117 | 111163 | 13135 | 13117 | 131163 |
| 3 | 12241 | 12219 | 122165 | 11141 | 11119 | 111165 | 13141 | 13119 | 131165 |
| 4 | 12259 | 12221 | 122167 | 11159 | 11121 | 111167 | 13159 | 13121 | 131167 |
| 5 | 12263 | 12223 | 122169 | 11163 | 11123 | 111169 | 13163 | 13123 | 131169 |
| 6 | 12265 | 12225 | 122171 | 11165 | 11125 | 111171 | 13165 | 13125 | 131171 |
| 7 | 12269 | 12255 | 122173 | 11169 | 11155 | 111173 | 13169 | 13155 | 131173 |
| 8 | 12273 | 12257 | 122175 | 11173 | 11157 | 111175 | 13173 | 13157 | 131175 |
| 9 | 12275 | 12259 | 122177 | 11175 | 11159 | 111177 | 13175 | 13159 | 131177 |
| 10 | 12281 | 12261 | 122179 | 11181 | 11161 | 111179 | 13181 | 13161 | 131179 |
| 11 | 12293 | 12263 | 122181 | 11193 | 11163 | 111181 | 13193 | 13163 | 131181 |
| 12 | 12295 | 12265 | 122183 | 11195 | 11165 | 111183 | 13195 | 13165 | 131183 |
| 13 | 12299 | 12295 | 122185 | 11199 | 11195 | 111185 | 13199 | 13195 | 131185 |
| 14 | 122103 | 12297 | 122187 | 111103 | 11197 | 111187 | 131103 | 13197 | 131187 |
| 15 | 122105 | 12299 | 122189 | 111105 | 11199 | 111189 | 131105 | 13199 | 131189 |
| 16 | 122117 | 122101 | 122191 | 111117 | 111101 | 111191 | 131117 | 131101 | 131191 |
| 17 | 122123 | 122103 | 122193 | 111123 | 111103 | 111193 | 131123 | 131103 | 131193 |
| 18 | 122131 | 122105 | 122195 | 111131 | 111105 | 111195 | 131131 | 131105 | 131195 |
| 19 | 122143 | 122135 | 122197 | 111143 | 111135 | 111197 | 131143 | 131135 | 131197 |
| 20 | 122147 | 122137 | 122199 | 111147 | 111137 | 111199 | 131147 | 131137 | 131199 |
| 21 | 122149 | 122139 | 122201 | 111149 | 111139 | 111201 | 131149 | 131139 | 131201 |
| 22 | 122153 | 122141 | 122203 | 111153 | 111141 | 111203 | 131153 | 131141 | 131203 |
| 23 | 122167 | 122143 | 122205 | 111167 | 111143 | 111205 | 131167 | 131143 | 131205 |
| 24 | 122169 | 122145 | 122207 | 111169 | 111145 | 111207 | 131169 | 131145 | 131207 |
| 25 | 122173 | 122175 | 122209 | 111173 | 111175 | 111209 | 131173 | 131175 | 131209 |
| 26 | 122183 | 122177 | 122211 | 111183 | 111177 | 111211 | 131183 | 131177 | 131211 |
| 27 | 122189 | 122179 | 122213 | 111189 | 111179 | 111213 | 131189 | 131179 | 131213 |
| 28 | 122191 | 122181 | 122215 | 111191 | 111181 | 111215 | 131191 | 131181 | 131215 |
| 29 | 122193 | 122183 | 122217 | 111193 | 111183 | 111217 | 131193 | 131183 | 131217 |
| 30 | 122205 | 122185 | 122219 | 111205 | 111185 | 111219 | 131205 | 131185 | 131219 |
| 31 | 122209 | 122215 | 122221 | 111209 | 111215 | 111221 | 131209 | 131215 | 131221 |
| 32 | 122219 | 122217 | 122223 | 111219 | 111217 | 111223 | 131219 | 131217 | 131223 |
| 33 | 122231 | 122219 | 122225 | 111231 | 111219 | 111225 | 131231 | 131219 | 131225 |
| 34 | 122237 | 122221 | 122227 | 111237 | 111221 | 111227 | 131237 | 131221 | 131227 |
| 35 | 122241 | 122223 | 122229 | 111241 | 111223 | 111229 | 131241 | 131223 | 131229 |
| 36 | 122245 | 122225 | 122231 | 111245 | 111225 | 111231 | 131245 | 131225 | 131231 |
| 37 | 122247 | 122255 | 122233 | 111247 | 111255 | 111233 | 131247 | 131255 | 131233 |
| 38 | 122249 | 122257 | 122235 | 111249 | 111257 | 111235 | 131249 | 131257 | 131235 |
| 39 | 122255 | 122259 | 122237 | 111255 | 111259 | 111237 | 131255 | 131259 | 131237 |
| 40 | 122259 | 122261 | 122239 | 111259 | 111261 | 111239 | 131259 | 131261 | 131239 |
| 41 | 122265 | 122263 | 122241 | 111265 | 111263 | 111241 | 131265 | 131263 | 131241 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 42 | 122269 | 122265 | 122243 | 111269 | 111265 | 111243 | 131269 | 131265 | 131243 |
| 43 | 122271 | 122295 | 122245 | 111271 | 111295 | 111245 | 131271 | 131295 | 131245 |
| 44 | 122275 | 122297 | 122247 | 111275 | 111297 | 111247 | 131275 | 131297 | 131247 |
| 45 | 122283 | 122299 | 122249 | 111283 | 111299 | 111249 | 131283 | 131299 | 131249 |
| 46 | 122293 | 122301 | 122251 | 111293 | 111301 | 111251 | 131293 | 131301 | 131251 |
| 47 | 122297 | 122303 | 122253 | 111297 | 111303 | 111253 | 131297 | 131303 | 131253 |
| 48 | 122305 | 122305 | 122255 | 111305 | 111305 | 111255 | 131305 | 131305 | 131255 |
| 49 | 122313 | 122335 | 122257 | 111313 | 111335 | 111257 | 131313 | 131335 | 131257 |
| 50 | 122315 | 122337 | 122259 | 111315 | 111337 | 111259 | 131315 | 131337 | 131259 |
| 51 | 122319 | 122339 | 122261 | 111319 | 111339 | 111261 | 131319 | 131339 | 131261 |
| 52 | 122321 | 122341 | 122263 | 111321 | 111341 | 111263 | 131321 | 131341 | 131263 |
| 53 | 122327 | 122343 | 122265 | 111327 | 111343 | 111265 | 131327 | 131343 | 131265 |
| 54 | 122333 | 122345 | 122267 | 111333 | 111345 | 111267 | 131333 | 131345 | 131267 |
| 55 | 122343 | 122375 | 122269 | 111343 | 111375 | 111269 | 131343 | 131375 | 131269 |
| 56 | 122349 | 122377 | 122271 | 111349 | 111377 | 111271 | 131349 | 131377 | 131271 |
| 57 | 122365 | 122379 | 122273 | 111365 | 111379 | 111273 | 131365 | 131379 | 131273 |
| 58 | 122375 | 122381 | 122275 | 111375 | 111381 | 111275 | 131375 | 131381 | 131275 |
| 59 | 122381 | 122383 | 122277 | 111381 | 111383 | 111277 | 131381 | 131383 | 131277 |
| 60 | 122389 | 122385 | 122279 | 111389 | 111385 | 111279 | 131389 | 131385 | 131279 |

### IX.3. 10mx10m-30% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 12211 | 1229 | 122161 | 11111 | 1119 | 111161 | 13111 | 1319 | 131161 |
| 2 | 12245 | 12211 | 122163 | 11145 | 11111 | 111163 | 13145 | 13111 | 131163 |
| 3 | 12251 | 12213 | 122165 | 11151 | 11113 | 111165 | 13151 | 13113 | 131165 |
| 4 | 12255 | 12249 | 122167 | 11155 | 11149 | 111167 | 13155 | 13149 | 131167 |
| 5 | 12259 | 12251 | 122169 | 11159 | 11151 | 111169 | 13159 | 13151 | 131169 |
| 6 | 12289 | 12253 | 122171 | 11189 | 11153 | 111171 | 13189 | 13153 | 131171 |
| 7 | 12291 | 12289 | 122173 | 11191 | 11189 | 111173 | 13191 | 13189 | 131173 |
| 8 | 12299 | 12291 | 122175 | 11199 | 11191 | 111175 | 13199 | 13191 | 131175 |
| 9 | 122121 | 12293 | 122177 | 111121 | 11193 | 111177 | 131121 | 13193 | 131177 |
| 10 | 122123 | 122129 | 122179 | 111123 | 111129 | 111179 | 131123 | 131129 | 131179 |
| 11 | 122129 | 122131 | 122201 | 111129 | 111131 | 111201 | 131129 | 131131 | 131201 |
| 12 | 122139 | 122133 | 122203 | 111139 | 111133 | 111203 | 131139 | 131133 | 131203 |
| 13 | 122163 | 122169 | 122205 | 111163 | 111169 | 111205 | 131163 | 131169 | 131205 |
| 14 | 122165 | 122171 | 122207 | 111165 | 111171 | 111207 | 131165 | 131171 | 131207 |
| 15 | 122169 | 122173 | 122209 | 111169 | 111173 | 111209 | 131169 | 131173 | 131209 |
| 16 | 122171 | 122209 | 122211 | 111171 | 111209 | 111211 | 131171 | 131209 | 131211 |
| 17 | 122201 | 122211 | 122213 | 111201 | 111211 | 111213 | 131201 | 131211 | 131213 |
| 18 | 122209 | 122213 | 122215 | 111209 | 111213 | 111215 | 131209 | 131213 | 131215 |
| 19 | 122211 | 122249 | 122217 | 111211 | 111249 | 111217 | 131211 | 131249 | 131217 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 20 | 122213 | 122251 | 122219 | 111213 | 111251 | 111219 | 131213 | 131251 | 131219 |
| 21 | 122215 | 122253 | 122241 | 111215 | 111253 | 111241 | 131215 | 131253 | 131241 |
| 22 | 122249 | 122289 | 122243 | 111249 | 111289 | 111243 | 131249 | 131289 | 131243 |
| 23 | 122251 | 122291 | 122245 | 111251 | 111291 | 111245 | 131251 | 131291 | 131245 |
| 24 | 122293 | 122293 | 122247 | 111293 | 111293 | 111247 | 131293 | 131293 | 131247 |
| 25 | 122297 | 122329 | 122249 | 111297 | 111329 | 111249 | 131297 | 131329 | 131249 |
| 26 | 122325 | 122331 | 122251 | 111325 | 111331 | 111251 | 131325 | 131331 | 131251 |
| 27 | 122329 | 122333 | 122253 | 111329 | 111333 | 111253 | 131329 | 131333 | 131253 |
| 28 | 122339 | 122369 | 122255 | 111339 | 111369 | 111255 | 131339 | 131369 | 131255 |
| 29 | 122365 | 122371 | 122257 | 111365 | 111371 | 111257 | 131365 | 131371 | 131257 |
| 30 | 122367 | 122373 | 122259 | 111367 | 111373 | 111259 | 131367 | 131373 | 131259 |

### IX.4. 20mx20m-30% plots

| | Kakamega Forest | | | Mt Elgon forest | | | Loruk DW forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | SRS | SSH | SSV | SRS | SSH | SSV | SRS | SSH | SSV |
| 1 | 1229 | 1229 | 122161 | 1115 | 1119 | 111161 | 1315 | 131161 | 131161 |
| 2 | 12281 | 12289 | 122165 | 11185 | 11113 | 111165 | 13185 | 131165 | 131161 |
| 3 | 12289 | 122169 | 122169 | 11189 | 11189 | 111169 | 13189 | 131169 | 131161 |
| 4 | 122241 | 122249 | 122173 | 11197 | 11193 | 111173 | 13197 | 131173 | 131161 |
| 5 | 122253 | 122329 | 122177 | 111169 | 111169 | 111177 | 131169 | 131177 | 131161 |
| 6 | 122325 | 12213 | 122241 | 111241 | 111173 | 111241 | 131241 | 131241 | 131161 |
| 7 | 122329 | 12293 | 122245 | 111321 | 111249 | 111245 | 131321 | 131245 | 131161 |

# APPENDIX X: TREE SPECIES AND FAMILY COMPOSITION IN THREE FOREST TYPES, KENYA

## X.1. Kakamega Tropical Rain forest Site

| S/No. | Species name | Family | Number of individuals ha$^{-1}$ | Relative Density % |
|---|---|---|---|---|
| 1 | *Trilepisium madagascariense* | Moraceae | 339 | 12.63 |
| 2 | *Funtumia africana* | Apocynaceae | 248 | 9.24 |
| 3 | *Teclea nobilis* | Rutaceae | 224 | 8.35 |
| 4 | *Strombosia scheffleri* | Olacaceae | 172 | 6.41 |
| 5 | *Antiaris toxcaria* | Moraceae | 150 | 5.59 |
| 6 | *Celtis gomphophylla* | Ulmaceae | 140 | 5.22 |
| 7 | *Flacourtia indica* | Flacourtiaceae | 108 | 4.02 |
| 8 | *Hagenia abyssinica* | Rosaceae | 107 | 3.99 |
| 9 | *Wenzoria* (Local) | | 104 | 3.87 |
| 10 | *Bequaertiodendron oblanceolatum* | Sapotaceae | 100 | 3.73 |
| 11 | *Rawsonia lucida* | Flacourtiaceae | 97 | 3.61 |
| 12 | *Celtis mildbraedii* | Ulmaceae | 87 | 3.24 |
| 13 | *Morus lactea* | Moraceae | 87 | 3.24 |
| 14 | *Trichilia emetica* | Meliaceae | 85 | 3.17 |
| 15 | *Aningeria altissima* | Sapotaceae | 68 | 2.53 |
| 16 | *Craibia brownii* | Papilionaceae | 60 | 2.24 |
| 17 | *Ficus exasperata* | Moraceae | 53 | 1.97 |
| 18 | *Dovyalis abyssinica* | Flacourtiaceae | 46 | 1.71 |
| 19 | *Polyscias fulva* | Araliaceae | 32 | 1.19 |
| 20 | *Kigelia moosa* | Bignoniaceae | 31 | 1.15 |
| 21 | *Markhamia lutea* | Bignoniaceae | 31 | 1.15 |
| 22 | *Zanthoxyllum gilletii* | Rutaceae | 27 | 1.01 |
| 23 | *Blighia unijugata* | Sapindaceae | 26 | 0.97 |
| 24 | *Diospyros abyssinica* | Ebenaceae | 23 | 0.86 |
| 25 | *Albizia gummifera* | Mimosaceae | 20 | 0.75 |
| 26 | *Vangueria volkensii* | Rutaceae | 20 | 0.75 |
| 27 | *Croton macrostachyus* | Euphorbiaceae | 16 | 0.60 |
| 28 | *Solanum mauritianum* | Solanaceae | 16 | 0.60 |
| 29 | *Spathodea campanulata* | Bignoniaceae | 16 | 0.60 |
| 30 | *Ficus sur* | Moraceae | 15 | 0.56 |
| 31 | *Trema orientellis* | Ulmaceae | 14 | 0.52 |
| 32 | *Clausena anisata* | Rutaceae | 13 | 0.48 |
| 33 | *Acanthus pubescens* | Acanthaceae | 12 | 0.45 |
| 34 | *Macaranga kilimandscharica* | Euphorbiaceae | 12 | 0.45 |
| 35 | *Bischofia javanica* | Euphorbiaceae | 11 | 0.41 |
| 36 | *Croton megalocarpus* | Euphorbiaceae | 11 | 0.41 |
| 37 | *Olea capensis ssp welwitschii* | Olacaceae | 7 | 0.26 |

| | | | | |
|---|---|---|---:|---:|
| 38 | *Prunus africana* | Rosaceae | 7 | 0.26 |
| 39 | *Chaetacme aristata* | Ulmaceae | 6 | 0.22 |
| 40 | *Maesopsis eminii* | Rhamnaceae | 6 | 0.22 |
| 41 | *Ficus thonningii* | Agavaceae | 6 | 0.22 |
| 42 | *Dracaena fragrans* | Melianthaceae | 5 | 0.19 |
| 43 | *Bersama abyssinica* | Sapotaceae | 5 | 0.19 |
| 44 | *Manilkara butugi* | Euphorbiaceae | 5 | 0.19 |
| 45 | *Sapium ellipticum* | Boraginaceae | 4 | 0.15 |
| 46 | *Cordia africana* | Moraceae | 4 | 0.15 |
| 47 | *Harungana madagascarensis* | Guttiferae | 3 | 0.11 |
| 48 | *Acacia tortilis* | Mimosaceae | 2 | 0.07 |
| *49* | *Balakaya* (Local) | x | 2 | 0.07 |
| 50 | *Fagaropsis angolensis* | Rutaceae | 1 | 0.04 |

### X.2. Mt Elgon moist montane forest Site

| **S/No.** | **Species name** | **Family** | **Number of individuals ha$^{-1}$** | **Relative Density %** |
|---|---|---|---:|---:|
| 1 | *Diospyros abyssinica* | Ebenaceae | 348 | 24.30 |
| 2 | *Aningeria altissima* | Sapotaceae | 159 | 11.10 |
| 3 | *Vangueria apiculata* | Rubiaceae | 119 | 8.31 |
| 4 | *Teclea simplicifolia* | Rutaceae | 108 | 7.54 |
| 5 | *Flacourtia indica* | Flacourtiaceae | 90 | 6.28 |
| 6 | *Turraea parvifolia* | Meliaceae | 82 | 5.73 |
| 7 | *Albizia gummifera* | Mimosaceae | 66 | 4.61 |
| 8 | *Dovyalis macrocalyx* | Flacourtiaceae | 66 | 4.61 |
| 9 | *Croton macrostachyus* | Euphorbiaceae | 59 | 4.12 |
| 10 | *Podocarpus falcatus* | Podocarpaceae | 50 | 3.49 |
| 11 | *Casaeria battiscombei* | Flacourtiaceae | 49 | 3.42 |
| 12 | *Celtis gomphophylla* | Ulmaceae | 46 | 3.21 |
| 13 | *Bersama abyssinica* | Melianthaceae | 43 | 3.00 |
| 14 | *Fagaropsis angolensis* | Rutaceae | 28 | 1.96 |
| 15 | *Maskat* (Local) | x | 25 | 1.75 |
| 16 | *Nuxia congesta* | Loganiaceae | 16 | 1.12 |
| 17 | *Podocarpus latifolius* | Podocarpaceae | 14 | 0.98 |
| 18 | *Dracaena steudneri* | Dracaenaceae | 8 | 0.56 |
| 19 | *Celtis mildbraedii* | Ulmaceae | 7 | 0.49 |
| 20 | *Maytenus heterophylla* | Celastraceae | 6 | 0.42 |
| 21 | *Ritchiea albersii* | Capparaceae | 6 | 0.42 |
| 22 | *Clausena anisata* | Rutaceae | 5 | 0.35 |
| 23 | *Celtis africana* | Ulmaceae | 4 | 0.28 |
| 24 | *Schrebera alata* | Oleaceae | 4 | 0.28 |
| 25 | *Solanum mauritianum* | Solanaceae | 4 | 0.28 |
| 26 | *Olinia rochetiana* | Oliniaceae | 3 | 0.21 |

| | | | | |
|---|---|---|---|---|
| 27 | *Senna didymobotrya* | Caesalpiniaceae | 3 | 0.21 |
| 28 | *Olea capensis* ssp *welwitschii* | Oleaceae | 2 | 0.14 |
| 29 | *Ficus thonningii* | Moraceae | 2 | 0.14 |
| 30 | *Markhamia lutea* | Bignoniaceae | 2 | 0.14 |
| 31 | *Vernonia auriculifera* | Compositae | 2 | 0.14 |
| 32 | *Solanum aculeastrum* | Solanaceae | 2 | 0.14 |
| 33 | *Sclerocarya birrea* | Anacardiaceae | 1 | 0.07 |
| 34 | *Ficus exasperata* | Moraceae | 1 | 0.07 |
| 35 | *Syzygium cordatum* | Myrtaceae | 1 | 0.07 |
| 36 | *Macaranga kilimandscharia* | Euphorbiaceae | 1 | 0.07 |

### X.3. Loruk dry woodland forest Site

| **S/No.** | **Species** | **Family** | **Number of trees ha$^{-1}$** | **Relative density %** |
|---|---|---|---:|---:|
| 1 | *Acacia reficiens* | Mimosaceae | 512 | 40.20 |
| 2 | *Acacia mellifera* | Mimosaceae | 295 | 23.10 |
| 3 | *Acacia tortilis* | Mimosaceae | 145 | 11.40 |
| 4 | *Boscia coriacea* | Capparaceae | 83 | 6.50 |
| 5 | *Acacia nubica* | Mimosaceae | 73 | 5.70 |
| 6 | *Acacia senegal* | Mimosaceae | 69 | 5.40 |
| 7 | *Mpirikwa* (local) | x | 45 | 3.50 |
| 8 | *Diospyros scabra* | Ebenaceae | 20 | 1.60 |
| 9 | *Euphorbia candelabrum* | Euphorbiaceae | 18 | 1.40 |
| 10 | *Acacia nilotica* | Mimosaceae | 8 | 0.60 |
| 11 | *Cissus rotundifolia* | Vitaceae | 5 | 0.40 |
| 12 | *Sukur* (local) | x | 2 | 0.10 |

# APPENDIX XI. SHARING OF TREE SPECIES AMONG THREE DIFFERENT FOREST TYPES IN KENYA BASED ON THE ASSESSED ONE HECTARE PLOT PER FOREST

| **Tree species** | **Forest type** | **Tree species** | **Forest type** |
|---|---|---|---|
| *Acacia mellifera* | DWF | *Croton megalocarpus* | TRF |
| *Acacia nilotica* | DWF | *Dovyalis abyssinica* | TRF |
| *Acacia nubica* | DWF | *Dracaena fragrans* | TRF |
| *Acacia reficiens* | DWF | *Ficus sur* | TRF |
| *Acacia senegal* | DWF | *Funtumia africana* | TRF |
| *Boscia coriacea* | DWF | *Hagenia abyssinica* | TRF |
| *Cissus rotundifolia* | DWF | *Harungana madagascarensis* | TRF |
| *Diospyros scabra* | DWF | *Kigelia moosa* | TRF |
| *Euphorbia candelabrum* | DWF | *Maesopsis eminii* | TRF |
| Mpirikwa (local, Loruk) | DWF | *Manilkara butugi* | TRF |
| Sukur (local, Loruk) | DWF | *Morus lactea* | TRF |
| *Acacia tortilis* | DWF-TRF | *Polyscias fulva* | TRF |
| *Casaeria battiscombei* | MMF | *Prunus africana* | TRF |
| *Celtis africana* | MMF | *Rawsonia lucida* | TRF |
| *Dovyalis macrocalyx* | MMF | *Sapium ellipticum* | TRF |
| *Dracaena steudneri* | MMF | *Spathodea campanulata* | TRF |
| Maskat (local, Mt Elgon) | MMF | *Strombosia scheffleri* | TRF |
| *Maytenus heterophylla* | MMF | *Teclea nobilis* | TRF |
| *Nuxia congesta* | MMF | *Trema orientellis* | TRF |
| *Olinia rochetiana* | MMF | *Trichilia emetica* | TRF |
| *Podocarpus falcatus* | MMF | *Trilepisium madagascariense* | TRF |
| *Podocarpus latifolius* | MMF | *Vangueria volkensii* | TRF |
| *Ritchiea albersii* | MMF | Wenzoria (Local, Kakamega) | TRF |
| *Schrebera alata* | MMF | *Zanthoxyllum gilletii* | TRF |
| *Sclerocarya birrea* | MMF | *Albizia gummifera* | TRF-MMF |
| *Senna didymobotrya* | MMF | *Aningeria altissima* | TRF-MMF |
| *Solanum aculeastrum* | MMF | *Bersama abyssinica* | TRF-MMF |
| *Syzygium cordatum* | MMF | *Celtis gomphophylla* | TRF-MMF |
| *Teclea simplicifolia* | MMF | *Celtis mildbraedii* | TRF-MMF |
| *Turraea parvifolia* | MMF | *Clausena anisata* | TRF-MMF |
| *Vangueria apiculata* | MMF | *Croton macrostachyus* | TRF-MMF |
| *Vernonia auriculifera* | MMF | *Diospyros abyssinica* | TRF-MMF |
| *Acanthus pubescens* | TRF | *Fagaropsis angolensis* | TRF-MMF |
| *Antiaris toxcaria* | TRF | *Ficus exasperata* | TRF-MMF |
| Balakaya (Local, Kakamega) | TRF | *Ficus thonningii* | TRF-MMF |
| *Bequaertiodendron oblanceolatum* | TRF | *Flacourtia indica* | TRF-MMF |
| *Bischofia javanica* | TRF | *Macaranga kilimandscharia* | TRF-MMF |
| *Blighia unijugata* | TRF | *Markhamia lutea* | TRF-MMF |
| *Chaetacme aristata* | TRF | *Olea capensis ssp welwitschii* | TRF-MMF |
| *Cordia africana* | TRF | *Solanum mauritianum* | TRF-MMF |
| *Craibia brownii* | TRF | | |

## APPENDIX XII. SHARING OF TREE GENERA AMONG THREE DIFFERENT FOREST TYPES IN KENYA BASED ON THE ASSESSED ONE HECTARE PLOT PER FOREST

| Genera | Forest type | Genera | Forest type |
|---|---|---|---|
| *Acacia* | DWF-TRF | *Rawsonia* | TRF |
| *Boscia* | DWF | *Sapium* | TRF |
| *Cissus* | DWF | *Spathodea* | TRF |
| *Euphorbia* | DWF | *Strombosia* | TRF |
| *Casaeria* | MMF | *Trema* | TRF |
| *Maytenus* | MMF | *Trichilia* | TRF |
| *Nuxia* | MMF | *Trilepisium* | TRF |
| *Olinia* | MMF | *Zanthoxyllum* | TRF |
| *Podocarpus* | MMF | *Albizia* | TRF-MMF |
| *Ritchiea* | MMF | *Aningeria* | TRF-MMF |
| *Schrebera* | MMF | *Bersama* | TRF-MMF |
| *Sclerocarya* | MMF | *Celtis* | TRF-MMF |
| *Senna* | MMF | *Clausena* | TRF-MMF |
| *Syzygium* | MMF | *Croton* | TRF-MMF |
| *Turraea* | MMF | *Dovyalis* | TRF-MMF |
| *Vernonia* | MMF | *Dracaena* | TRF-MMF |
| *Acanthus* | TRF | *Fagaropsis* | TRF-MMF |
| *Antiaris* | TRF | *Ficus* | TRF-MMF |
| *Bequaertiodendron* | TRF | *Flacourtia indica* | TRF-MMF |
| *Bischofia* | TRF | *Macaranga* | TRF-MMF |
| *Blighia* | TRF | *Markhamia* | TRF-MMF |
| *Chaetacme* | TRF | *Olea* | TRF-MMF |
| *Cordia* | TRF | *Solanum* | TRF-MMF |
| *Craibia* | TRF | *Teclea* | TRF-MMF |
| *Funtumia* | TRF | *Vangueria* | TRF-MMF |
| *Hagenia* | TRF | *Diospyros* | TRF-MMF-DWF |
| *Harungana* | TRF | | |
| *Kigelia* | TRF | | |
| *Maesopsis* | TRF | | |
| *Manilkara* | TRF | | |
| *Morus* | TRF | | |
| *Polyscias* | TRF | | |
| *Prunus* | TRF | | |

# APPENDIX XIII. SHARING OF TREE FAMILIES AMONG THREE DIFFERENT FOREST TYPES IN KENYA BASED ON THE ASSESSED ONE HECTARE PLOT PER FOREST

| Families | Forest type |
|---|---|
| Vitaceae | DWF |
| Anacardiaceae | MMF |
| Caesalpiniaceae | MMF |
| Celastraceae | MMF |
| Compositae | MMF |
| Dracaenaceae | MMF |
| Loganiaceae | MMF |
| Myrtaceae | MMF |
| Oleaceae | MMF |
| Oliniaceae | MMF |
| Podocarpaceae | MMF |
| Rubiaceae | MMF |
| Capparaceae | MMF-DWF |
| Acanthaceae | TRF |
| Agavaceae | TRF |
| Apocynaceae | TRF |
| Araliaceae | TRF |
| Boraginaceae | TRF |
| Guttiferae | TRF |
| Papilionaceae | TRF |
| Rhamnaceae | TRF |
| Rosaceae | TRF |
| Sapindaceae | TRF |
| Bignoniaceae | TRF-MMF |
| Flacourtiaceae | TRF-MMF |
| Meliaceae | TRF-MMF |
| Melianthaceae | TRF-MMF |
| Moraceae | TRF-MMF |
| Olacaceae | TRF-MMF |
| Rutaceae | TRF-MMF |
| Sapotaceae | TRF-MMF |
| Solanaceae | TRF-MMF |
| Ulmaceae | TRF-MMF |
| Ebenaceae | TRF-MMF-DWF |
| Euphorbiaceae | TRF-MMF-DWF |
| Mimosaceae | TRF-MMF-DWF |

# APPENDIX XIV: BIOPHYSICAL CHARACTERISATION OF VERTICAL STRUCTURE AND TREE DIAMETER DISTRIBUTION FOR THE THREE FOREST TYPES, KENYA

## XIV.1. Characteristics of top canopy height (m) for Tropical rain forest, Moist Lower Montane Forest and Tropical Dry Woodland of Kenya

| TRF | No. plots | median | Mean ± SE | SD | CV% | Overall Mean (m) |
|---|---|---|---|---|---|---|
| 20 m x 20 m plots | 25 | 35 | 34.72 ± 0.43$^{a}$ | 1.06 | 3.06 | 30.5 |
| 5 m x 5 m plots | 200 | 30 | 30.36 ± 1.14$^{b}$ | 4.11 | 13.54 | |
| 5 m x 5 m plots | 400 | 30 | 30.45 ± 0.39$^{b}$ | 4.04 | 13.27 | |
| MMF | | | | | | |
| 20 m x 20 m plots | 25 | 35 | 32.20 ± 2.06$^{a}$ | 5.02 | 15.58 | 22.8 |
| 5 m x 5 m plots | 200 | 25 | 23.08 ± 1.69$^{b}$ | 6.10 | 26.42 | |
| 5 m x 5 m plots | 400 | 23 | 22.84 ± 0.71$^{b}$ | 7.25 | 31.74 | |
| DWF | | | | | | |
| 20 m x 20 m plots | 25 | 6 | 6.64 ± 0.33$^{a}$ | 0.81 | 12.20 | 5.1 |
| 5 m x 5 m plots | 200 | 5 | 5.22 ± 0.51$^{b}$ | 1.85 | 35.53 | |
| 5 m x 5 m plots | 400 | 5 | 5.06 ± 0.18$^{b}$ | 1.78 | 35.13 | |

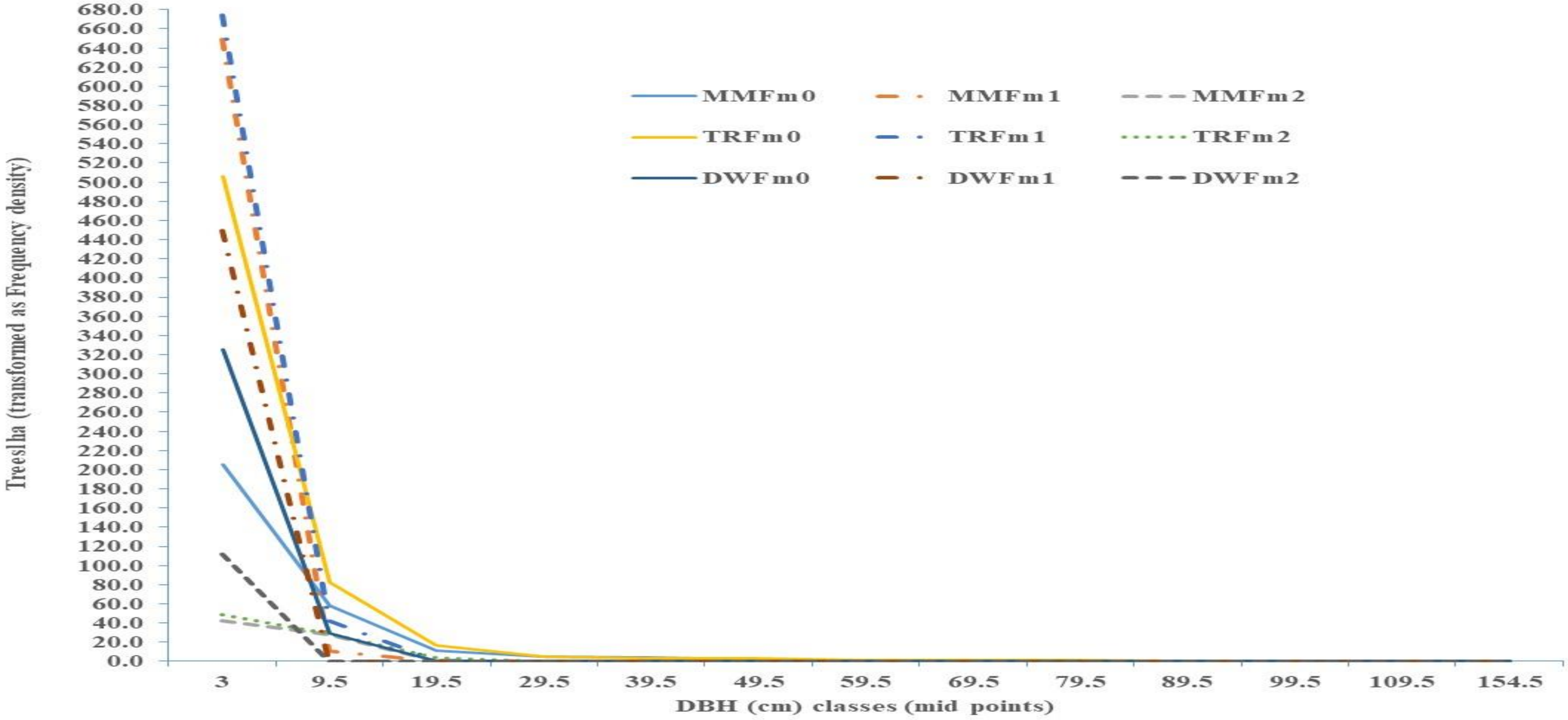
Mean top height values followed by same letter in a column within each forest type are not significantly different ($\alpha=0.05$)

## XIV.2: Diameter Distribution trends

### Modelling diameter size distribution and graphical illustrations

| DBH class | Moist montane forest | | | Tropical rain forest | | | Dry woodland forest | | |
|---|---|---|---|---|---|---|---|---|---|
| | *MMF* $m_0$ | *MMF* $m_1$ | *MMF* $m_2$ | *TRF* $m_0$ | *TRF* $m_1$ | *TRF* $m_2$ | *DWF* $m_0$ | *DWF* $m_1$ | *DWF* $m_2$ |
| 3.0 | 5.33 | 6.48 | 3.78 | 6.23 | 6.52 | 3.90 | 5.79 | 6.11 | 4.73 |
| 9.5 | 4.07 | 2.47 | 3.35 | 4.42 | 3.78 | 3.39 | 3.40 | - | - |
| 19.5 | 2.51 | - | - | 2.87 | 0.72 | 1.43 | 0.34 | - | - |
| 29.5 | 1.79 | - | - | 1.79 | - | - | 0.34 | - | - |
| 39.5 | 1.57 | - | - | 1.48 | - | - | 0.10 | - | - |
| 49.5 | 1.28 | - | - | 1.31 | - | - | - | - | - |
| 59.5 | 0.34 | - | - | 0.83 | - | - | - | - | - |
| 69.5 | 0.26 | - | - | 0.83 | - | - | - | - | - |
| 79.5 | 0.26 | - | - | 0.92 | - | - | - | - | - |
| 89.5 | - | - | - | 0.59 | - | - | - | - | - |
| 99.5 | - | - | - | 0.34 | - | - | - | - | - |
| 109.5 | - | - | - | 0.41 | - | - | - | - | - |
| 154.5 | 0.01 | - | - | 0.11 | - | - | - | - | - |

$m_0$ =actual forest data – zero model; $m_1$ = Model 1 ($Y = Y_0 X^{-b}$) estimates, $m_2$ = Model 2 ($N = N_0 e^{-bD}$) estimates



**Dbh sizes distribution structure of the studied one hectare -blocks in different forest formations of Kenya based on actual forests data (solid lines) versus hypothetical mathematical models (dotted lines)**

[MMF = Tropical moist montane forest; TRF = Tropical rain forest; and DWF = Tropical dry woodland forest. $m_0$ = actual forests data model; $m_1$ and $m_2$ are $Model_1$ = Negative power model ($Y = Y_0 X^{-b}$) and $Model_2$ = Negative exponential model ($N = N_0 e^{-bD}$) estimated data, respectively].

**Comparison between tropical natural forest types based on stocking, diameter size distribution and regular dbh classes for tree individuals ≥ 1 cm dbh**[a]

| **Model$_1$ ($Y = Y_0 X^{-b}$) = m$_1$** | | | | | **Model$_2$ ($N = N_0 e^{-bD}$) = m$_2$** | | | |
|---|---|---|---|---|---|---|---|---|
| **Forest types** | **Yo** | **b** | **Adj. $R^2$** | **Prob.** | **Yo** | **b** | **Adj. $R^2$** | **Prob.** |
| TRF | 6348.666 | 2.041 | 0.98 | 0.000 | 55.813 | 0.047 | 0.80 | 0.000 |
| MMF | 8673.26 | 2.36 | 0.90 | 0.000 | 51.265 | 0.061 | 0.89 | 0.000 |
| DWF | 15740.62 | 3.236 | 0.94 | 0.004 | 214.005 | 0.216 | 0.82 | 0.021 |

[a] Regular class interval of 10 cm-dbh (frequency density was used to standardize class sizes and remove any bias from unequal class intervals (Eason, Coles & Gettinby, 1992). The first class (1-5 cm) has a width of 4 cm, the last class (110-160cm) has a width of 50 cm and intermediate classes have a constant width of 10 cm each. Frequency density = frequency / class width)

# APPENDIX XV: SPECIES –AREA CURVE MODELS AND THEIR QUALITIES

| Plot size | Forest | Actual model for no.spp/ha factoring spp total census | Predictive power ($R^2$) | RMSE% | MPE% | Predictive model for no. spp /ha based on 30% sample | Predictive power (R^2) | RMSE% | MPE% | Actual no. spp/ha |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 m x 5 m | TRF | $y(H) = 6.6673\ln(x) + 55.217$ | $R^2 = 0.974$ | 2.0275 | -0.0006 | $y(H^*) = 7.9895\ln(x) + 58.202$ | $R^2 = 0.992$ | 3.5657 | -1.5561 | 54 |
|  |  | $y(V) = 7.7865\ln(x) + 53.432$ | $R^2 = 0.99$ | 1.2252 | 0.0007 | $y(V^*) = 7.1696\ln(x) + 52.039$ | $R^2 = 0.988$ | 1.8372 | 0.7270 | 54 |
|  | MMF | $y(H) = 6.0081\ln(x) + 35.547$ | $R^2 = 0.9362$ | 4.3037 | 0.0006 | $y(H^*) = 4.4293\ln(x) + 31.982$ | $R^2 = 0.8717$ | 6.6827 | 2.7131 | 37 |
|  |  | $y(V) = 5.587\ln(x) + 35.264$ | $R^2 = 0.9207$ | 4.4992 | 0.0001 | $y(V^*) = 3.7004\ln(x) + 31.004$ | $R^2 = 0.8811$ | 7.5868 | 3.2414 | 37 |
|  | DWF | $y(H) = 0.581\ln(x) + 11.943$ | $R^2 = 0.8703$ | 1.8983 | -0.0035 | $y(H^*) = 0.5186\ln(x) + 11.802$ | $R^2 = 0.6692$ | 1.9975 | 0.3279 | 12 |
|  |  | $y(V) = 0.6293\ln(x) + 11.421$ | $R^2 = 0.6381$ | 4.0107 | -0.0005 | $y(V^*) = 10$ | $R^2 = N/A$ | 7.4536 | 3.3333 | 12 |
|  |  |  |  |  |  |  |  |  |  |  |
| 5 m x 10 m | TRF | $y(H) = 5.9519\ln(x) + 55.056$ | $R^2 = 0.975$ | 1.7654 | 0.0001 | $y(H^*) = 7.0995\ln(x) + 57.647$ | $R^2 = 0.992$ | 3.0980 | -1.3503 | 54 |
|  |  | $y(V) = 6.9899\ln(x) + 52.94$ | $R^2 = 0.979$ | 1.9028 | 0.0001 | $y(V^*) = 5.838\ln(x) + 50.339$ | $R^2 = 0.9785$ | 3.1862 | 1.3560 | 54 |
|  | MMF | $y(H) = 6.0081\ln(x) + 35.547$ | $R^2 = 0.9362$ | 4.8196 | 1.0817 | $y(H^*) = 4.4293\ln(x) + 31.982$ | $R^2 = 0.8717$ | 6.4820 | 3.7942 | 37 |
|  |  | $y(V) = 5.587\ln(x) + 35.264$ | $R^2 = 0.9207$ | 4.4992 | 0.0001 | $y(V^*) = 3.7004\ln(x) + 31.004$ | $R^2 = 0.8811$ | 7.5868 | 3.2414 | 37 |
|  | DWF | $y(H) = 1.1137\ln(x) + 12.407$ | $R^2 = 0.6952$ | 6.2410 | -0.0016 | $y(H^*) = 1.5559\ln(x) + 13.405$ | $R^2 = 0.6692$ | 7.6438 | -2.3399 | 12 |
|  |  | $y(V) = 0.6293\ln(x) + 11.421$ | $R^2 = 0.6381$ | 4.0107 | -0.0005 | $y(V^*) = 10$ | $R^2 = N/A$ | 7.4536 | 3.3333 | 12 |
|  |  |  |  |  |  |  |  |  |  |  |
| 10 m x 10 m | TRF | $y(H) = 6.9233\ln(x) + 57.232$ | $R^2 = 0.777$ | 6.9713 | 0.0000 | $y(H^*) = 10.435\ln(x) + 65.162$ | $R^2 = 0.853$ | 10.4551 | -4.1349 | 54 |
|  |  | $y(V) = 6.2695\ln(x) + 51.571$ | $R^2 = 0.861$ | 4.7233 | 0.0005 | $y(V^*) = 3.6303\ln(x) + 45.612$ | $R^2 = 0.669$ | 7.5229 | 3.1067 | 54 |
|  | MMF | $y(H) = 4.1103\ln(x) + 35.668$ | $R^2 = 0.9074$ | 3.6036 | 0.0009 | $y(H^*) = 2.6632\ln(x) + 32.401$ | $R^2 = 0.8272$ | 5.9109 | 2.4855 | 37 |
|  |  | $y(V) = 5.0442\ln(x) + 33.983$ | $R^2 = 0.7772$ | 7.4121 | 0.0012 | $y(V^*) = 1.7661\ln(x) + 26.582$ | $R^2 = 0.4851$ | 12.9456 | 5.6303 | 37 |
|  | DWF | $y(H) = 0.931\ln(x) + 12.71$ | $R^2 = 0.6572$ | 5.6896 | 0.0034 | $y(H^*) = 1.703\ln(x) + 14.454$ | $R^2 = 0.9021$ | 9.5814 | -4.0929 | 12 |
|  |  | $y(V) = 0.6293\ln(x) + 11.421$ | $R^2 = 0.6381$ | 4.0107 | -0.0005 | $y(V^*) = 10$ | $R^2 = N/A$ | 7.4536 | 3.3333 | 12 |
|  |  |  |  |  |  |  |  |  |  |  |
| 20 m x 20m | TRF | $y(H) = 4.9218\ln(x) + 55.185$ | $R^2 = 0.954$ | 2.0111 | -0.0003 | $y(H^*) = 6.2094\ln(x) + 58.092$ | $R^2 = 0.985$ | 3.4933 | -1.5152 | 54 |
|  |  | $y(V) = 4.5673\ln(x) + 50.61$ | $R^2 = 0.722$ | 5.3185 | -0.0005 | $y(V^*) = 0.8831\ln(x) + 42.291$ | $R^2 = 0.485$ | 9.7516 | 4.3365 | 54 |
|  | MMF | $y(H) = 4.6734\ln(x) + 36.782$ | $R^2 = 0.947$ | 3.0066 | -0.0004 | $y(H^*) = 4.4363\ln(x) + 36.247$ | $R^2 = 0.859$ | 3.1029 | 0.4060 | 37 |
|  |  | $y(V) = 3.4611\ln(x) + 33.815$ | $R^2 = 0.638$ | 7.1542 | 0.0003 | $y(V^*) = 26$ | $R^2 = N/A$ | 13.2955 | 5.9459 | 37 |
|  | DWF | $y(H) = 0.6646\ln(x) + 12.478$ | $R^2 = 0.7118$ | 3.5790 | 0.0018 | $y(H^*) = 1.1844\ln(x) + 13.652$ | $R^2 = 0.9519$ | 23.3051 | -22.4472 | 12 |
|  |  | $y(V) = 0.7104\ln(x) + 11.753$ | $R^2 = 0.8132$ | 29.8202 | -29.1139 | $y(V^*) = 0.4415\ln(x) + 11.145$ | $R^2 = 0.4851$ | 29.3847 | -28.7100 | 12 |

# APPENDIX XVI: INVENTORY COST AND SAMPLING ERRORS FOR TESTED SCHEMES IN DIFFERENT FOREST TYPES

## Sampling Effort for Schemes Having Sampling Error < 25%

### XVI.1. Regeneration density per hectare

| Forest | Sampling design | Plot size | Sampling intensity | Sampling effort | | Regeneration sampling error |
|---|---|---|---|---|---|---|
| | | | | hours/ha | ha/hour | |
| TRF | SRS | 25 | 100 | 50.42 | 0.02 | 15.36 |
| TRF | SRS | 50 | 100 | 25.28 | 0.04 | 16.17 |
| TRF | SRS | 100 | 100 | 12.47 | 0.08 | 18.40 |
| TRF | SSH (E-W) | 50 | 5 | 26.00 | 0.04 | 22.51 |
| TRF | SSH (E-W) | 25 | 100 | 50.42 | 0.02 | 15.36 |
| TRF | SSH (E-W) | 50 | 100 | 25.28 | 0.04 | 16.17 |
| TRF | SSH (E-W) | 100 | 100 | 12.47 | 0.08 | 18.40 |
| TRF | SSV (N-S) | 25 | 30 | 50.89 | 0.02 | 20.92 |
| TRF | SSV (N-S) | 50 | 30 | 25.17 | 0.04 | 23.53 |
| TRF | SSV (N-S) | 25 | 100 | 50.42 | 0.02 | 15.36 |
| TRF | SSV (N-S) | 50 | 100 | 25.28 | 0.04 | 16.17 |
| TRF | SSV (N-S) | 100 | 100 | 12.47 | 0.08 | 18.40 |
| MMF | SRS | 25 | 100 | 40.68 | 0.02 | 14.74 |
| MMF | SRS | 50 | 100 | 20.10 | 0.05 | 15.62 |
| MMF | SRS | 100 | 100 | 9.98 | 0.10 | 18.22 |
| MMF | SRS | 400 | 100 | 2.43 | 0.41 | 24.04 |
| MMF | SSH (E-W) | 25 | 100 | 40.68 | 0.02 | 14.74 |
| MMF | SSH (E-W) | 50 | 100 | 20.10 | 0.05 | 15.62 |
| MMF | SSH (E-W) | 100 | 100 | 9.98 | 0.10 | 18.22 |
| MMF | SSH (E-W) | 400 | 100 | 2.43 | 0.41 | 24.04 |
| MMF | SSV (N-S) | 25 | 100 | 40.68 | 0.02 | 14.74 |
| MMF | SSV (N-S) | 50 | 100 | 20.10 | 0.05 | 15.62 |
| MMF | SSV (N-S) | 100 | 100 | 9.98 | 0.10 | 18.22 |
| MMF | SSV (N-S) | 400 | 100 | 2.43 | 0.41 | 24.04 |
| DWF | SRS | 400 | 10 | 1.17 | 0.86 | - |
| DWF | SRS | 25 | 20 | 21.75 | 0.05 | 24.40 |
| DWF | SRS | 50 | 20 | 11.00 | 0.09 | 21.42 |
| DWF | SRS | 25 | 30 | 21.83 | 0.05 | 18.39 |
| DWF | SRS | 50 | 30 | 11.11 | 0.09 | 20.62 |
| DWF | SRS | 100 | 30 | 5.72 | 0.17 | 21.18 |
| DWF | SRS | 25 | 100 | 22.38 | 0.04 | 9.87 |
| DWF | SRS | 50 | 100 | 11.35 | 0.09 | 10.67 |
| DWF | SRS | 100 | 100 | 5.65 | 0.18 | 12.12 |
| DWF | SRS | 400 | 100 | 1.45 | 0.69 | 18.64 |
| DWF | SSH (E-W) | 50 | 10 | 11.33 | 0.09 | 21.09 |
| DWF | SSH (E-W) | 25 | 20 | 22.17 | 0.05 | 21.31 |
| DWF | SSH (E-W) | 50 | 20 | 11.25 | 0.09 | 21.94 |
| DWF | SSH (E-W) | 25 | 30 | 22.00 | 0.05 | 18.76 |
| DWF | SSH (E-W) | 50 | 30 | 11.50 | 0.09 | 19.12 |
| DWF | SSH (E-W) | 25 | 100 | 22.38 | 0.04 | 9.87 |
| DWF | SSH (E-W) | 50 | 100 | 11.35 | 0.09 | 10.67 |
| DWF | SSH (E-W) | 100 | 100 | 5.65 | 0.18 | 12.12 |
| DWF | SSH (E-W) | 400 | 100 | 1.45 | 0.69 | 18.64 |
| DWF | SSV (N-S) | 25 | 20 | 22.00 | 0.05 | 22.82 |
| DWF | SSV (N-S) | 50 | 20 | 10.83 | 0.09 | 24.39 |

| | | | | | | |
|---|---|---|---|---|---|---|
| DWF | SSV (N-S) | 25 | 30 | 21.89 | 0.05 | 17.97 |
| DWF | SSV (N-S) | 50 | 30 | 10.89 | 0.09 | 18.39 |
| DWF | SSV (N-S) | 100 | 30 | 5.44 | 0.18 | 19.76 |
| DWF | SSV (N-S) | 400 | 30 | 1.28 | 0.78 | 19.73 |
| DWF | SSV (N-S) | 25 | 100 | 22.38 | 0.04 | 9.87 |
| DWF | SSV (N-S) | 50 | 100 | 11.35 | 0.09 | 10.67 |
| DWF | SSV (N-S) | 100 | 100 | 5.65 | 0.18 | 12.12 |
| DWF | SSV (N-S) | 400 | 100 | 1.45 | 0.69 | 18.64 |

### XVI.2. Density of stems per hectare

| Forest | Sampling design | Plot size | Sampling intensity | Sampling effort | | Stem density sampling error |
|---|---|---|---|---|---|---|
| | | | | hours/ha | ha/hour | |
| TRF | SRS | 100 | 5 | 12.7 | 0.08 | 15.1 |
| TRF | SRS | 25 | 10 | 50.5 | 0.02 | 17.7 |
| TRF | SRS | 50 | 10 | 24.5 | 0.04 | 23.7 |
| TRF | SRS | 25 | 20 | 49.8 | 0.02 | 13.9 |
| TRF | SRS | 50 | 20 | 25.0 | 0.04 | 13.1 |
| TRF | SRS | 100 | 20 | 12.1 | 0.08 | 15.2 |
| TRF | SRS | 25 | 30 | 50.3 | 0.02 | 10.8 |
| TRF | SRS | 50 | 30 | 24.8 | 0.04 | 9.5 |
| TRF | SRS | 100 | 30 | 12.5 | 0.08 | 11.3 |
| TRF | SRS | 400 | 30 | 2.7 | 0.37 | 15.1 |
| TRF | SRS | 25 | 100 | 50.4 | 0.02 | 5.3 |
| TRF | SRS | 50 | 100 | 25.3 | 0.04 | 5.6 |
| TRF | SRS | 100 | 100 | 12.5 | 0.08 | 6.0 |
| TRF | SRS | 400 | 100 | 3.1 | 0.33 | 7.7 |
| TRF | SSH (E-W) | 25 | 5 | 51.3 | 0.02 | 20.2 |
| TRF | SSH (E-W) | 50 | 5 | 26.0 | 0.04 | 19.9 |
| TRF | SSH (E-W) | 25 | 10 | 51.2 | 0.02 | 15.2 |
| TRF | SSH (E-W) | 50 | 10 | 25.2 | 0.04 | 13.5 |
| TRF | SSH (E-W) | 100 | 10 | 12.0 | 0.08 | 22.1 |
| TRF | SSH (E-W) | 25 | 20 | 50.6 | 0.02 | 10.9 |
| TRF | SSH (E-W) | 50 | 20 | 25.3 | 0.04 | 11.9 |
| TRF | SSH (E-W) | 100 | 20 | 12.4 | 0.08 | 15.4 |
| TRF | SSH (E-W) | 25 | 30 | 50.5 | 0.02 | 9.1 |
| TRF | SSH (E-W) | 50 | 30 | 25.2 | 0.04 | 10.2 |
| TRF | SSH (E-W) | 100 | 30 | 12.0 | 0.08 | 11.6 |
| TRF | SSH (E-W) | 400 | 30 | 2.8 | 0.35 | 17.1 |
| TRF | SSH (E-W) | 25 | 100 | 50.4 | 0.02 | 5.3 |
| TRF | SSH (E-W) | 50 | 100 | 25.3 | 0.04 | 5.6 |
| TRF | SSH (E-W) | 100 | 100 | 12.5 | 0.08 | 6.0 |
| TRF | SSH (E-W) | 400 | 100 | 3.1 | 0.33 | 7.7 |
| TRF | SSV (N-S) | 25 | 5 | 54.7 | 0.02 | 19.0 |
| TRF | SSV (N-S) | 50 | 5 | 27.0 | 0.04 | 15.4 |
| TRF | SSV (N-S) | 100 | 5 | 13.7 | 0.07 | 20.0 |
| TRF | SSV (N-S) | 25 | 10 | 51.8 | 0.02 | 13.4 |
| TRF | SSV (N-S) | 50 | 10 | 27.2 | 0.04 | 16.9 |
| TRF | SSV (N-S) | 100 | 10 | 13.5 | 0.07 | 15.4 |
| TRF | SSV (N-S) | 25 | 20 | 51.4 | 0.02 | 11.3 |
| TRF | SSV (N-S) | 50 | 20 | 25.7 | 0.04 | 12.5 |
| TRF | SSV (N-S) | 100 | 20 | 12.8 | 0.08 | 13.0 |
| TRF | SSV (N-S) | 400 | 20 | 3.3 | 0.31 | 24.9 |
| TRF | SSV (N-S) | 25 | 30 | 50.9 | 0.02 | 9.2 |
| TRF | SSV (N-S) | 50 | 30 | 25.2 | 0.04 | 10.5 |
| TRF | SSV (N-S) | 100 | 30 | 12.5 | 0.08 | 11.1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| TRF | SSV (N-S) | 400 | 30 | 2.9 | 0.34 | 15.8 |
| TRF | SSV (N-S) | 25 | 100 | 50.4 | 0.02 | 5.3 |
| TRF | SSV (N-S) | 50 | 100 | 25.3 | 0.04 | 5.6 |
| TRF | SSV (N-S) | 100 | 100 | 12.5 | 0.08 | 6.0 |
| TRF | SSV (N-S) | 400 | 100 | 3.1 | 0.33 | 7.7 |
| MMF | SRS | 25 | 10 | 42.3 | 0.02 | 21.0 |
| MMF | SRS | 100 | 10 | 10.2 | 0.10 | 21.6 |
| MMF | SRS | 400 | 10 | 1.3 | 0.75 | 20.9 |
| MMF | SRS | 25 | 20 | 38.6 | 0.03 | 16.6 |
| MMF | SRS | 50 | 20 | 19.4 | 0.05 | 16.9 |
| MMF | SRS | 100 | 20 | 9.3 | 0.11 | 15.6 |
| MMF | SRS | 25 | 30 | 40.2 | 0.02 | 13.6 |
| MMF | SRS | 50 | 30 | 19.2 | 0.05 | 14.8 |
| MMF | SRS | 100 | 30 | 8.3 | 0.12 | 13.5 |
| MMF | SRS | 400 | 30 | 2.3 | 0.43 | 13.6 |
| MMF | SRS | 25 | 100 | 40.7 | 0.02 | 7.3 |
| MMF | SRS | 50 | 100 | 20.1 | 0.05 | 7.6 |
| MMF | SRS | 100 | 100 | 10.0 | 0.10 | 8.1 |
| MMF | SRS | 400 | 100 | 2.4 | 0.41 | 10.6 |
| MMF | SSH (E-W) | 25 | 10 | 39.8 | 0.03 | 24.8 |
| MMF | SSH (E-W) | 100 | 10 | 9.0 | 0.11 | 23.1 |
| MMF | SSH (E-W) | 400 | 10 | 1.2 | 0.86 | 0.0 |
| MMF | SSH (E-W) | 25 | 20 | 39.6 | 0.03 | 16.9 |
| MMF | SSH (E-W) | 50 | 20 | 19.0 | 0.05 | 20.2 |
| MMF | SSH (E-W) | 100 | 20 | 8.7 | 0.12 | 15.9 |
| MMF | SSH (E-W) | 400 | 20 | 1.7 | 0.60 | 24.9 |
| MMF | SSH (E-W) | 25 | 30 | 39.3 | 0.03 | 13.2 |
| MMF | SSH (E-W) | 50 | 30 | 19.3 | 0.05 | 14.5 |
| MMF | SSH (E-W) | 100 | 30 | 8.7 | 0.11 | 13.9 |
| MMF | SSH (E-W) | 400 | 30 | 1.7 | 0.58 | 21.5 |
| MMF | SSH (E-W) | 25 | 100 | 40.7 | 0.02 | 7.3 |
| MMF | SSH (E-W) | 50 | 100 | 20.1 | 0.05 | 7.6 |
| MMF | SSH (E-W) | 100 | 100 | 10.0 | 0.10 | 8.1 |
| MMF | SSH (E-W) | 400 | 100 | 2.4 | 0.41 | 10.6 |
| MMF | SSV (N-S) | 25 | 10 | 38.2 | 0.03 | 20.3 |
| MMF | SSV (N-S) | 50 | 10 | 17.7 | 0.06 | 24.5 |
| MMF | SSV (N-S) | 25 | 20 | 36.9 | 0.03 | 14.3 |
| MMF | SSV (N-S) | 50 | 20 | 17.7 | 0.06 | 14.8 |
| MMF | SSV (N-S) | 100 | 20 | 8.3 | 0.12 | 14.4 |
| MMF | SSV (N-S) | 25 | 30 | 38.2 | 0.03 | 13.0 |
| MMF | SSV (N-S) | 50 | 30 | 18.0 | 0.06 | 13.2 |
| MMF | SSV (N-S) | 100 | 30 | 8.7 | 0.12 | 14.2 |
| MMF | SSV (N-S) | 400 | 30 | 1.8 | 0.55 | 16.8 |
| MMF | SSV (N-S) | 25 | 100 | 40.7 | 0.02 | 7.3 |
| MMF | SSV (N-S) | 50 | 100 | 20.1 | 0.05 | 7.6 |
| MMF | SSV (N-S) | 100 | 100 | 10.0 | 0.10 | 8.1 |
| MMF | SSV (N-S) | 400 | 100 | 2.4 | 0.41 | 10.6 |
| DWF | SRS | 50 | 10 | 11.2 | 0.09 | 20.9 |
| DWF | SRS | 25 | 20 | 21.8 | 0.05 | 17.0 |
| DWF | SRS | 50 | 20 | 11.0 | 0.09 | 17.7 |
| DWF | SRS | 25 | 30 | 21.8 | 0.05 | 12.8 |
| DWF | SRS | 50 | 30 | 11.1 | 0.09 | 17.7 |
| DWF | SRS | 100 | 30 | 5.7 | 0.17 | 17.1 |
| DWF | SRS | 25 | 100 | 22.4 | 0.04 | 7.6 |
| DWF | SRS | 50 | 100 | 11.4 | 0.09 | 9.1 |
| DWF | SRS | 100 | 100 | 5.7 | 0.18 | 10.2 |

| | | | | | | |
|---|---|---|---|---|---|---|
| DWF | SRS | 400 | 100 | 1.5 | 0.69 | 16.9 |
| DWF | SSH (E-W) | 25 | 20 | 22.2 | 0.05 | 20.4 |
| DWF | SSH (E-W) | 50 | 20 | 11.3 | 0.09 | 17.6 |
| DWF | SSH (E-W) | 100 | 20 | 5.6 | 0.18 | 21.1 |
| DWF | SSH (E-W) | 25 | 30 | 22.0 | 0.05 | 15.6 |
| DWF | SSH (E-W) | 50 | 30 | 11.5 | 0.09 | 15.4 |
| DWF | SSH (E-W) | 100 | 30 | 5.7 | 0.17 | 18.2 |
| DWF | SSH (E-W) | 25 | 100 | 22.4 | 0.04 | 7.6 |
| DWF | SSH (E-W) | 50 | 100 | 11.4 | 0.09 | 9.1 |
| DWF | SSH (E-W) | 100 | 100 | 5.7 | 0.18 | 10.2 |
| DWF | SSH (E-W) | 400 | 100 | 1.5 | 0.69 | 16.9 |
| DWF | SSV (N-S) | 50 | 5 | 11.0 | 0.09 | 24.2 |
| DWF | SSV (N-S) | 25 | 10 | 22.0 | 0.05 | 23.3 |
| DWF | SSV (N-S) | 50 | 10 | 11.2 | 0.09 | 18.8 |
| DWF | SSV (N-S) | 100 | 10 | 5.5 | 0.18 | 22.9 |
| DWF | SSV (N-S) | 400 | 10 | 1.2 | 0.86 | 10.0 |
| DWF | SSV (N-S) | 25 | 20 | 22.0 | 0.05 | 14.4 |
| DWF | SSV (N-S) | 50 | 20 | 10.8 | 0.09 | 14.5 |
| DWF | SSV (N-S) | 100 | 20 | 5.4 | 0.18 | 15.7 |
| DWF | SSV (N-S) | 400 | 20 | 1.4 | 0.71 | 19.0 |
| DWF | SSV (N-S) | 25 | 30 | 21.9 | 0.05 | 12.2 |
| DWF | SSV (N-S) | 50 | 30 | 10.9 | 0.09 | 12.3 |
| DWF | SSV (N-S) | 100 | 30 | 5.4 | 0.18 | 12.7 |
| DWF | SSV (N-S) | 400 | 30 | 1.3 | 0.78 | 13.4 |
| DWF | SSV (N-S) | 25 | 100 | 22.4 | 0.04 | 7.6 |
| DWF | SSV (N-S) | 50 | 100 | 11.4 | 0.09 | 9.1 |
| DWF | SSV (N-S) | 100 | 100 | 5.7 | 0.18 | 10.2 |
| DWF | SSV (N-S) | 400 | 100 | 1.5 | 0.69 | 16.9 |

**XVI.3. Basal area per hectare**

| Forest | Sampling design | Plot size | Sampling intensity | Sampling effort | | Basal area Sampling error |
|---|---|---|---|---|---|---|
| | | | | hours/ha | ha/hour | |
| TRF | SRS | 25 | 100 | 50.42 | 0.02 | 20.6 |
| TRF | SRS | 50 | 100 | 25.28 | 0.04 | 21.4 |
| TRF | SRS | 100 | 100 | 12.47 | 0.08 | 19.9 |
| TRF | SRS | 400 | 100 | 3.07 | 0.33 | 21.5 |
| TRF | SSH (E-W) | 400 | 10 | 2.33 | 0.43 | 14.0 |
| TRF | SSH (E-W) | 25 | 100 | 50.42 | 0.02 | 20.6 |
| TRF | SSH (E-W) | 50 | 100 | 25.28 | 0.04 | 21.4 |
| TRF | SSH (E-W) | 100 | 100 | 12.47 | 0.08 | 19.9 |
| TRF | SSH (E-W) | 400 | 100 | 3.07 | 0.33 | 21.5 |
| TRF | SSV (N-S) | 400 | 10 | 2.67 | 0.38 | 14.6 |
| TRF | SSV (N-S) | 25 | 100 | 50.42 | 0.02 | 20.6 |
| TRF | SSV (N-S) | 50 | 100 | 25.28 | 0.04 | 21.4 |
| TRF | SSV (N-S) | 100 | 100 | 12.47 | 0.08 | 19.9 |
| TRF | SSV (N-S) | 400 | 100 | 3.07 | 0.33 | 21.5 |
| MMF | SRS | 25 | 100 | 40.68 | 0.02 | 21.1 |
| MMF | SRS | 50 | 100 | 20.10 | 0.05 | 21.8 |
| MMF | SRS | 100 | 100 | 9.98 | 0.10 | 21.6 |
| MMF | SRS | 400 | 100 | 2.43 | 0.41 | 22.0 |
| MMF | SSH (E-W) | 25 | 100 | 40.68 | 0.02 | 21.1 |
| MMF | SSH (E-W) | 50 | 100 | 20.10 | 0.05 | 21.8 |
| MMF | SSH (E-W) | 100 | 100 | 9.98 | 0.10 | 21.6 |
| MMF | SSH (E-W) | 400 | 100 | 2.43 | 0.41 | 22.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| MMF | SSV (N-S) | 25 | 100 | 40.68 | 0.02 | 21.1 |
| MMF | SSV (N-S) | 50 | 100 | 20.10 | 0.05 | 21.8 |
| MMF | SSV (N-S) | 100 | 100 | 9.98 | 0.10 | 21.6 |
| MMF | SSV (N-S) | 400 | 100 | 2.43 | 0.41 | 22.0 |
| DWF | SRS | 25 | 100 | 22.38 | 0.04 | 20.7 |
| DWF | SRS | 50 | 100 | 11.35 | 0.09 | 21.4 |
| DWF | SRS | 100 | 100 | 5.65 | 0.18 | 21.7 |
| DWF | SRS | 400 | 100 | 1.45 | 0.69 | 22.5 |
| DWF | SSH (E-W) | 25 | 100 | 22.38 | 0.04 | 20.7 |
| DWF | SSH (E-W) | 50 | 100 | 11.35 | 0.09 | 21.4 |
| DWF | SSH (E-W) | 100 | 100 | 5.65 | 0.18 | 21.7 |
| DWF | SSH (E-W) | 400 | 100 | 1.45 | 0.69 | 22.5 |
| DWF | SSV (N-S) | 25 | 100 | 22.38 | 0.04 | 20.7 |
| DWF | SSV (N-S) | 50 | 100 | 11.35 | 0.09 | 21.4 |
| DWF | SSV (N-S) | 100 | 100 | 5.65 | 0.18 | 21.7 |
| DWF | SSV (N-S) | 400 | 100 | 1.45 | 0.69 | 22.5 |

### XVI.4. Quadratic mean diameter

| Forest | Sampling design | Plot size | Sampling intensity | Sampling effort | | Quadratic mean diameter sampling error |
|---|---|---|---|---|---|---|
| | | | | **hours/ha** | **ha/hour** | |
| TRF | SRS | 25 | 30 | 50.3 | 0.02 | 19.9 |
| TRF | SRS | 50 | 30 | 24.8 | 0.04 | 15.8 |
| TRF | SRS | 100 | 30 | 12.5 | 0.08 | 20.6 |
| TRF | SRS | 400 | 30 | 2.7 | 0.37 | 22.9 |
| TRF | SRS | 25 | 100 | 50.4 | 0.02 | 10.0 |
| TRF | SRS | 50 | 100 | 25.3 | 0.04 | 9.9 |
| TRF | SRS | 100 | 100 | 12.5 | 0.08 | 10.0 |
| TRF | SRS | 400 | 100 | 3.1 | 0.33 | 9.8 |
| TRF | SSH (E-W) | 400 | 20 | 3.0 | 0.33 | 24.3 |
| TRF | SSH (E-W) | 25 | 30 | 50.5 | 0.02 | 19.7 |
| TRF | SSH (E-W) | 50 | 30 | 25.2 | 0.04 | 23.6 |
| TRF | SSH (E-W) | 100 | 30 | 12.0 | 0.08 | 23.5 |
| TRF | SSH (E-W) | 400 | 30 | 2.8 | 0.35 | 19.8 |
| TRF | SSH (E-W) | 25 | 100 | 50.4 | 0.02 | 10.0 |
| TRF | SSH (E-W) | 50 | 100 | 25.3 | 0.04 | 9.9 |
| TRF | SSH (E-W) | 100 | 100 | 12.5 | 0.08 | 10.0 |
| TRF | SSH (E-W) | 400 | 100 | 3.1 | 0.33 | 9.8 |
| TRF | SSV (N-S) | 400 | 10 | 2.7 | 0.38 | 21.5 |
| TRF | SSV (N-S) | 25 | 20 | 51.4 | 0.02 | 24.0 |
| TRF | SSV (N-S) | 25 | 30 | 50.9 | 0.02 | 19.2 |
| TRF | SSV (N-S) | 50 | 30 | 25.2 | 0.04 | 20.8 |
| TRF | SSV (N-S) | 100 | 30 | 12.5 | 0.08 | 23.2 |
| TRF | SSV (N-S) | 400 | 30 | 2.9 | 0.34 | 20.1 |
| TRF | SSV (N-S) | 25 | 100 | 50.4 | 0.02 | 10.0 |
| TRF | SSV (N-S) | 50 | 100 | 25.3 | 0.04 | 9.9 |
| TRF | SSV (N-S) | 100 | 100 | 12.5 | 0.08 | 10.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| TRF | SSV (N-S) | 400 | 100 | 3.1 | 0.33 | 9.8 |
| MMF | SRS | 100 | 10 | 10.2 | 0.10 | 23.0 |
| MMF | SRS | 25 | 20 | 38.6 | 0.03 | 17.1 |
| MMF | SRS | 50 | 20 | 19.4 | 0.05 | 19.8 |
| MMF | SRS | 100 | 20 | 9.3 | 0.11 | 14.0 |
| MMF | SRS | 400 | 20 | 2.1 | 0.48 | 13.3 |
| MMF | SRS | 25 | 30 | 40.2 | 0.02 | 15.9 |
| MMF | SRS | 50 | 30 | 19.2 | 0.05 | 15.3 |
| MMF | SRS | 100 | 30 | 8.3 | 0.12 | 14.8 |
| MMF | SRS | 400 | 30 | 2.3 | 0.43 | 16.5 |
| MMF | SRS | 25 | 100 | 40.7 | 0.02 | 8.7 |
| MMF | SRS | 50 | 100 | 20.1 | 0.05 | 10.5 |
| MMF | SRS | 100 | 100 | 10.0 | 0.10 | 10.7 |
| MMF | SRS | 400 | 100 | 2.4 | 0.41 | 14.0 |
| MMF | SSH (E-W) | 25 | 10 | 39.8 | 0.03 | 24.2 |
| MMF | SSH (E-W) | 25 | 20 | 39.6 | 0.03 | 15.7 |
| MMF | SSH (E-W) | 50 | 20 | 19.0 | 0.05 | 20.0 |
| MMF | SSH (E-W) | 100 | 20 | 8.7 | 0.12 | 19.3 |
| MMF | SSH (E-W) | 400 | 20 | 1.7 | 0.60 | 24.5 |
| MMF | SSH (E-W) | 25 | 30 | 39.3 | 0.03 | 12.2 |
| MMF | SSH (E-W) | 50 | 30 | 19.3 | 0.05 | 16.0 |
| MMF | SSH (E-W) | 25 | 100 | 40.7 | 0.02 | 8.7 |
| MMF | SSH (E-W) | 50 | 100 | 20.1 | 0.05 | 10.5 |
| MMF | SSH (E-W) | 100 | 100 | 10.0 | 0.10 | 10.7 |
| MMF | SSH (E-W) | 400 | 100 | 2.4 | 0.41 | 14.0 |
| MMF | SSV (N-S) | 25 | 20 | 36.9 | 0.03 | 16.9 |
| MMF | SSV (N-S) | 50 | 20 | 17.7 | 0.06 | 18.6 |
| MMF | SSV (N-S) | 100 | 20 | 8.3 | 0.12 | 16.1 |
| MMF | SSV (N-S) | 25 | 30 | 38.2 | 0.03 | 14.8 |
| MMF | SSV (N-S) | 50 | 30 | 18.0 | 0.06 | 15.7 |
| MMF | SSV (N-S) | 100 | 30 | 8.7 | 0.12 | 16.1 |
| MMF | SSV (N-S) | 400 | 30 | 1.8 | 0.55 | 22.1 |
| MMF | SSV (N-S) | 25 | 100 | 40.7 | 0.02 | 8.7 |
| MMF | SSV (N-S) | 50 | 100 | 20.1 | 0.05 | 10.5 |
| MMF | SSV (N-S) | 100 | 100 | 10.0 | 0.10 | 10.7 |
| MMF | SSV (N-S) | 400 | 100 | 2.4 | 0.41 | 14.0 |
| DWF | SRS | 25 | 5 | 22.0 | 0.05 | 23.5 |
| DWF | SRS | 25 | 10 | 21.7 | 0.05 | 19.1 |
| DWF | SRS | 50 | 10 | 11.2 | 0.09 | 13.1 |
| DWF | SRS | 100 | 10 | 5.7 | 0.18 | 13.4 |
| DWF | SRS | 25 | 20 | 21.8 | 0.05 | 21.6 |
| DWF | SRS | 50 | 20 | 11.0 | 0.09 | 22.1 |
| DWF | SRS | 100 | 20 | 5.4 | 0.18 | 10.5 |
| DWF | SRS | 25 | 30 | 21.8 | 0.05 | 13.8 |

| | | | | | | |
|---|---|---|---|---|---|---|
| DWF | SRS | 50 | 30 | 11.1 | 0.09 | 14.7 |
| DWF | SRS | 100 | 30 | 5.7 | 0.17 | 23.5 |
| DWF | SRS | 400 | 30 | 1.3 | 0.75 | 17.6 |
| DWF | SRS | 25 | 100 | 22.4 | 0.04 | 6.9 |
| DWF | SRS | 50 | 100 | 11.4 | 0.09 | 7.8 |
| DWF | SRS | 100 | 100 | 5.7 | 0.18 | 9.1 |
| DWF | SRS | 400 | 100 | 1.5 | 0.69 | 12.4 |
| DWF | SSH (E-W) | 25 | 5 | 21.0 | 0.05 | 24.1 |
| DWF | SSH (E-W) | 25 | 10 | 21.7 | 0.05 | 14.7 |
| DWF | SSH (E-W) | 50 | 10 | 11.3 | 0.09 | 22.0 |
| DWF | SSH (E-W) | 400 | 10 | 1.3 | 0.75 | 18.6 |
| DWF | SSH (E-W) | 25 | 20 | 22.2 | 0.05 | 10.8 |
| DWF | SSH (E-W) | 50 | 20 | 11.3 | 0.09 | 17.3 |
| DWF | SSH (E-W) | 100 | 20 | 5.6 | 0.18 | 17.1 |
| DWF | SSH (E-W) | 25 | 30 | 22.0 | 0.05 | 11.2 |
| DWF | SSH (E-W) | 50 | 30 | 11.5 | 0.09 | 19.2 |
| DWF | SSH (E-W) | 100 | 30 | 5.7 | 0.17 | 12.7 |
| DWF | SSH (E-W) | 25 | 100 | 22.4 | 0.04 | 6.9 |
| DWF | SSH (E-W) | 50 | 100 | 11.4 | 0.09 | 7.8 |
| DWF | SSH (E-W) | 100 | 100 | 5.7 | 0.18 | 9.1 |
| DWF | SSH (E-W) | 400 | 100 | 1.5 | 0.69 | 12.4 |
| DWF | SSV (N-S) | 25 | 5 | 22.3 | 0.04 | 16.0 |
| DWF | SSV (N-S) | 50 | 10 | 11.2 | 0.09 | 20.0 |
| DWF | SSV (N-S) | 100 | 10 | 5.5 | 0.18 | 23.2 |
| DWF | SSV (N-S) | 25 | 20 | 22.0 | 0.05 | 16.9 |
| DWF | SSV (N-S) | 50 | 20 | 10.8 | 0.09 | 20.5 |
| DWF | SSV (N-S) | 25 | 30 | 21.9 | 0.05 | 13.1 |
| DWF | SSV (N-S) | 50 | 30 | 10.9 | 0.09 | 15.6 |
| DWF | SSV (N-S) | 100 | 30 | 5.4 | 0.18 | 18.3 |
| DWF | SSV (N-S) | 25 | 100 | 22.4 | 0.04 | 6.9 |
| DWF | SSV (N-S) | 50 | 100 | 11.4 | 0.09 | 7.8 |
| DWF | SSV (N-S) | 100 | 100 | 5.7 | 0.18 | 9.1 |
| DWF | SSV (N-S) | 400 | 100 | 1.5 | 0.69 | 12.4 |