THE POTENTIAL FOR SUSTAINABLE WOOD HARVESTING IN MALAWI'S MIOMBO WOODLANDS: ESTIMATING TREE GROWTH, BIOMASS PRODUCTION, AND DEGRADATION

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ABSTRACT

Tropical forests, including the Miombo woodlands in Malawi, are important in addressing climate change and mitigation through biomass and carbon storage. The primary objectives were to study tree growth and biomass accumulation through dendrochronology and to understand how degradation affects biomass availability for wood energy in Malawi. Dendrochronology was used to observe growth increments and estimate biomass accumulation in the Liwonde Forest Reserve in Malawi. The growth rates of the destructively sampled and analyzed species were particularly low in the range of 1.85mm to 2.97mm per year. The disc increment percentage diameter growth values for size classes ranged from as high as 17% annual growth experienced in the 5cm-9.99cm diameter size class to 3% growth experienced in the above 25cm diameter size class.

Most countries in Africa lack quantitative data on forest degradation rates, and this study demonstrates how a remote sensing fractional cover tool that maps across a broad landscape of forests and trees outside of forests can be used to do this quantitative analysis. The study presents a new detailed forest map for Malawi, with spatial and quantitative measurements of both forest degradation and deforestation.

The study estimated the maximum biomass stock in the Liwonde forest reserve through forest inventory data and growth increments obtained from the dendrochronology analysis. The average above-ground carbon accumulation estimated in this Miombo forest inventory was 33.77 t C ha per year and increased to 37.3 t C ha over a one-year period. After forecasting wood provision from the forest reserve and comparing it to the current supply from the forestry inventory, the findings indicate that the reserve cannot meet the district's demand. Currently, 38% of its 26,472.8 hectares are deforested and degraded. The findings call for stringent

management proscriptions for the reserve to be sustainably utilized to meet the community's wood fuel needs.

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CHAPTER 1: EXPLORING THE FORESTRY LANDSCAPE OF MALAWI: FOREST BIOMASS ACCUMULATION AND WOOD FUEL.

1.1 Introduction

Tropical woodlands and forests are under increasing land use pressure, resulting in their permanent conversion and degradation over large areas. The solution in maintaining forest loss lies in coming up with effective sustainable approaches which heavily rely on having exact information on tree age and forest productivity (Randriamalala et al., 2017). This information is lacking in Malawi Miombo woodlands and dendrochronology has proven that it can be applied to help acquire information about tree age and growth patterns (Zuidema, 2016).

Annual tree-ring formation has been observed in the savanna and dry tropical trees (Worbes, 1999; Syampungani et al., 2010; David et al., 2014; Gaspard et al., 2018). Dendrochronology studies in semi-arid parts of Africa have shown the ecological importance of tree rings (Mbow et al., 2013; Gebrekirstos et al., 2008; Tolera et al., 2013; Gaspard et al., 2018). Trees in the arid and semi-arid tropics are well suited for historical reconstruction of biomass accumulation via dendrochronological analysis. Dendrochronology has been used in extrapolating historical patterns of diameter growth to understand annual aboveground biomass and carbon dynamics (Mbow et al., 2013; David et al., 2014). Trees increase in girth, diameter, basal area, height, volume during a given period. In Forest management, the term increment is often used to refer to only volume increment rather than individual trees, it relates to the volume and age of the trees (Bowman et al., 2013).

The focus of this dissertation is on biomass accumulation and tree growth rate knowledge since forests are recognized as significant carbon sinks, absorbing and storing substantial amounts of carbon dioxide which they remove through photosynthesis from the atmosphere and store in their biomass (FAO, 2022). The dissertation will investigate whether trees in Liwonde forest reserve are suitable for dendrochronological analysis and observe how they accumulate biomass as they grow.

The primary drivers of degradation in Malawi are the use of Miombo woodlands for fuelwood and charcoal production as highlighted in the National Charcoal Strategy (GoM, 2017). Charcoal wood harvesting occurs in both protected woodlands of forest reserves and on customary and agricultural lands outside managed forest areas. Intergovernmental Panel on Climate Change (IPCC, 2007) explains that forest disturbances by human activities in tropical forests and woodlands occur along a gradient of severity, from complete forest conversion (deforestation) to various degrees of degradation within forests. Deforestation results in a complete change from forest cover to another land cover whilst forest degradation occurs without altering the forest canopy but involves a negative trend in land condition due to human-induced processes, including climate change (Gao et al., 2020; FAO, 2020). Therefore, it is crucial to distinguish between deforestation and forest degradation, as they carry different implications for long-term land health and sustainability.

The forest cover data in Malawi shows a decline in the forest resource stock; the government reported a 36% forest cover (2010) and yet it recently estimated the same cover to be between 32-33% in 2022 showing a decline of almost 4% of the forest cover. Jingwa and Assonge (2012) had projected that Malawi's forest area would decrease from 36.3% to 33.1% by 2030 if deforestation was not controlled by using country level data to model changes in forest area. It is one of the objectives of this dissertation to contribute to these estimates by analyzing the status of deforestation and degradation in Malawi. Forest loss through degradation has an impact on the available carbon stocks. Practical methods for estimating carbon stocks using remote sensing have been recommended in the Good Practice Guide for LULUCF (Land Use Change, Land-Use Change, and Forestry) by the Intergovernmental Panel on Climate Change (IPCC, 2007).

The scientific and technical community in Malawi must provide policy and evidence-based information on strategies for finding alternatives for wood use and charcoal production. Most efforts have focused on reducing demand for wood through more efficient cook stoves or wood fuel substitution (GoM, 2009; GoM, 2017). There is insufficient information readily available on the tree growth and biomass accumulation in Malawi's forests (Kachamba, 2016). Hence the need to conduct research that involves mapping forest degradation and forest pressure to identify high-impact intervention locations. This includes providing credible projections of carbon stocks based on new data on natural forest regrowth rates (Birdsey & Pan, 2015). These efforts are vital for protecting regenerating forests and implementing enrichment and assisted natural regeneration.

This dissertation is comprised of three components of the aforementioned research needs:

1. It begins with an analysis of Malawi forest deforestation and forest degradation, providing direct data on areas where FLR in protected forests could take place. This includes an analysis of the impact of deforestation and degradation on carbon emissions, providing an estimate of the amount of mitigation required to significantly decrease emissions. This work responds to the need for knowing hotspots and addressing them as presented in Chapters 2.
2. Then the dissertation develops an analysis of tree biomass growth rates using dendrochronology from destructive field work, that used samples of dominant natural tree samples, which were harvested for analysis of annual ring growth increments for the life

history of the tree. These growth ring increments are transformed into diameter increments and used to estimate biomass growth rates using allometric equations as described in Chapter 3. This data form the basis for a model that estimates the species- and age-specific annual biomass increment averages and estimates biomass increase at the tree level, which is then estimated per hectare from plot calculations (Chapter 3).

3. The next component of the dissertation uses the dendrochronology estimates of growth rates to make estimates of the maximum sustainable harvest available in Liwonde forest reserve and compares it with wood demand and evaluates its potential for sustainable wood provision. This analysis also uses an inventory of forest carbon sample plots from Liwonde to set the baseline (Chapter 4). In this component I also explore the long-term sustainable yield using the FORest Simulation-Optimization Model (FORSOM).

1.2 Tree growth and biomass accumulation

Tree growth increment and biomass accumulation are related concepts. Tree growth increment refers to the increase in the size or volume of a tree over time and is often measured in grams or kilograms. Biomass accumulation refers to the increase in the amount of living matter, mostly plant matter, in any ecosystem over time (Pretzsch, 2020; Forrester, 2021).

Biomass accumulation and tree growth increment are both important and important parameters for estimating forest carbon stocks. Biomass accumulation is a rate measure of carbon stock changes over time (Bowman et al., 2013). The IPCC (2007) refers to tree and forest carbon stock estimates as Emission Factors (EF). For most measurement approaches carbon stocks and carbon stock changes, (i.e. biomass and biomass accumulation) are derived from various measurement methods that measure static size or volume attributes of trees or tree growth increments, which are size or volume changes over time (Hann and Weiskittel, 2010). This use of size or volume estimators is the basis for tree allometric scaling which uses stem diameter to estimate biomass, which can be either a onetime measurement to estimate biomass or over time to estimate biomass change (Watt and Kirschbaum, 2011). Change over time can be measured with repeat measurements or through records of the tree's growth increment, as is evidenced in tree ring growth (Worbes, 2002).

Increases in biomass accumulation are associated with increases in tree increment, as more organic matter becomes available to support growth (Stephenson et al., 2014). However, other factors, such as competition for resources, can limit the amount of growth that individual trees are able to achieve. In addition, changes in environmental conditions, such as drought or increased temperatures, can have negative effects on both biomass accumulation and tree increment (Seedre et al., 2020). In estimating biomass increment at plot level in this dissertation I considered fire and mortality as key factors affecting growth and biomass accumulation.

In most terrestrial ecosystems, trees are important contributors to biomass accumulation (IPCC, 2007). This is due to their large size and long lifespan; they can store significant amounts of carbon over time. When forests accumulate biomass through the combined growth of individual trees, they absorb carbon from the atmosphere, and are referred to as sinks (Gunderson et al., 2021). Old growth forests continue to grow as a sink (Canell, 1996) and due to their ability to sustainably grow and develop in their local environments, indigenous tree species such as the Miombo woodlands species have a greater capacity for long-term carbon storage compared to other trees. As they accumulate biomass over decades and centuries, indigenous trees can sequester and retain substantial amounts of carbon from the atmosphere (Adeoti et al., 2023).

1.3 The Malawi forest estate

Malawi forest ecosystems are dominated by the Miombo forest type, a semi-arid tropical woodland. The Miombo woodlands cover 92.4% of the natural forest area in Malawi with some dense evergreen forest located in the highlands. Other forest types exist with less coverage, including the Northern Zambezian and Mopane types. The Miombo woodland ecosystem is the most extensive vegetation type in Africa, covering an estimated ~2 million km^2 in regions receiving greater than 700 mm mean annual rainfall on nutrient-poor soils (Campbell, 1996; Kachamba et al., 2016). Miombo is a type of tropical woodland which is dominated by the genera *Brachystegia, Julbernadia* and *Isoberlinia*. These woodlands cover vast areas of Africa stretching from Angola through Zimbabwe, Zaire to Mozambique, the entirety of Zambia, Tanzania, and most of Malawi (see figure 1 showing countries where the woodlands are found).

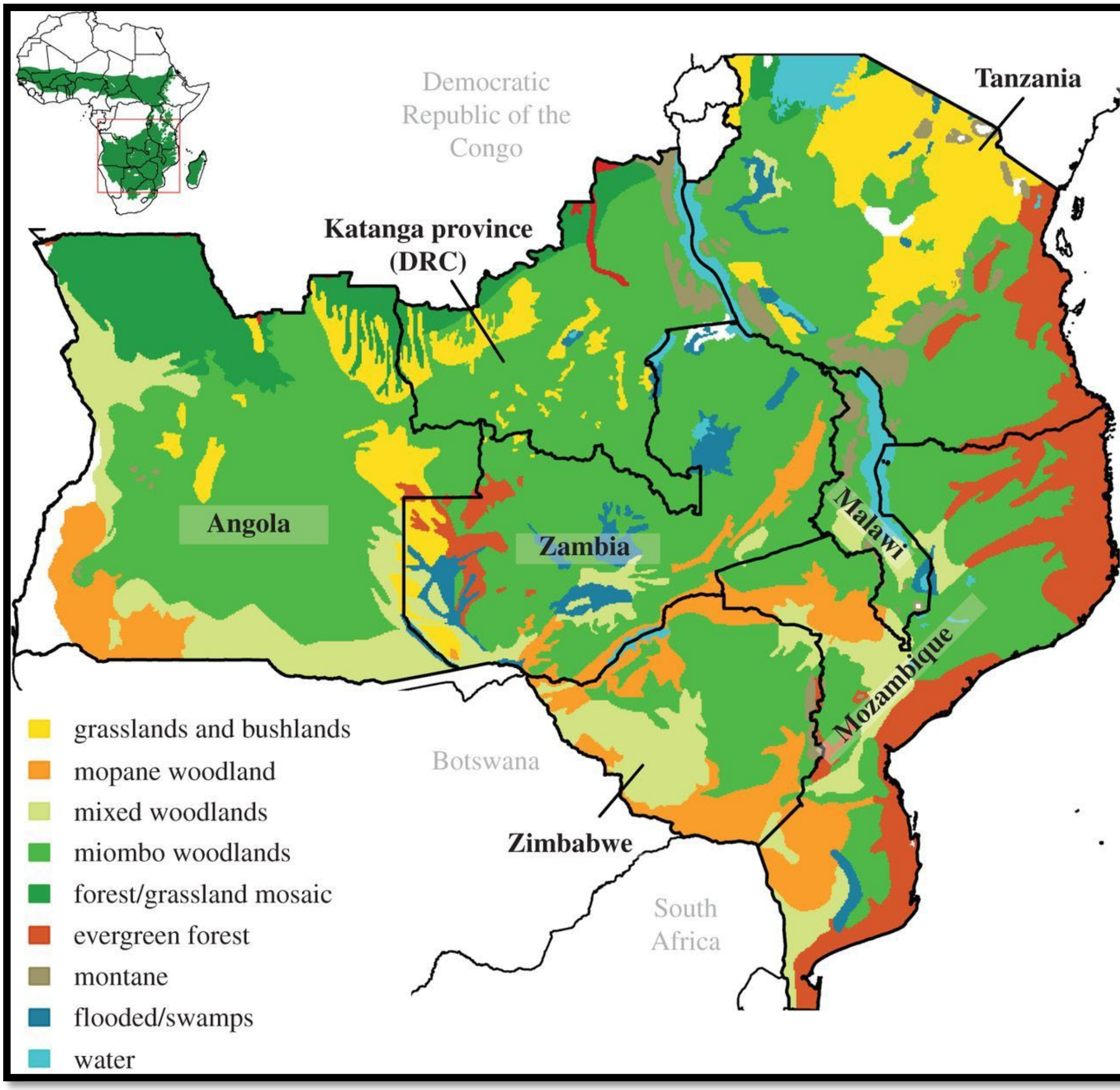

Figure 1 The extent of the Miombo woodlands in Africa (Ryan et al., 2016).

Malawi's public forests cover 23,677 km^2 representing 25% of the country's total surface land area, out of which 22,857 km^2 stretches over Miombo woodlands (DoF, 2023). The indigenous vegetation is dominated by the Miombo species viz, *Brachystegia bussei, Brachystegia spiciformis, Julbernardia globiflora, Uapaca kirkiana, Colophospermum mopane,* which make up more than 50% of the total tree biomass in Malawi (GoM, 2018). The Miombo forests are spread across all 3 regions of the country. They are mostly found in protected areas (PAs), some of which lie along the country's borders. The PAs include forest reserves, national parks and wildlife reserves which cover almost one million hectares.

Malawi has 88 government managed forest reserves covering 9,185 km^2 (DoF, 2023). Most of the forests under government management are protected and have open access status even though Malawi has adopted a loosely regulated joint or co-management approach with local communities (Kamoto, 2023; Gondwe, 2020). This brings with it issues of land disputes due to shifting cultivation, illegal harvesting of wood fuel, poles and timber, and heavy pressure for conversion to other competing land uses, such as agriculture and at times industrial development.

There is a need to improve the management of Miombo in Malawi by addressing the challenges the woodlands face with science-based efforts as opposed to misguided efforts due to poor information (Chawanje, 2014). Gondwe et al., (2021) record some major challenges of Miombo management in Malawi as; lack of strong local organization, the increase in population, and poverty influenced livelihood pressure on woodlands. Miombo woodlands are sources of various wood products including poles and saw logs apart from non-wood forest products (Nerfa et al., 2019).

The capacity of the forest to provide wood energy and wood products depends on forest condition and stand structure dynamics (Chidumayo, 2019). Harvesting of wood products is usually selective and therefore may result in forest loss and forest degradation. This dissertation document estimates the biomass production in Liwonde reserve to see whether the available stock can continue to meet the community needs sustainably as efforts must be made to help in ensuring the forest conditions are retained at an agreed productive level.

Fuelwood harvesting and culling of wood for charcoal energy production constitute a significant share of forest degradation (GoM, 2016, Kadzuwa and Missanjo, 2023). The most reliable and detailed analysis of the use of biomass for energy in Malawi was developed as part of the national Biomass Energy Strategy (BEST) in 2008. The BEST was derived from policy actions under the National Energy Policy of 2003, which estimated that biomass accounted for 93% of total energy consumption in 2000 and went on to make similar estimates of 88.5% in 2008. Policy concerns with reliance on biomass energy arose from the observation that biomass fuels have historically been associated with environmental degradation, poverty, and the under-development of the country's energy demand (Gamula, 2013; Zalengera 2014).

For a long time, the national energy policy has been to transform the country's economy from high dependency on biomass energy towards greater reliance on other energy sources, particularly electricity (Zalengera et al., 2014), but the Malawi Government has recognized that biomass energy would likely be part of the national fuel mix for some time, a strategic approach was needed. This saw the publication of the Biomass Energy Strategy (BEST) in 2009. The BEST objective was to develop a rational and implementable approach to the management of Malawi's biomass energy sector through a combination of measures designed to improve the sustainability of biomass energy supply, raise end-user efficiencies, and promote appropriate alternatives.

The BEST analysis was an extensive review of quantitative estimates of biomass production and wood fuel consumption, and it concluded that wood fuel consumption was already more than what was sustainable for large parts of central and southern regions of the country and recommended that measures were therefore urgently required to prepare for, and to respond to, a substantial and imminent growth in the fuel wood market. The policy analysis suggested, based on these projections, that the amount of biomass produced cannot be harvested sustainably due to conflicting existing land policies, especially between the agricultural sector and the environment and natural resources management sector. The agriculture sector was estimated to be responsible for the loss of approximately 669,000 hectares of woodlands which were converted to agriculture farmlands (GoM, 2009). Moreover, estimates of supply in the report often credited conversion of woodlands to croplands as a source of biomass that improved the supply-to-demand ratios. The report also focused on an ambitious view that electrical energy would be a ready solution to shortfalls in domestic energy from wood if policy measures were implemented. The subsequent policy tools including Malawi Vision 2020 and the Malawi Growth and Development Strategies and currently Malawi Vision 2063 share similar sentiments to the energy situation, viz it needs to find alternatives to biomass (wood fuel energy) as it is not sustainable as evidenced by the heavy utilization of biomass to meet a high proportion.

Amidst the discussion of non-fossil solutions to energy consumption and production, such as with biomass, reducing their consumption through end-use management, such as improved cook stoves were heavily emphasized. There has been less focus on the production side such as woodlots for energy farming or limits on harvesting to implement sustainable harvest rates based on maximum sustained yield targets. However, in the broader dialog on charcoal as another source of fuel wood, there lies a desire to achieve sustainable management of forest resources. For example, Pillar 5 of the Malawi National charcoal Strategy (GoM, 2017) encourages exploring efficient ways of producing charcoal sustainably (with no ban).

What sets trees apart from other plants is their remarkable ability to extend growth over long periods and add successive layers of growth both in height and diameter. Long-term monitoring of forest dynamics at permanent sample plots (PSPs) provides crucial data for understanding and validating remotely sensed estimates of forest degradation and recovery. Consequently, there is a need to explore how such data can be transformed into valuable information for decision-making (Chidumayo, 2019). In Malawi, the Forestry Research Institute of Malawi (FRIM) is tasked with collecting data and offering information on changes in forest productivity, necessitating comprehensive data on tree diameter increment and basal area dynamics (GoM, 2016). FRIM continues to collect and analyze various forestry data through collaborations with stakeholders and diverse assessments beyond traditional forestry inventories.

Numerous site-based forest inventories have been conducted in Malawi over the past two decades by the Government of Malawi, often with support from international donors and organizations such as the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and Japan International Cooperation Agency (JICA). These inventories primarily serve to guide site-based forest management and, more recently, to inform the country's approach to REDD+ readiness. While many of these inventories have been successfully executed, their focus has been limited to specific geographical areas, typically within protected areas and forest reserves (GoM, 2016).

Aggregate data from these diverse inventories indicated that the national weighted average total biomass stock in Malawi was 97.7 ± 8.3 t C ha^{-1} (AGB+BGB), equivalent to 45.9 ± 3.9 t C ha^{-1}, with an uncertainty of 8.5% (GoM, 2020). These figures align closely with reports from Zambia and Tanzania, where forest carbon stocks were reported as 41.2 t C ha^{-1} (with an uncertainty of 7%) and a range of 33.6 to 12.3 t C ha^{-1} (with uncertainties ranging from 1 to 7.5%), respectively (GoM, 2022). Sakala and Vinya (2020) concur with (FAO, 2017b) that eastern, southern, and northern sub-regions of Africa which are covered by the dry forests and woodlands, have less above ground living woody biomass and their biomass stock may not significantly differ (McNicol, 2014).

1.4 Firewood and charcoal situation

Fuelwood stands as one of the most critical forest products for the livelihoods of smallholder farmers in the sub-Saharan region (Gumbo et al., 2018, Zulu 2009). However, their harvesting and utilization poses a significant threat to forest management, causing forest degradation (Bailis et al., 2015). Any kind of utilization or management plan would require one knows where to implement it and what the maximum sustainable biomass of that area is then impose harvest limits, which requires knowledge of location specific conditions as proposed by this dissertation.

The demand for wood energy in Malawi is closely tied to a growing human population, with over 80% relying on biomass for their energy (GoM, 2018). Ninety-seven percent of Malawi's population (90.3% urban; 99.7% rural) rely on solid fuels (e.g., firewood, charcoal., crop residues) for cooking (GoM, 2018). Additionally, Jumbe and Angelsen (2011) had reported that approximately 75% of this biomass was supplied from forest reserves. This demand for biomass energy (charcoal and firewood) has created pressure on government forest reserves, leading to a continued loss of forest cover (GoM, 2017) and this has signaled a decline in the wood resource base for the country.

The motivation of this dissertation is to evaluate whether forest reserves can continue to supply and satisfy the community's fuel wood (biomass) requirements. An analysis of biomass energy use by Kambewa and Chiwaula (2010) suggested that any sustainable management model for the Miombo woodlands of Malawi must be tailored to the specific characteristics of the region. It should be easily adopted and implemented by area forest managers to ensure the continued protection of forest resources. This dissertation explores this site-specific production and consumption of biomass for Machinga district (where Liwonde forest reserve is), in an effort to respond to the call for location specific solutions and it presents a science-based approach in setting management proscriptions for the sustainable utilization of Liwonde forest reserve.

Charcoal production has also caused degradation in forest reserves, leading to total land use changes in some cases (Gondwe et al., 2019). In response to the escalating demand, the Malawi National Charcoal Strategy (GoM, 2017) aims to explore efficient ways of producing charcoal sustainably, without imposing a ban. This strategic approach acknowledges the ban on charcoal production in the Forestry Policy, clarifying its intent to focus on efficient and sustainable charcoal production. Charcoal, being the solid residue left after wood carbonization, is popular due to its high energy content, ease of storage, transportation, and lower smoke production compared to fuelwood (Arnold et al., 2003). It plays a crucial role in driving African economies (Kambewa et al., 2007; Broadhead and Killman, 2008).

While fuelwood production remains relatively stable worldwide, charcoal production and use is on the rise in many African urban households (Tomaselli, 2007). This increasing demand for charcoal puts pressure on peri-urban wood sources, especially in the absence of effective sector management (Arnold et al., 2006). The environmental costs of charcoal production, often not internalized in product prices, contribute to resource depletion, posing a threat to the sustainability of this livelihood activity (Chidumayo and Gumbo, 2013).

The government has undertaken various energy supply-side initiatives, such as the Blantyre City Fuelwood project, to curb perceived high deforestation rates. However, these initiatives have not been entirely successful. The Forestry Department has attempted to keep firewood prices low to discourage reliance on free wood resources, particularly concerning their impact on urban poor communities (Kambewa and Chiwaula, 2010; Zulu, 2010).

The current ambitious goal in Malawi's National Energy Policy (2018) is to electrify 80% of the rural population and achieve universal modern energy access by 2030. Simultaneously, the Forestry Department plans to redirect biomass use demand and reduce unsustainable wood fuel demand by promoting alternative cooking energies and fuel-efficient technologies. This involves strengthening the business and regulatory environment (GoM, 2016). These policies and projects aim to alleviate pressure on existing biomass energy resources through the promotion of alternative sources, such as the Modern Cooking for Healthy Forests project, which encourages the promotion of alternative livelihood sources, and the sensible management and utilization of existing biomass.

1.5 Justification and significance

There is a significant lack of information on evaluating forest productivity and stand dynamics in the Miombo woodlands of Malawi hence the need for improved forest management information in the forest estate (Chawanje, 2014; Stanturf et al., 2015, GoM, 2017). This work is possible as it builds on work in the savannah in Senegal by Mbow et al., (2013) and David et al., (2014) where they used dendrochronology in extrapolating historical patterns of diameter growth to understand annual aboveground biomass and carbon dynamics in Kenya by made it possible for this study to start considering building growth increments to estimate biomass accumulation in Liwonde forest reserve.

This dissertation research explores question having the necessary technical data and models to inform the harvest and rotation of a biomass removal in the sustainable utilization of trees , which is the supply side of biomass, as so many other studies (Jumbe et al., 2007, Zulu 2008, 2009, Bandyopadhyay et al., 2011, Senganimalunje et al., 2015 & 2022, Kamoto et al., 2023) have focused on the question with a lot of socio-economic research being done.

Forest ecosystems are not only complex but dynamic, with interactions among biotic and abiotic factors within an ecosystem, which calls for the need for precise quantitative and qualitative information that is essential to manage the forests sustainably (Samalca, 2007). Understanding the tree growth patterns is an important prerequisite for the timing of silvicultural measures both in natural and plantation forests in the tropics (Killmann and Thong, 1995).

Given the significance of Miombo woodlands to the Malawi forestry estate, acquisition of biomass incremental information is prerequisite to the national climate change mitigation strategies (GoM, 2016). This work is aimed at beginning to develop and synthesize growth rate information for Malawi's Miombo. With forest restoration efforts being a government priority (GoM, 2017), adding knowledge of how the Miombo species grow and the duration it takes to reach harvestable ages, including the amount of biomass and carbon sequestered by individual trees, this additional information is key in the planning and implementation of this national goal as it brings out degradation status in the analysis. The best approach is to use long term tree growth studies in the Miombo region to ensure better understanding of forest growth in the woodlands as this assists in monitoring and observing tree growth (Chidumayo 2019). The study will employ methods that replicable in setting up some of the required information for the Malawi case.

Another reason for a study like this one is that despite the growing and known socio-ecological importance of Miombo woodlands (Kamoto et al., 2023; Gondwe et al., 2020; Senganimalunje et al., 2016), their carbon stock content continues to be poorly assessed and documented, especially in Malawi (Kachamba et al., 2016). This lack of information impacts decision making when it comes to the analysis of the woodland's contribution to the global and national carbon stock levels. The variability in aboveground carbon data reported points to stand characteristics and age, environmental effects, and disturbances that are not consistently recorded across most studies (Bulusu et al., 2021). One of the key outcomes from this study will be an understanding of the rate at which the Miombo stock accumulates from the analysis of the discs which will provide panel data.

Additionally, there is no data on the rate at which indigenous forests are accumulating biomass (GoM, 2015, GoM, 2017). If there was enough information related to the rate at which the forest was growing, it would be easier to put the losses in context, as that would be easier to deduce from calculations of biomass being accumulated versus biomass being offset. Additionally, I would have quantitative estimates of biomass production that could be used to determine a sustainable yield to support sustainable energy production. The Malawi Biomass strategy (2009) though it was never adopted as an official strategy by the Malawi government attempted to provide figures on the biomass amounts being utilized against how much was being produced by the various forests in the country.

Understanding the tree growth patterns is an important prerequisite for the timing of silvicultural measures both in natural and plantation forests in the tropics (Killmann and Thong, 1995). This study aims to investigate biomass increment to understand sustainable harvest potentials of Miombo woodlands in Liwonde Forest Reserve, which was chosen as case study as one of the potential subnational-and local sites for inclusion in the Malawi REDD+ program. This was done so that better policy recommendations can be made to the government on the implications of considering sustainability of the forest resource under current utilization patterns.

Finally, this dissertation addresses the lack of quantitative spatial information on forest degradation in understanding of anthropogenic forest disturbance in the dry tropical woodlands of Malawi (Hosonuma et al., 2012; McNicol et al., 2008). This is important as Bhattarai et al.,

(2020) observed that in places where deforestation rates and spatial extent have not been well monitored, high carbon emissions and biodiversity loss are usually observed in the analysis.

1.6 Research Approach

The overall objective of this dissertation is to investigate tree growth and biomass accumulation using dendrochronological analysis and how forest degradation dynamics affects the availability of biomass for wood energy in Malawi.

To achieve the objective above, the following approaches were carried out.

1. Quantify and map deforestation and forest degradation for the country of Malawi using remote sensing. Determine main drivers and location of hot spots (hint: degradation for charcoal in forest reserves).
2. Obtain an inventory of forest carbon for a carbon stock baseline with composition and distribution of tree sizes and species, using sample plot framework.
3. Analyze carbon increment of tree growth by species and tree size class using dendrochronology data and local allometry. Harvest sample trees in the carbon inventory plots.
4. Estimate total one-year increment of C in Liwonde Forest Reserve based on species and size class specific distribution of growth increments.
5. Compare annual wood Carbon growth estimates with estimates of wood fuel demand.
6. Formulate a management proscription for Liwonde forest reserve.

1.7 Research Questions

This research was largely built around the question, "Is sustainable utilization/ harvesting possible in Malawi based on the current forest degradation rates and community's fuel wood demands?"

Answering this question will involve understanding the growth dynamics of the various Miombo tree species, finding out their growth rates and knowing the maximum sustainable yield for the reserve. Bearing in mind that these trees are currently being utilized, the purpose is to unearth enough on the supply side (tree growth) to be sure if the demand side(utilization) can be met. The implications that growth has on potential interventions are key in the decision-making process for sustainably.

Some of the questions I immediately raised to guide in the process were.

1. What is the current degradation rate in Malawi's Miombo, is it important (i.e. exceeds deforestation) and where is it happening?
2. What management units and land management units are experiencing high degradation rates, i.e. forest reserves compared to customary land?
3. What is the maximum annual biomass increment in these areas and can dendrochronology be a novel way to ascertain these rates?
4. Can wood harvest limited to its sustainable yield (in biomass) be used to supply important quantities of charcoal to communities surrounding these areas?

This dissertation document consists of five chapters. This chapter has introduced and set the context for understanding the need for tree biomass research in Malawi amidst high deforestation and degradation rates. It also gave an insight into the country's forestry estate. The research goal and objectives that have been outlined will be discussed in the following chapters in the following order.

In CHAPTER 2 of this dissertation, I present a method for measuring deforestation and degradation using a fractional tool covering forest and non-forest land and update the land cover and land use for Malawi and discuss their implications.

In CHAPTER 3, I present the methods applied from the disc data obtained from dendrochronological analysis of 45 discs that were destructively sampled from Liwonde Forest Reserve to come up with the ring width and biomass increment percentages based on size class and species. The main goal of this chapter is to present the methods and link between the inventory data and dendrochronological data set for determining the maximum sustainable yield for the forest reserve.

In CHAPTER 4, I explore whether the biomass production in Liwonde Forest Reserve can meet the fuel wood consumption of the communities surrounding the forest reserve. I do so by combining forest inventory data and biomass ring width percentage increments from (Chapter 3). I proceed to make an estimate of the average increment between the inventory year vs the newly calculated plot values. Then I finish the chapter with implications on management and suggest ways of increasing biomass production in the forest reserve.

CHAPTER 5 Summarizes the conclusions and gives an overview of the findings of the study. In this chapter I summarize the main findings of each chapter and discuss their consequences and make recommendations from a local and global perspective on how to integrate them to the Malawi case.

CHAPTER 2: MEASUREMENT AND MAPPING OF AREAS OF FOREST AND DEGRADATION RATES IN MALAWI FORESTS

2.1 Introduction

The lack of quantitative spatial information on forest degradation is an important gap in our understanding of anthropogenic forest disturbance throughout the tropics, but especially in tropical woodlands and other sparse tree ecosystems (Hosonuma et al., 2012; McNicol et al., 2008). Although deforestation rates and spatial extent are being monitored increasingly well, degradation rates are less well documented, even if they are as important as deforestation data for estimating carbon emissions and biodiversity loss (Bhattarai et al., 2020). Forest disturbances by human activities in tropical forests and woodlands occur as a gradient of severity, from complete forest conversion to various degrees of degradation within forests. While deforestation results in complete change from forest cover to another land cover, degradation occurs without removal of the forest canopy nor as a change in the land cover (Gao et al., 2020, Penman et al., 2013; Watson et al., 2013).

In Malawi, there is informal evidence that degradation is a major form of forest disturbance. The Miombo is a woodland type of immense value covering about 2 million square kilometers in seven countries and supporting over 150 million people (Shukla et al., 2019). They are open forests of low carbon stocks, ranging from 35 to 45 Mg ha^{-1} (Ribeiro, et al., 2020; Kachamba 2016, Missanjo & Kamangathole 2010) and in some cases as low as 8 Mg ha^{-1} (Chidumayo and Gumbo, 2010) in Malawi. One of the major human disturbance factors is the removal of biomass by culling individual trees to produce charcoal for domestic energy and as a small-scale commercial enterprise (Kuyah et al., 2014; Zulu 2010; Sedano et al., 2016). These activities reduce standing biomass in an already sparce woodland ecosystem. Over the last 30 years there has been a significant loss of woodlands outside the gazetted forest estate as these forests have been converted to agriculture (Sedano et al., 2020, Bone et al., 2016). Today, a large amount of charcoal biomass extraction occurs within national forest reserves (Minde et al., 2001; Ngwira and Watanabe, 2019). Due to a lack of resources, ground-based monitoring and protection of these woodlands has been difficult.

Detecting changes due to forest degradation using remote sensing has been difficult even for highly degraded areas (Gao et al., 2020). Selective removal of biomass without complete canopy loss leaves conventional remote sensing classification methods ineffective. Spectral classification using low resolution data do not reveal sub pixel level variation necessary to detect degradation (Katumbi et al., 2015). Natural variation in tree density results in a range of canopy and carbon densities in undisturbed Miombo (Mbow et al., 2015), so a single observation or single-date analysis makes it difficult to separate human disturbances from natural variation. Another factor that has hindered the quantification of Miombo woodland biomass loss is the lack of good biomass or carbon inventories (Gumbo et al., 2018). Miombo woodlands have not been considered a commercially important timber resource. There has never been an important argument for using scarce human and financial resources to maintain a national forest inventory. However, with the emerging importance of carbon and biodiversity ecosystem services it is important to demonstrate new woodland measurement applications for biomass and habitat management in countries such as Malawi.

This paper reports on a tool deployed country-wide in Malawi. The tool measures and maps both deforestation and forest degradation separately in an internally consistent framework. There has been some uncertainty about the rates of deforestation in Malawi. There is considerably more uncertainty on the additional impacts from degradation. Often reports will combine or overlap deforestation and degradation, even though carbon stocks, emission factors, and drivers may be very different. This causes reporting confusion and makes interventions, policies, and measures ineffective.

2.2. National policy context for forest degradation monitoring.

The lack of quantitative data on forest degradation rates, location and biomass is an important constraint to policy formulation related to mitigation of greenhouse gas emissions in Malawi, as in most countries in Africa (Chidumayo, 2019; Kundhlande et al., 2017). As a result of the new international climate agreements from Conference of the Parties (COP) 21 in Paris in 2015, national governments are taking steps to include forests in their nationally determined contributions (NDCs) to climate change mitigation and their REDD+ policies. There are five agreed scope elements under the REDD+ framework: 1) Conservation of Carbon Stocks, 2) Reducing Emissions from Deforestation, 3) Reducing Emissions from Forest Degradation, 4) Enhancement of Carbon Stocks, and 5) Sustainable Forest Management. Yet, many countries are uncertain about the appropriate scope for implementing their REDD+ programs. Much of this uncertainty relates to the availability of tools and methods for the measurement and monitoring of forest degradation as part of these scope elements (Zomer et al., 2016). Many countries have important disturbance regimes related to both deforestation and degradation (Brandt et al., 2016). Excluding forest degradation in the scope of a national REDD+ program limits the actions that would reduce an important greenhouse gases (GHG) emission source. Furthermore, countries that include enhancement actions, such as forest landscape restoration (FLR), would overestimate the positive impact of these mitigation efforts without also accounting for degradation. This could lead to misleading reporting on progress with Nationally Determined Contributions (NDCs).

Under the Warsaw Framework, countries developing national REDD+ programs are requested to include five fundamental measurement and reporting streams in their national planning: 1) a national REDD+ strategy, 2) a National Forest Monitoring System (NFMS), 3) forest reference emission levels (REL), 4) safeguards information systems, and 5) a national reporting structure. This REDD+ framework requires countries to develop a national platform for measuring, reporting, and verifying (MRV) GHG emissions and removals on a regular basis. For the most part, this requires that countries have the technical capacity to systematically measure a set of factors related to; a) changes in the extent and condition of forest cover; b) carbon stocks in forests of various stature and condition, and changes over time in those stocks; and c) emissions or removals of GHGs associated with changes in forest cover and changes in carbon stocks.

The government of Malawi (GoM) is active in developing capacity for its national REDD+ program (Mbow et al., 2020). However technical limitations in MRV are obstacles to achieving advanced readiness. For instance, in Malawi's recent publication of a national forest reference emission level (FREL) uses one method for forest cover stratification (medium resolution national cover from remote sensing), another method for estimating rates of deforestation (sample based visual interpretation of Google Earth), and an indirect modeling method for estimating degradation (fuelwood demand model using proxy data) (Mbow et al., 2020). This can result in incompatible and inaccurate results (Stringer et al., 2012). For instance, the direct visual sampling method covers all forest areas while the indirect estimation fuelwood demand model using external data, such as population, does not accommodate for these areas. As such, this could easily result in double counting when observed deforestation was due to fuelwood extraction. Thus, improvements in MRV are needed to develop a uniform and consistent methodology, which is what this study aims to demonstrate.

2.3. Materials and methods

2.3.1 Basic approach

This project developed, tested, and deployed a remote-sensing based tool as a prototype for mapping REDD+ Activity Data for the country of Malawi. Activity Data are observations of the rate and spatial extent of activities that drive GHG emissions to the atmosphere and GHG removals from the atmosphere (sequestration) in the forest landscape (Gibbs et al., 2007; Chiotha et al., 2018). The focus of this analysis is on geospatial quantitative measurement of rates and extent of deforestation and forest degradation to support the development of a NFMS for Malawi's national REDD+ programming. The tool, referred to as the fC Tool, uses Landsat-class satellite data at 30-meter spatial resolution with national coverage. The fC Tool produces a continuous field product using a spectral mixing model with 2 endmembers over a time series (Mbow et al., 2012; GoM, 2019; Grainger and Kim 2020). With a continuous field approach, the difference in fractional cover values over time portrays changes within forests due to degradation (FAO, 2017), as well as changes from forest to other land covers due to deforestation. The choice of a fractional cover approach is based on the rationale that it is a well-tested method for forest monitoring (Stringer, 2012; Angelsen et al., 2011; Goetz et al. 2015, Grainger and Kim 2020) and thus represents an appropriate and accessible approach, given Malawi's human and technical resources context. The fractional cover algorithm is a remote sensing method used to monitor and assess forest loss, gain, and health (Chen et al., 2023). The amount of visible foliage is vital for understanding land surface conditions as it serves as a proxy for various plant functions and characteristics. Fractional cover informs analyses of ecological processes, forest growth, food webs, vegetation, land management, hydrology, soil carbon, disasters, and drought (Ghazali et al., 2022). Fractional cover is used as an input parameter for modeling the land-atmosphere exchange, its values also capture biophysical impacts of natural and human disturbances (Kim, 2020). Estimating fractional forest cover in remote sensing data enables long-term, accurate regional forest monitoring. However, the specific application of this approach to REDD+ MRV has not been widely demonstrated (Gao et al., 2020).

A continuous field approach is also well suited to monitoring the Miombo woodlands of Malawi. These sparse forest systems are ubiquitous throughout Southern Africa and are similar forests to the Acacia woodlands in East Africa. Traditional classification mapping using supervised or unsupervised methods is less effective due to variability in tree and crown density, an attribute that may be better addressed through sub pixel mixture model methods (Matricardi et al., 2010). Conversely compute-intensive approaches using very large datasets, such as machine learning (FAO, 2017), present obstacles to developing nationally owned forest monitoring products, as do some big data processing frameworks that are done externally to national agencies and their forest management units (Matricardi et al., 2012; Matricardi et al., 2020).

In a methods development context, our focus is on using direct observations and to measure and map forest degradation over large areas at moderate spatial resolution (30m), in conjunction with deforestation mapping. Deforestation measurement and mapping with remote sensing has been studied for a long time with considerable success (Bullock et al., 2020), although there has been less progress for woodlands than for closed tropical forests (Goetz et al., 2015; Mayes et al., 2017). Forest degradation is particularly difficult to map, (Gao et al., 2020) since it occurs within forests and is characterized by changes in forest cover density rather than an outright loss of forest and conversion to another land cover type.

2.3.2 National study area

This work was conducted for the country of Malawi. Malawi forest ecosystems are dominated by the Miombo forest type, a semi-arid tropical woodland. The forest environment in Malawi is almost completely represented by the Miombo woodlands. The Miombo system covers 92% of the natural forest area (GoM, 2016) with some dense evergreen forest located in the highlands. Other forest types exist with less coverage, including the Mopane type. The Miombo woodland ecosystem is the most extensive vegetation type in Africa, covering an estimated ~2 million km^2 in regions receiving greater than 700 mm mean annual rainfall on nutrient-poor soils (Shukla et al., 2020; Hansen et al., 2013). Miombo is a type of tropical woodland which is dominated by the genera *Brachystegia, Julbernadia* and *Isoberlinia*. These woodlands cover vast areas of Africa stretching from Angola through Zimbabwe, the Democratic Republic of Congo (DRC) to Mozambique, the entire Zambia, Tanzania, and most of Malawi.

Although there are no reliable data on the area of Miombo that has been degraded, for recent years it is believed to be more extensive than the area cleared outright. Anthropogenic activities play an important role in the land use dynamics and ecological impacts in Malawi Miombo woodlands. Charcoal production, firewood collection for subsistence use and for tobacco curing, conversion of woodlands to cropland, and seasonal fires are among the major drivers of deforestation and forest degradation (Minde et al., 2001; Ngwira and Watanabe, 2019; Melo et al., 2018). Informal estimates of deforestation in Malawi have been reported to vary widely from 50,000 to 150,000 ha yr^{-1} (Sedano et al., 2016), but there has not been a systematic assessment in which there is clear distinction between rates of deforestation and rates of degradation within forests (Skole and Cochrane, 2004). Other issues include vagaries in how much tree cover is included in forest cover, and how much change is tabulated in forests compared to tree formations outside of forests.

Most of the standing forests exist in national forest reserves and other protected areas. Approximately 1.0 million hectares of forest are in these nationally gazetted forest areas, protected areas and perhaps an additional 1.1 million hectares in intact dense forests not on agricultural land (Melo et al., 2018; Petersen et al., 2018). Other forests are found in customary land, that is managed by local communities often under control of traditional authorities (Seymour and Harris, 2018) and may account for an additional 1.1 million hectares (Campbell, 1996). Agricultural land contains systems of trees outside of forests, sometimes at very high densities. Our study includes all three of these forest categories.

2.3.3 Data processing

The fC Tool is a method for using remote sensing data and specific algorithms to produce forest cover maps along continuous fields. Most forest and land cover maps from satellite remote sensing are based on discrete classes of forest or land cover, represented as homogeneous polygons of a single cover type. The continuous fields approach produces land and forest cover maps with robust gradients of cover, more accurately representing natural and anthropogenic variations within cover types. Without a continuous fields approach it is not possible to measure carbon stock degradation or capture natural variations in carbon stocks within forest cover classes. The fC Tools produces forest fractional cover, fC, which is a measure of the fractional cover in forest vegetation, ranging from 0 to 100 percent. It maps variations in these fractional cover values to represent variation in the landscape of forest density, and changes in these fractional cover values to represent various intensities of degradation and deforestation. It is produced from 30 m resolution Landsat data, which are free to the user, to produce a spatial product at a landscape scale relevant to the scale of the disturbance regime in Malawi, and useful for community-based interventions and forest management planning.

I use 30-meter Landsat TM, ETM+ and OLI data for three dates, 2000, 2009 and 2015, to detect and map changes in Miombo woodlands in Malawi. The analysis derives vegetation continuous fields, fractional cover (fC) data products for the whole of Malawi and computes pixel-level changes through a spatially explicit model. The fC products are used to map deforestation and forest degradation inside national forest reserves and in customary land outside of the forest reserves.

The acquisition of Landsat data was based on the following criteria: (1) WRS2 path row images for complete coverage, wall-to-wall, of Malawi, (2) three years of analysis, 2000, 2009 and 2015 plus or minus two years from the target year, with a preference for along path, same date imagery, (3) seasonal phenology in the early dry season prior to leaf senescence with reduced agricultural field productivity (months of April - June), and (4) minimal cloud cover. For path row images where clouds were present, I acquired multiple images to be used for gap-filling. Fifty-eight (58) images covering 11 WRS2 path/row combinations at three dates were used to provide complete cloud-free coverage of the country (Table 2). All data were level 1G or 1T and acquired through the United States Geologic Service's Eros Data Center (See Appendix G).

The data analysis workflow included seven processing steps: Level 1 digital number (DN) data were converted to top of atmosphere reflectance (TOA) values using (World Bank, 2019). TOA reflectance NIR and Red bands were used to produce an NDVI (Normalized Difference Vegetation Index) product. I created a vegetation continuous-field, fractional cover (fC) product from the NDVI data using a two endmember, linear un-mixing algorithm following (Mbow et al., 2012). I identified cloud and cloud shadow pixels in each path/row scene using the Fmask software (Coutts et al., 2019; Mauambeta et al., 2010) and then masked these "contaminated" pixels from each path/row image. The national fC product was then developed by gap-filling, mosaicking path/row images, and clipping the mosaicked data to the Malawi border for each target year. This product was then adjusted by masking pixels of no-data, wetland, marsh, and water bodies. A two-date fC change detection analysis was performed for the periods, 2000-2010 and 2010-2015, which produced national ΔfC change intensity maps. This was done for woodland forest areas within protected areas and in areas of trees outside of forest (ToF) in customary lands and village forest areas (VFAs).

I used the constants and radiometric calibration procedure for each sensor (TM, ETM+ and OLI) provided in (World Bank, 2019). This pre-requisite step of radiometric characterization and calibration is known to produce higher quality "down-stream" products, by reducing errors in observed Earth surface changes from sensor artifacts when using long-term series of remote sensing data for scientific information (Chander et al., 2009). The computation for the spectral radiance at the sensor's aperture uses scene specific metadata that accompanies each set of spectral bands when data are acquired from the USGS EROS Data Center. These constants are also noted in a series of tables in (World Bank, 2019). The conversion of at-sensor spectral radiance to exo-atmospheric TOA reflectance reduces the scene-to-scene variability. Conversion to TOA reflectance uses scene specific data related to the date of acquisition and position relative to the sun's position at the time of acquisition. The conversion from level 1, digital numbers (DNs) data to at-sensor spectral radiance and then to TOA reflectance is done for each spectral band for each acquired image.

Normalized Difference Vegetation Index data products are created using the NIR and Red TOA reflectance bands (FAO, 2013). The NDVI product is a measure of vegetation across the landscape with values between -1 and 1. NDVI pixel values closer to one contain vegetation with high photosynthetic capacity.

The equation for NDVI is.

(NIR – Red) / (NIR + RED). Equation 1.

The detection of pixels "contaminated" by cloud and cloud shadow is accomplished with the "Function of mask" or Fmask series of algorithms first developed by (Zhu et al., 2012) and later improved by (Zhu et al., 2015). Fmask runs as a DOS prompt executable and processes data through a series of algorithms that identify Landsat pixels as clear-sky, cloud, cloud shadow, water, and ice. Missing pixels from the cloud removal are gap-filled with clear sky pixels from other, overlapping data to create a near complete cloud-free landscape for all of Malawi. Recoding was done for specific agricultural areas in Malawi where irrigated lands included growing crops at the date of acquisition. Pixels in these areas that showed a high fC value were recoded to a value of 0 but included in the deforestation analysis. A wetland mask was also used to exclude marsh vegetation mapped as high fC. A water mask is also created using national spatial data layers.

2.3.4 Deforestation and forest degradation models

Vegetation continuous field fractional cover (fC) data products are generated from the NDVI data using a two endmember, linear un-mixing algorithm. The algorithm uses two end members representing pure soil (VI_{soil}) and 100% closed canopy vegetation (VI_{forest}) (Mbow et al., 2012; GoM, 2019). The endmembers are selected using an AOI tool through expert knowledge visual analysis for each Landsat NDVI image or along-path mosaic paired with a histogram stretched RGB three-band false-color composite image. Several AOI samples are selected for each endmember throughout an image. The minimum, maximum, mean, and standard deviation are computed from the AOI end-member samples. Along path (same date) and individual scene fC products are created using the minimum, maximum and average end-member values and each are evaluated for path-to-path and gap-filling consistency prior to selection for mosaicking and gap-filling. The fC data are produced as thematic integers and scaled 0 to 100. The fC algorithm is specified as follows:

$(NDVI - VI_{soil}) / (VI_{forest} - VI_{soil})$. Equation 2.

Figure 2A presents an example of the fC product. The final version of the along-path and individual Landsat fC products are then mosaicked and clipped to the national boundary of Malawi.

Each year-date is referred to as an observation year (OY). Change detection between three OY data layers of national fC is used to measure and map deforestation and forest degradation. Each OY fC data layer and change-intensity ΔfC products are created using separate models for deforestation and forest degradation specified as fC (OY_{t+1}-OY_t). The deforestation and forest degradation models identify pixels that meet pre-defined threshold and criteria in terms of fC values when comparing one date to a second date. These are spatially explicit models written in ERDAS Imagine modeling language. Two input data sets fC_t and fC_{t+1} are compared. The quantitative subtraction of two values produces a continuous field of ΔfC which is the change intensity value (Figure 2B).

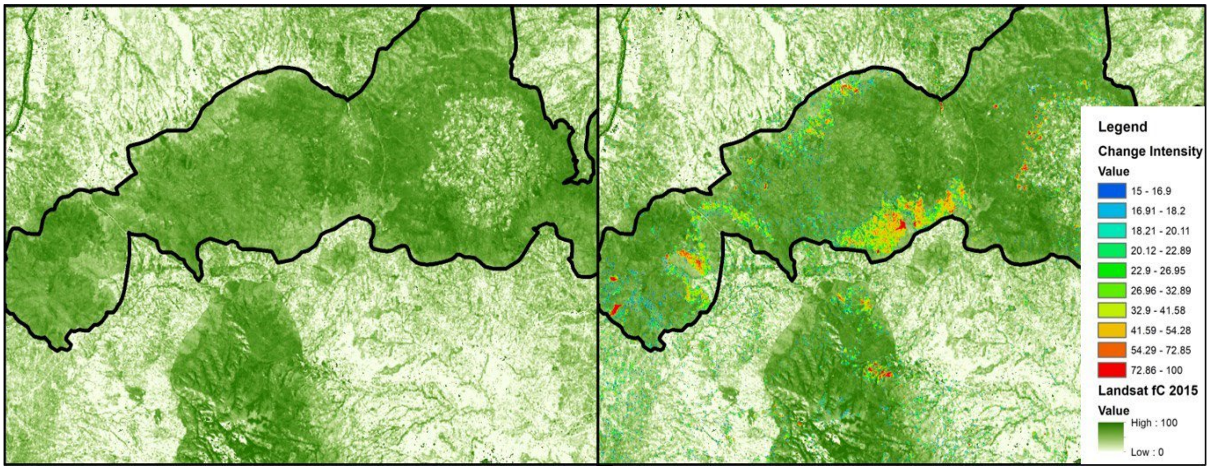

Figure 2 AB The fC model of forest cover and change measures the intensity of forest disturbance as a continuous field of observations.

A) The fC forest cover product for 2015, where shading of green represents a continuous field of forest cover. B) Using change detection, ΔfC, is computed from two dates and presented as a continuous gradient of change. If the change is significant it is labeled as deforestation. If the change is within the range of fC values for forest, the intensity of degradation can be estimated and mapped as shown here, where tones of blue and green are low intensity degradation, and tones of orange and red are high intensity degradation.

An initial evaluation of the value of ΔfC is made to test for a minimum magnitude of change, which accommodates for normal variation in fC values unrelated to disturbance (e.g., phenology). All pixels with $\Delta fC \geq 15$ are considered change cases. Deforested pixels are those where $fC_t \geq 45$ and $fC_{t+1} < 45$. Forest degradation occurs when the pixel value of $fC_t \geq 45$ and in the $fC_{t+1} \geq 45$. Because of the continuous fields' characteristic of the fC change detection, I can map the magnitude of change, ΔfC, which I refer to as change intensity. This change intensity mapping is demonstrated in Figure 2B and can be used to measure and map the intensity of forest degradation.

2.3.5 Delineation of tree cover and forest base layer

The analysis uses a base layer of forest cover with which I quantify and map deforestation and forest degradation from the fC product and the change detection products. I define forest extent as all pixels with an fC value greater than or equal to 45. In addition, forests as defined in this analysis include mapped areas larger than 0.1 ha, which is essentially the Malawi national definition. The types included are Miombo woodlands and other woody systems with canopy cover equal to or greater than 10%. Included are forest reserves, other protected areas such as game parks and national parks, village forest areas, community woodlots, other tree covers in agricultural areas, and clusters of trees outside of forests in customary lands. Our base data layer was measured at 4,270,000 ha. This represents ~45% of the land area for Malawi. The value I use includes both sparce tree covers and closed canopy forests, and thus is larger than some other reported areas. I recognize that this area of tree and forest cover is larger than has been reported for forest cover alone. A national map of forest and tree cover using the fC method is shown in Figure 3 for 2009 and 2015. Figure 3 shows a detail section around the Liwonde Forest Reserve and shows how our multi-date change-detection based on ΔfC produces a gradient of change intensities.

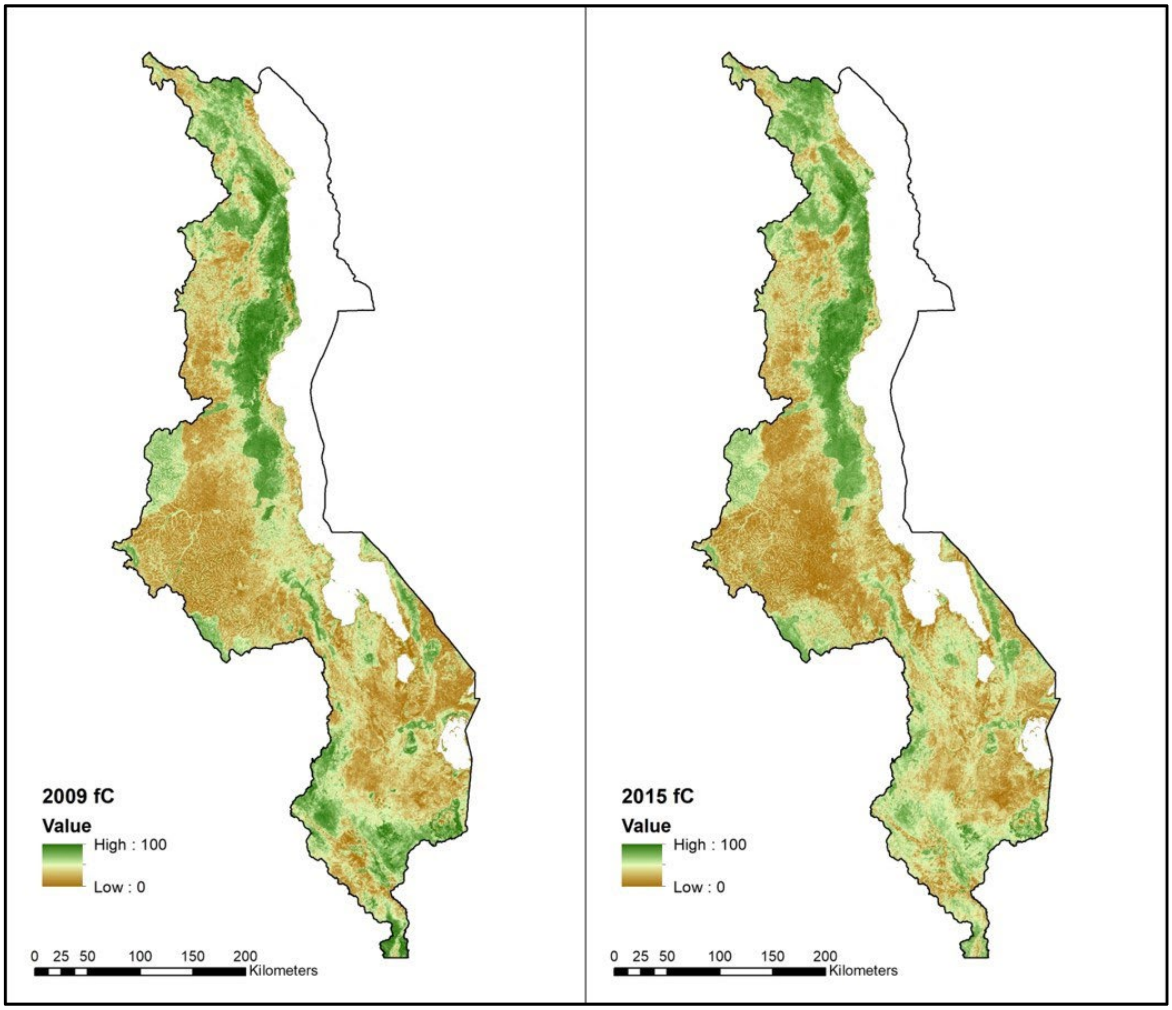

Figure 3: The fractional forest cover product for the years 2009 and 2015. The scale represents a continuous field gradient of values for fC, and subtraction of two dates produces a change product, ΔfC, i.e, 2000-2009, 2010-2015.

2.4. Results

2.4.1 National Forest Area

Our analysis estimated and mapped the total forested area in forest reserves, other protected forests, customary lands, village forest areas and community woodlots. The total area in 2000 was estimated to be 4, 270, 000 ha. (Figure 4, Table 3), which includes 2, 560, 000 Ha of forests in reserves and protected areas, and 1, 700, 000 Ha of tree systems, woodlots and village forest areas in customary or rural land. This map was used as a baseline and was reprocessed in 2009 and 2015 to detect areas of deforestation and forest degradation based on the change in forest fractional cover (ΔfC). The forest area definition I use includes small patches of forest greater than 0.1 ha. The Malawi national definition of forest in the reporting of Reference Emission Levels (RELs) to the United Nations Framework Convention on Climate Change uses a patch size of 0.5 hectares. When all patches less than 0.5 ha are eliminated from our dataset, I do not see a significant change in the total area nor its distribution. Using a minimum mapping unit of 0.5 ha, the total forest area is 4, 170, 000 Ha, 98% of our baseline forest area. Table 2 shows the total baseline forest area using different definitions of the minimum area specification. The total area deforested or degraded between time periods and the average annual rates in time periods are presented.

Table 1:Area estimates of deforestation and forest degradation in Malawi. Estimates are present for two time periods, 2000-2009 and 2010-2015 for both intact forests and forest reserves and forest land in agriculture and customary land

	Area (ha)			
Land Class	MMU=.1 ha	MMU = .27 ha	MMU = .54 ha	MMU = .9 ha
Intact forests, forest reserves and protected areas	2,561,722	2,556,864		2,530,602
Customary forests on rural and customary lands	1,703,708	1,666,980		1,570,397
Total Area	4,265,431	4,223,844		4,101,000

2.4.2 Deforested areas and annual rates.

From 2000 to 2009 the total area deforested, which is the complete conversion of forest to another land cover, was 201,688 ha (Table 3). The average annual rate of deforestation was 22,410 ha yr^{-1}. The area deforested between 2009 and 2015 was slightly higher at 233,624 ha. This is an annual average rate of deforestation of 38,937 ha yr^{-1}. The annual rate of deforestation increased markedly during the study period, with the rate increasing by 74% for 2009-2015 over 2000-2009, although I do not have interannual data to evaluate if there were any years that deviated from average rates. Through the study period the total area deforested was 435,312 Ha, or 17% of the forest area.

Table 2 (below) also shows estimates for deforestation areas and rates in protected areas and other gazetted forests under government management compared to deforestation in customary and other rural land. These results are very interesting in that they portray a marked shift in the location of deforestation over the 15-year period. From 2000-2009, 80% of all deforestation occurred in customary woodlots, tree complexes, and forests (162, 000 ha) compared to 20% (397, 000 ha) in forest reserves and protected areas. By 2009-2015 only 42% of deforestation occurred in customary landscapes (976,000 ha), while fraction of deforestation occurring in forest reserves and protected areas rose to 58% (136, 000 ha). These results demonstrate the importance of separately mapping forest reserves and rural customary land because the drivers and dynamics are different and change differently over time. Moreover, considerable tree cover loss occurs outside of government-managed areas and contribute to Malawi's greenhouse gas emissions.

Table 2: Deforested areas and annual rates from 2000 to 2009 the total area deforested. (Appendix F presents an updated version of these estimates for the period 2016-2021*)*

2000 - 2009:	Area (ha)		Rate (ha yr-1)	
	Deforested	Degraded	Deforested	Degraded
Intact forests, forest reserves and protected areas	39,661	248,576	4,407	27,620
Customary forests on agricultural and other land	162,028	138,072	18,003	15,341
TOTAL	201,688	386,648	22,410	42,961
2010 - 2015:				
Intact forests, forest reserves and protected areas	136,040	309,694	22,673	51,616
Customary forests on agricultural and other land	97,584	121,572	16,264	20,262
TOTAL	233,624	431,266	38,937	71,878

2.4.3 Forest degradation areas and annual rates.

The total area of forest degradation from 2000 to 2009 was 386,648 ha, and from 2009 to 2015 was 431,266 ha (Table 2). On an average annual basis, I estimated forest degradation rates for the period, 2000-2009, to be 42,961 ha yr^{-1} and from 2009 to 2015 to be 71,878 ha yr^{-1}. Unlike deforestation, forest degradation has always been highest in forest reserves and other government managed areas: 64% of all degradation detected in 2000-2009 was in government managed areas, increasing to 72% in 2009-2015. Forest degradation exceeds deforestation throughout the time series, and by a significant amount in some locations when examined as a map. In 2000-2009 forest degradation was 92% higher than deforestation, and 2009-2015 forest degradation was 85% higher. It is notable that in 2000-2009 forest degradation rates were 6-fold higher than deforestation in forest reserves, declining considerably to 2-fold during the period 2009-2015. Generally, in customary and other rural landscapes deforested and degraded areas and rates were quantitatively approximately equal., but in the early period deforestation areas and rates slightly exceed forest degradation areas and rates. Thus, currently forest degradation is the dominant form of anthropogenic forest cover disturbance.

The combined disturbance from deforestation and forest degradation during 2000-2009 was 588,336 ha, and from 2009-2015 was 664,890 ha, an increase of 13%. Total forest disturbance for the entire period was 1,253,226 ha.

2.4.4 Analysis by district.

When deforestation and forest degradation rates are examined by district, I see a general shift in the location of these disturbances from the northern districts to the southern districts (Table 3). For both deforestation and forest degradation, the districts in the north generally declined during the second period, while districts in the south generally increased. For the most part, all districts had higher degradation rates than deforestation rates. These regional characteristics reflect some significant hot spots at the district level. In the north Mzimba District had the highest levels of disturbance, with the highest deforestation levels in the country. In the south the districts of Mangochi, Thyolo and Chikwawa were important hot spots, with the Chikwawa district presenting the highest forest degradation levels in the country. The districts of Kasungu, Nkhotakota and Salima represented the Central regions hot spots.

Table 3:Reporting of deforestation and forest degradation quantities by District (ha).

Region	District	2000 - 2009 Deforestation	2000 - 2009 Degradation	20010 - 2015 Deforestation	2010 - 2015 Degradation
Northern	Chitipa	10,458	47,618	8,495	10,979
Northern	Karonga	14,540	74,749	15,820	12,837
Northern	Mzimba	64,966	87,013	35,180	32,717
Northern	Mzuzu City	566	1,056	546	434
Northern	Nkhata Bay	687	21,433	4,776	27,317
Northern	Rumphi	13,936	41,037	12,364	20,021
Regional Sub total		111,154	272,906	77,182	104,306
Central	Dedza	7,250	9,053	9,402	18,591
Central	Dowa	9,178	6,941	8,378	6,691
Central	Kasungu	10,622	17,064	16,358	20,357
Central	Lilongwe	4,625	4,001	7,870	19,381
Central	Lilongwe City	655	366	734	591
Central	Mchinji	386	654	2,425	2,242
Central	Nkhotakota	8,370	11,829	7,369	15,877
Central	Ntcheu	5,351	5,860	5,143	9,703

Table 3 cont'd

Central	Ntchisi	8,317	8,257	7,128	7,921
Central	Salima	7,150	6,335	9,258	10,559
Regional Sub total		61,904	70,361	74,065	111,914
Southern	Balaka	4,417	4,848	1,073	2,275
Southern	Blantyre	1,088	1,808	1,263	2,833
Southern	Blantyre City	427	523	753	874
Southern	Chikwawa	1,484	1,999	15,507	56,150
Southern	Chiradzulu	587	814	2,233	2,226
Southern	Machinga	3,019	3,124	1,969	6,328
Southern	Mangochi	8,875	13,840	14,406	30,130
Southern	Mulanje	881	2,273	6,641	18,733
Southern	Mwanza	384	1,019	6,408	21,297
Southern	Neno	1,480	3,159	6,601	21,472
Southern	Nsanje	1,869	2,533	4,171	5,716
Southern	Phalombe	653	908	1,442	2,975
Southern	Thyolo	841	2,554	11,467	34,940

Table 3 (cont'd)

Southern	Zomba	1,964	2,788	7,344	7,414
Southern	Zomba City	44	81	222	409
Regional Sub total		28,014	42,272	81,501	213,772
TOTAL (ha)		201,072	385,539	232,748	429,992

2.4.5 Spatio-temporal trends in forest disturbance 2000 - 2015

The analysis using remote sensing provides a mechanism to map forest and forest cover change with considerable spatial detail over the entire country. I have two basic formats of our spatial datasets. In the first format I present the direct measurement of continuous fields as products from the fC analysis. This spatial dataset can be inspected at the landscape level, at the full 30-meter spatial resolution of the fC product (Figure 2, 3). Disturbance intensity shows the degree of disturbance and is the primary tool for mapping forest degradation. The use of a pixel mixing model allows each pixel's representation to reflect the sub-pixel fractions of cover. Figure 2A illustrates this point. This is a display of the map derived around the Liwonde Forest Reserve and reveals the continuous fields delineation of forest and woodland density (shades of green). The use of multi-date ΔfC allows for mapping the magnitude, or intensity, of change (color tones, blue/green as low to yellow/red as high). Figure 2B shows this map as a change intensity where the highest intensities represent complete forest conversion (deforestation) while the lower intensities represent forest degradation. The continuous results are split into separate classes for degraded areas and deforested areas. Based on a measure of intensity of change, the spatial dataset can be used to locate specific "hot spots" of deforestation or degradation.

The second mapping product is produced by aggregating 30m resolution pixels into grid cells of 25 km^2 for presenting national coverage. Figure 2 shows the fractional cover map of baseline forest cover for this study. The northern region of Malawi has considerably more forest cover than the other regions of the country, although there are isolated areas with important dense Miombo woodlands throughout the country. Dense forest cover above 75% (fC>75) of each 25 km^2 grid cell exists only in isolated clusters, most of which are forest reserves and other protected areas under government management. To map nationally the pressure from deforestation, I computed at the pixel level the change in fC (ΔfC) between dates, and all pixels that drop fC levels below 45 are considered deforested and aggregated to the 25 km^2 grid cell and presented (Figure 4). Not surprisingly, many of the areas of high deforestation are also areas of high forest cover. There are definite hot spots of deforestation in both periods of time, and these have shifted south over the course of the 15 years of analysis. Spatially, deforestation expands considerably into the agricultural landscapes in the second period of analysis, even while the annual rate remains almost constant (Table 2).

The national situation for forest degradation can be examined in a map produced when ΔfC is between 15 and 55 with the final fC value is equal to or exceeds 45 (Figure 4). Forest degradation also expands considerably into agricultural landscapes, while increasing only slightly in magnitude (Table 2). However, it increases more in forest reserves and intact forests, also expanding considerably to the south of the country.

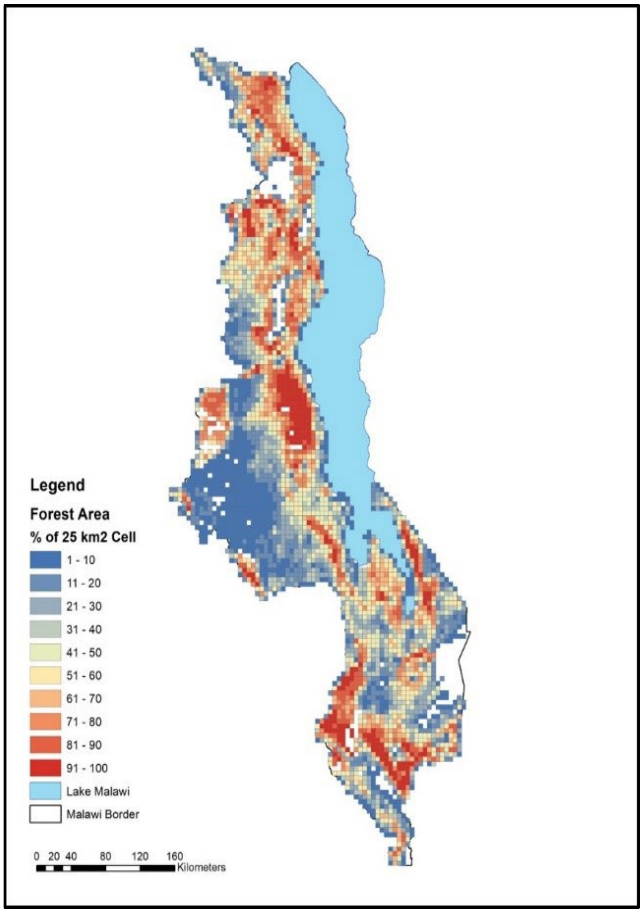

Figure 4: Mapping of forest cover density aggregated to 25 km2 grid cells. Forest area is represented as a proportion (%) of each 25 km2 grid cell, from low values in blue to high values in red.

The data are produced at 30 m resolution, and a large dataset at that resolution is available for the entire country. Aggregation is used for display at this scale.

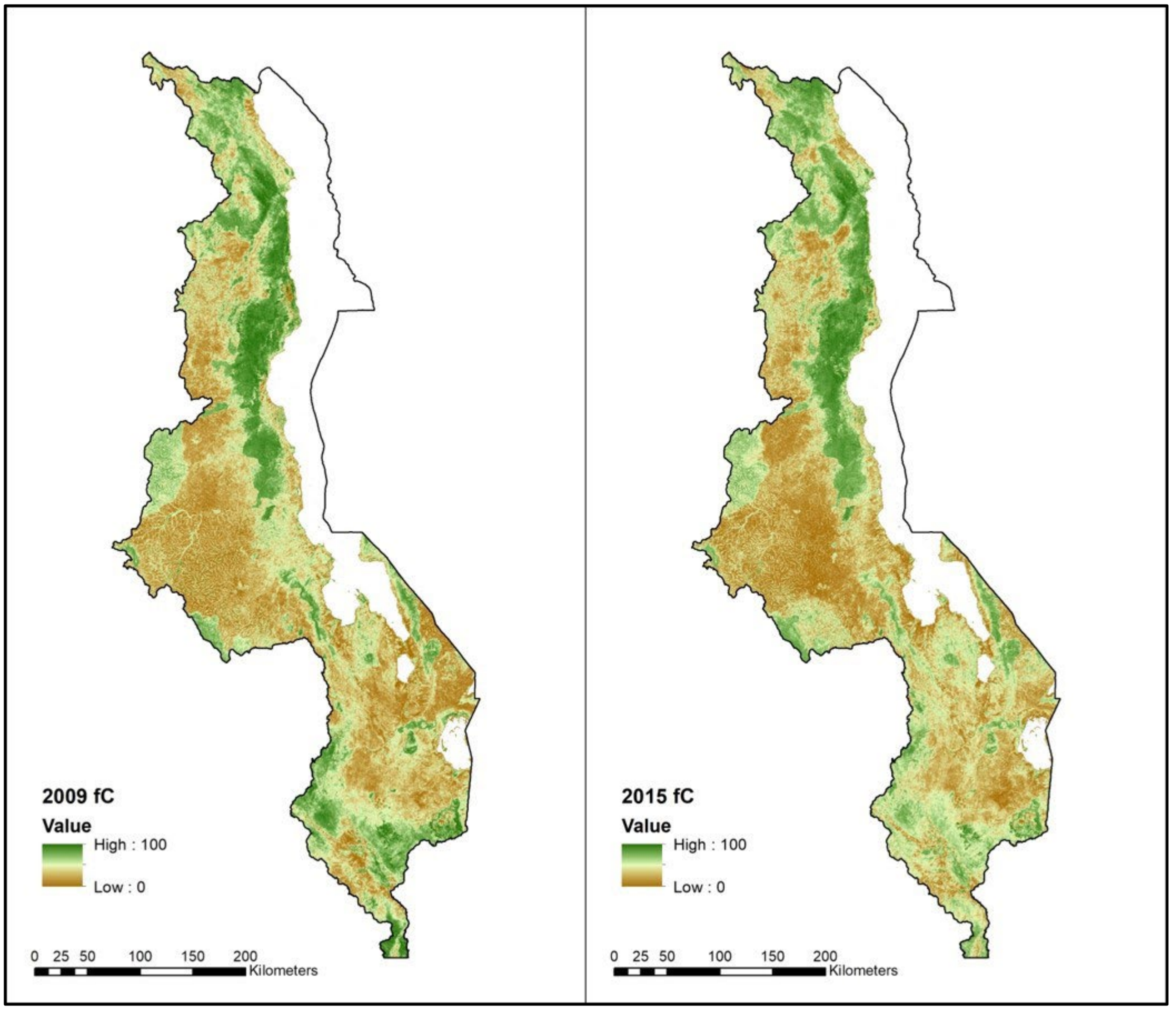

Figure 5: The fractional forest cover product for the years 2009 and 2015. The scale represents a continuous field gradient of values for fC, and subtraction of two dates produces a change product, ΔfC, i.e., 2000-2009, 2010-2015.

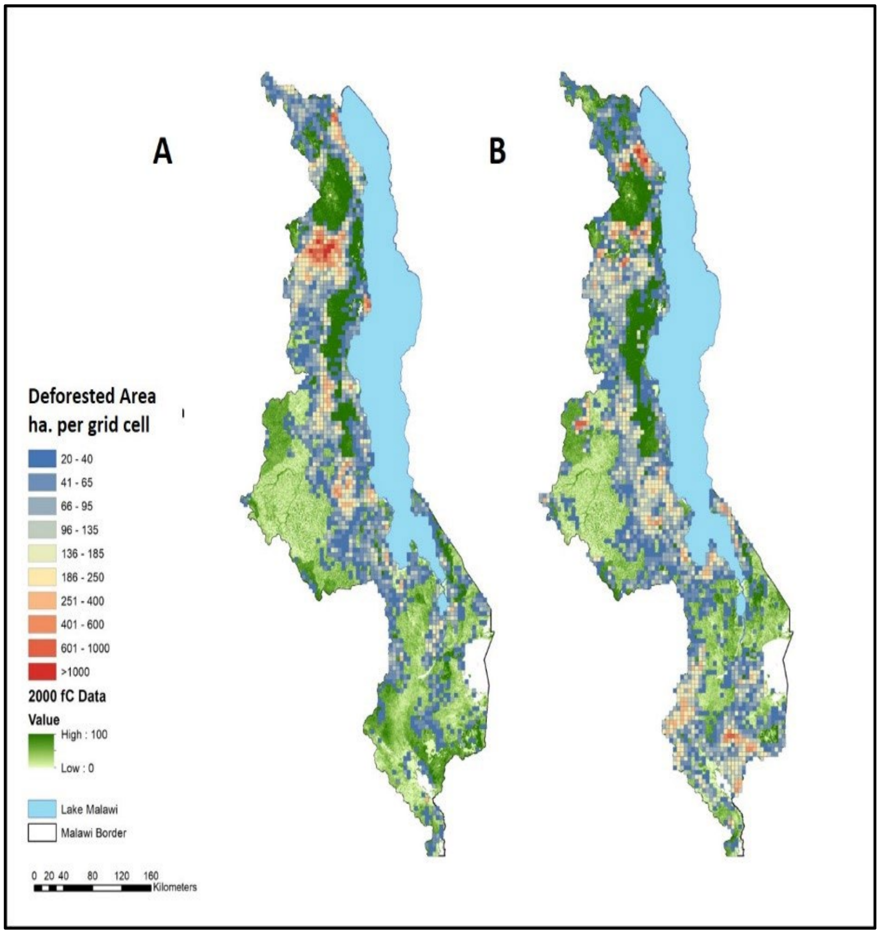

Figure 6: Mapped areas of deforestation, 2000 to 2009 (left) and 2010 to 2015 (right), as the area of total new deforested land (ha) created during the period within each 25 km^2 grid cell. Cells where deforested area is <20 ha are not shown.

As noted, forest degradation can occur as a gradient of change, within an intensity range. Higher forest degradation has a higher impact on carbon stocks. To spatially quantify the impact of forest degradation I used the continuous field and compute an index of degradation intensity for each 25 km^2 grid cell, where the reported value is based on the magnitude of the change in *f*C (ΔfC) at each pixel and summed for the cell (Figure 7). The intensity gives us a perspective on how severe the degradation is over time and place. The map shows hot spots of higher intensity degradation, but generally most of the country has uniform moderate degradation intensities.

Over time there has been a significant shift from north to south in the location of high intensity degradation.

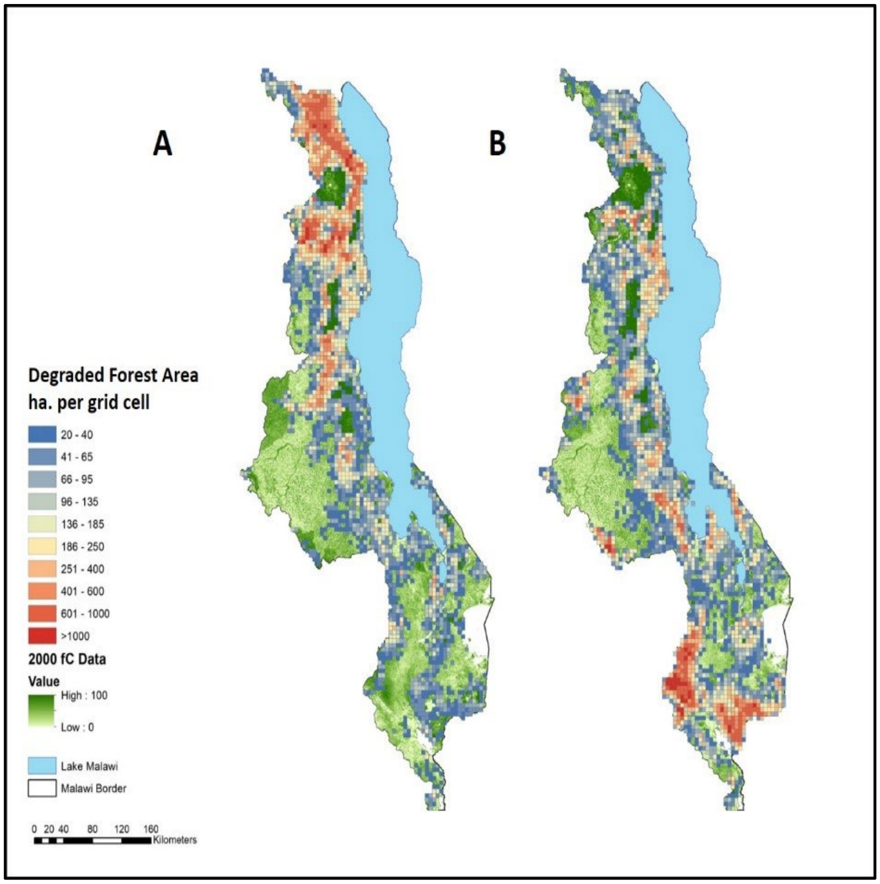

Figure 7: Mapped areas of forest degradation, 2000-2009 (left), 2010-2015 (right), as the area of total new degraded forest (ha) created during each period within each 25 km^2 grid cell. Cells where degraded area is less than (<20) ha are not shown.

2.4.6 Accuracy analysis and quality control

A detailed visual inspection of the forest cover product suggests that it well represents features in the landscape when I compare it to hyperspatial resolution imagery, as shown in Figure 8. I made a more quantitative assessment of the accuracy of the fC forest cover product using three analyses. In the first analysis I used hyperspatial resolution data to map the forest in the landscape and compare the quantitative estimates of forest cover by the fC product aggregated at the pixel level into an 80-ha grid overlay in three test landscapes in and around the Perekezi and Liwonde forest reserves (Figure 3A). There was very good agreement between the independent estimate of forest area from hyperspatial mapping at 0.5 m resolution and the predicted estimate from the Landsat fC product, with linear regression R^2 of approximately 0.9 or better.

In the second analysis I overlaid the fC product against a sample of ground validation plot. I deployed 346 30-meter fixed radius plots to measure tree cover, tree density, and biomass. A simplified error table was produced for error estimation, suggesting overall accuracy of the fC forest cover product was 93-98%.

In a third quantitative analysis, I used hyperspatial satellite data to prepare an fC product in which the fine resolution data (0.5m) were resampled to the 30 m resolution of our fC product and compared using a standard contingency matrix, as shown in Figure 3A and Table 3. Overall accuracy is 84% across all test sites. Producer's and user's accuracy were 84% and 94%, respectively, for forest cover mapping. It is important to note that the user's accuracy, or how often the mapped forest areas are also identified as forests on the ground, is very high.

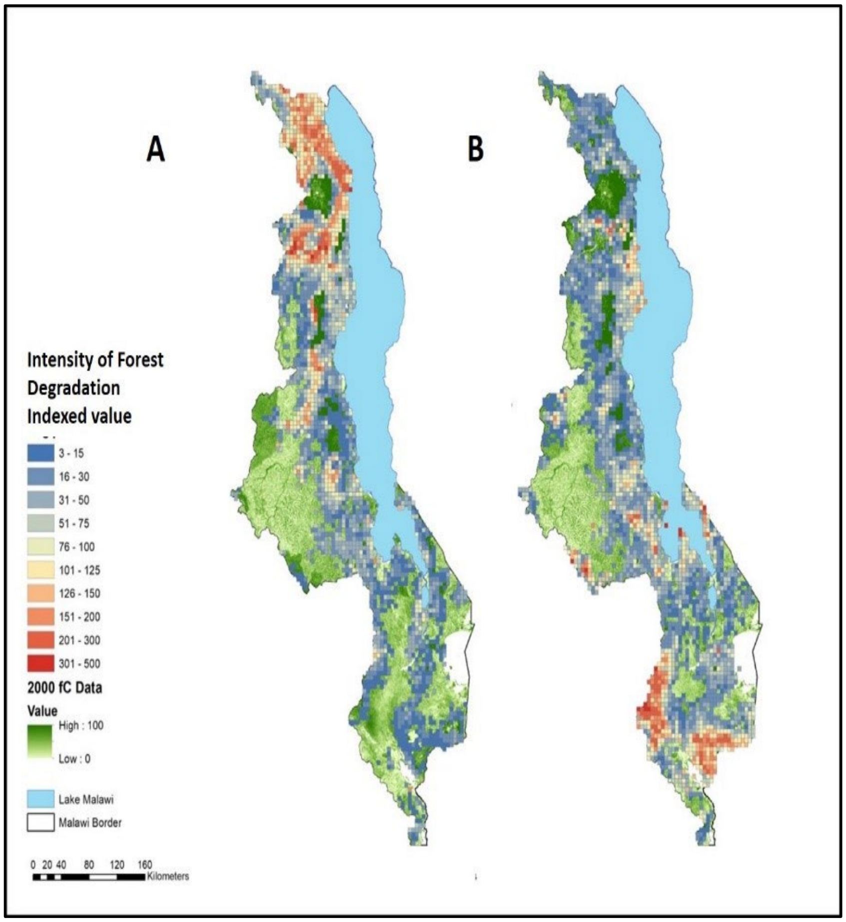

Figure 8: Mapping of degradation intensity, 2000-2009 and 2010-2015.

These maps are used to display where degradation is most severe. Thus, two cells could have the same area of forest degradation but containing different intensities of degradation. To compute the intensity, I use the following equation: $\sum (100 * \Delta fC/55)/Af$, where the difference in fC values between dates is divided by the maximum amount of degradation weighted against a proxy for biomass emission factors and summed for all pixels in each 25 km^2 grid cell. This value is divided by the area of forest in the grid cell. Much degradation is low intensity, but there are some notable areas of more severe degradation. Further, over time there is a north to south shift in the location of highest intensity degradation.

2.5. Discussion

Most estimates of Malawi's forest area are reported only for the recorded forest area in government reserves and protected areas, and often include designated forestland that may not contain tree cover at the time of reporting. Despite recent assertions that Malawi has the highest rate of deforestation in Southern Africa (Chander et al., 2002), I find almost no consistent and comprehensive data on the national deforestation rates and location. There is considerably less information available on forest degradation, which is also common across most of Africa (Gao et al., 2020; Zhu and Woodstock, 2002). There are considerable policy requirements for quantitative data on Malawi's forest status, and growing interest in having improved monitoring capacity to support a range of national policies and measures (PAMs), including implementing Malawi's new National Forest Policy (Zhu, 2015), National Forest Landscape Restoration Strategy (Stanturf, et al., 2015), national initiatives for scaling tree-based systems (Roy et al., 2002), and National Charcoal Strategy (GoM, 2017). Accurate spatial data (maps) are particularly critical to support Malawi's full participation in the United Nations Framework Convention on Climate Change, including its Nationally Determined Contributions (Pearson et al., 2017), National Forest Reference Emission Levels (Mbow et al., 2020), and REDD+ National Forest Monitoring System (Melo et al., 2018; Changer et al., 2009; Zhu et al., 2015). Having capacity for a National Forest Monitoring System is necessary for receiving performance and results-based payments such as REDD+ that require setting of baselines to work from and account for carbon sequestered.

There have been several previous remote sensing mapping exercises that have taken a broad examination of Malawi's forests but based on a thorough review by GoM, (2016) these products are highly variable and inconsistent in estimating national forest cover area, which ranges from

18-29% of the country area. The forest area in these studies ranged from 2.15 to 3,490, 000 ha in 2010. The minimum mapping unit (MMU) for these analyses is much larger than our study, representing MMUs as large as 25-100 ha. In these reports no attempt was made to explicitly quantify forest cover outside of the recorded forest area (reserves and protected areas) or to include tree clusters, woodlots, agroforestry, and village forests on agricultural or customary land. My analysis reports area estimates that are comparable to these previous estimates for 2010 if I am only to use the area of forest cover confined to the forest reserves (2, 520, 000 ha for this study), but I have considerably higher estimates overall because I include forests and tree cover on customary and rural land outside of the recorded forest areas (4, 270, 000 ha).

Estimates for the rate of deforestation during the period of our analysis range from ~6000 ha yr^{-1} to 30,000 ha yr^{-1} (Petersen et al., 2018; GoM, 2017a, GoM, 2017b), while our estimate ranges from 22, 000 ha yr^{-1} to 39, 000 ha yr^{-1}. The Global Forest Watch (GFW) estimated total deforested area (i.e., total converted tree cover) between 2001 and 2009 of 518, 000 ha. Our measurement for the same period was 2, 017, 000 ha, almost four-fold higher (Table 3; Appendix F). Likewise, the GFW estimates for total deforested area between 2010 and 2015 was 607, 000 ha compared to our estimate of 2, 336, 000 ha. These differences are most apparent over the entire period of analysis, 2000-2015 where our measurement of the total area deforested is 4, 353, 000 ha, which is considerably higher than GFW (Table 3; Appendix F). The most likely explanation for the difference is perhaps the consideration of deforestation in rural and customary land in addition to the contiguous forests of the national reserves and parks, which constitute 60% of our measurement of deforestation. These areas of customary forests, village forests, woodlots and agroforestry are abundant but are widely scattered and do not constitute an extensive and continuous canopy and are thus features that may get removed when processing medium resolution imagery. It has been known that there is substantial tree cover in areas outside of national parks and reserves (GoM, 2017) and informal evidence that tree-based systems are increasing (Roy et al., 2002). Our measurements suggest that 40% of the national forest cover is on customary or other rural land, which is consistent with Petersen et al., (2019) who report 42% of forest cover is in trees outside of forests. This implies that Malawi can start to take more interest on trees outside of forests as they can contribute to the national REDD plans too apart from forest reserves.

The contribution of customary forests is important, but quantitative information has heretofore been hard to find. Some customary forests have been officially designated as Village Forest Areas (VFAs) which are supervised by traditional authorities and managed by Village National Resources Management Committees (VNRMC). The VFAs are important tools for sustainable land management and conservation of community forestlands. However, only a small number of VFA have been registered, and fewer have been surveyed. The exact area and cadastral information do not readily exist (GoM, 2017) and his would prove problematic for REDD purposes. The fC Tool used in this analysis could be deployed to create an inventory and monitoring framework for VFAs, although information concerning species would be difficult. Further investigation of this potential could be productive; supplementing this with very high resolution (VHR) imagery (Figure2A) might be required.

Our analysis suggests that rates of deforestation are increasing, although the location of the deforestation has notably shifted away from customary forests to public forests (Table 3). There is some indication from informal reports that rates of deforestation during the period prior to 2000 were higher, particularly during the period of one-party government under Hastings Banda. One widely cited assessment (GoM, 2017), which was used in the FAOs Forest Outlook Studies in Africa, reports that 2, 500, 000 ha of forests were cleared, or 125, 000 ha yr^{-1}, between 1972 and 1992. It is difficult to evaluate these estimates because no formal study was published, and the methods and definitions are unclear. I know that it was a two-date analysis using Landsat MSS and TM data, so it is quite possible that the results included areas of heavy forest degradation in addition to deforestation. Also, possible effects of phenology could have introduced errors because the Landsat collection was not very large, and older coarse resolution MSS data would be difficult to use for this application.

The Malawi State of the Environment and Outlook Report from 2010 (GoM, 2017) reports deforestation rates during the period after the formation of multi-party government. From 1992 to 2010, forest cover change is reported at five-year intervals, with annual deforestation rates at a constant 33,000 ha yr^{-1}. Whether rates were exceptionally high in the 1970s and 1980s and declined thereafter, as these reports suggest, is difficult to evaluate. Thus, I have no reliable long term, multi-decadal record of deforestation in Malawi, but it might be possible to reconstruct a reasonable picture, at least to 1986 using Landsat's historical archive that extends back to 1975. This would be useful for historical, political and economic development studies.

There have been no national-scale direct measurements of forest degradation for Malawi, although it is likely that past deforestation estimates produced without mapping or direct observations also included areas that were heavily degraded rather than completely cleared. Differences between various reports are likely to be directly related to the degree to which an estimate includes degraded forest in addition to deforestation, or the degree to which the study included disturbances in customary and agricultural landscapes. The result from this study highlights the importance of having a means to make direct measurements of forest degradation, since most of the forest disturbance is associated with forest degradation; degraded forest is almost 2-fold higher than cleared forest. Most of the forest degradation is occurring in public land (Table 3). In the current set of programs and activities under the national REDD+ program, forest degradation rates are estimated indirectly from models of fuelwood demand.

An important aim of a National Forest Monitoring System for REDD+ is to identify important locations of both deforestation and forest degradation to prescribe specific controls and interventions, such as forest landscape restoration (FLR). This requires capacity to monitor drivers and post-intervention tree cover outcomes across whole landscapes, especially outside the public forest estate. The dense time series that are provided by these "big data" models may be less necessary than improved specificity of landscape-scale tree cover pattern, distribution, and status.

Our spatial analysis suggests that in places where the forest resource base has diminished, deforestation and forest degradation has shifted location in response. This changing geography over time appears to have had three components: 1) an increase in the use of forest reserves, especially due to increased deforestation rates, 2) an expansion of the forest degradation of forests and tree complexes in customary land across a wider swath of landscape, and 3) a shift in the location of most deforestation and forest degradation from the northern region of the country to the southern region of the country (Figures 4 and 5). Likewise, the intensity, or severity, of degradation has increased and has shifted from north to south, meaning more forests are being degraded and they are being more severely degraded, especially in the south (Figure 7).

I can examine the pressure on the forest resource base by calculating the ratio of deforestation or degradation per unit of forest, localized within 25 km^2 area (Figures 6 and 7). This can be done spatially which gives a more accurate representation of resource pressure than using nationally aggregate or average estimates. Some areas stand out because they are experiencing significant pressure on their local forests. In terms of both deforestation and particularly degradation forest pressure has declined in the north while increased in the south over the period of record. Commonly though, local pressure on the forest resource from deforestation, and forest degradation is stabilizing, or declining in some places. However, deforestation and forest degradation rates are indeed increasing because the degradation is expanding spatially over more area and this would affect availability of wood for use by communities and other sectors that rely on forests to supply, which led to the fuel wood consumption investigation as will be discussed in Chapter 4 where the maximum available stock is compared to the community consumption of the forest resource produced.

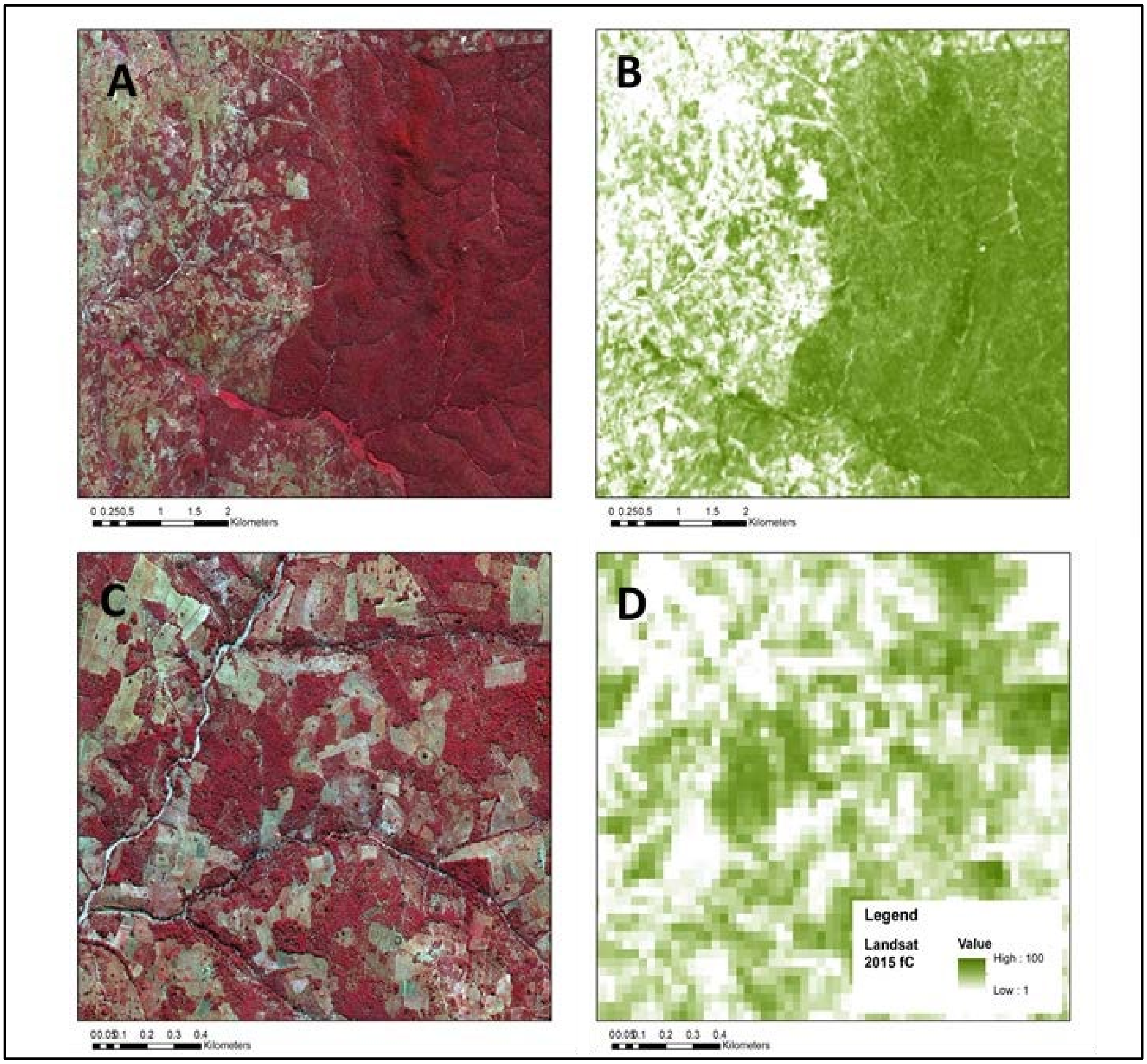

Figure 9: Examples of the fC product compared with very high resolution (VHR) satellite data at 0.5 m resolution. A) VHR, wide area perspective, B) fC product, wide area perspective, C) VHR, local area perspective, D) fC product, local area perspective.

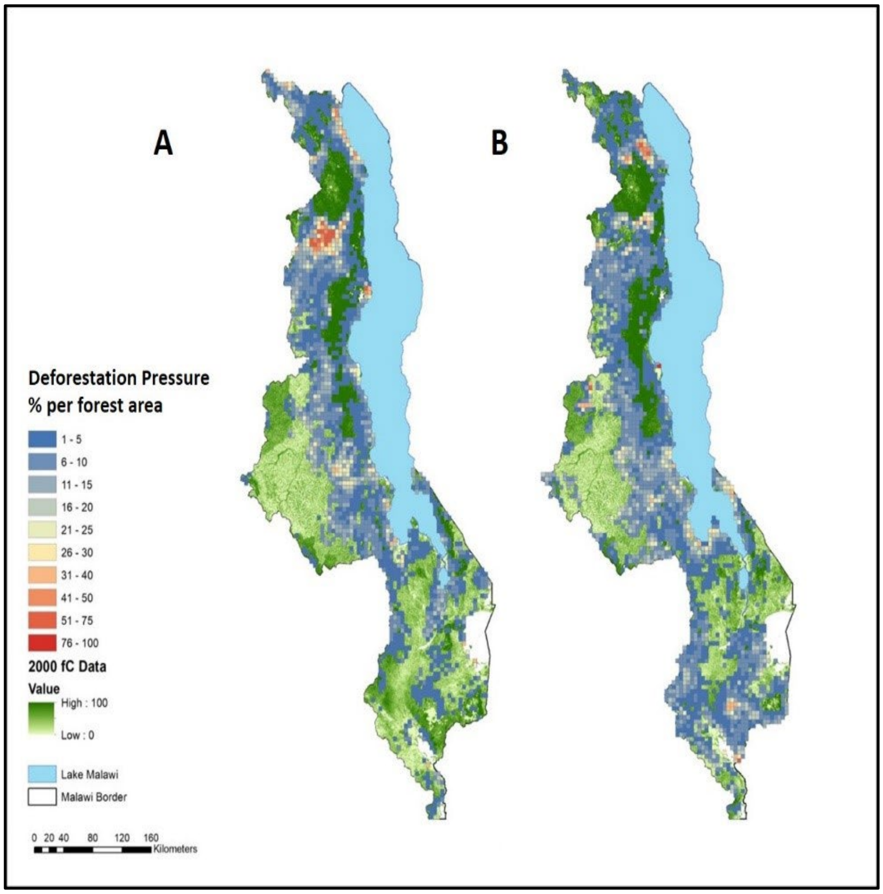

Figure 10: Mapping of the pressure on remaining forest resources from deforestation, 2000-2009 (left), 2010-2015 (right). The total area deforested at each date is expressed as a percent fraction of the forest area in each 25 km2 grid cell.

Regions with the highest rates of disturbance are also, generally, areas of highest amount and density of forest cover. This is particularly true for the northern region of the country, during the first period of analysis and the southern region in the second period of analysis. Thus, while the rates of conversion may be high the pressure on the remaining stock of forest may be lower than other places where there is considerable pressure on low density remaining forest. Typically, conservation priority would be placed on these threatened forests. But from a carbon context these areas of high forest cover density where relative pressure is lower may also need mitigation because the emissions may be higher from these forests. The usual management prescriptions to conserve areas of vestige forests may not result in emissions reductions compared to conservation of high cover and high-density forests. Therefore, a multi-level approach to management will be required that places conservation strategies on endangered forests and high emissions forests.

The Government of Malawi (GoM) has produced its first national forest reference emissions level report (Mbow et al., 2020), in which they use a sampling approach based on visual interpretation of tree cover using Google Earth for deforestation only, limited to forest reserves. Their estimate of the total area deforested between 2006 and 2016 was 88,474 ha. By comparison, our estimate of deforestation for the period 2009-2015 was 233,624 ha, which is considerably higher. The GoM estimate for the annual rate of 8,847 ha yr^{-1} is low compared to our estimate of 38,937 ha yr^{-1}. When I include forest degradation as well, our annual estimate is 12-fold higher at 110,815 ha yr^{-1}. This is a significant difference and will affect calculations of greenhouse gas emissions considerably. Moreover, the GoM reporting does not measure forest degradation directly, but instead uses a model of fuelwood collection derived from proxy estimators rather than direct measurements.

The considerable difference in estimates is due to three factors. First, GoM sample approach is very limited in the sample density, where the complete sample frame covered only 27% of the land areas of Malawi, and 61% of the forest area with a sampling density of only 0.04% within the sample frame. Because the spatial distributions of deforestation and forest degradation are not uniform, low sample densities can produce errors. The GoM report does not report an accuracy assessment for the estimated deforestation rates. Further, the low sample frame for rural and customary land eliminates important emission sources from both forest degradation and deforestation. Second, the GoM report uses a minimum mapping unit of 0.5 ha, while I use 0.1 ha. Although the difference between 0.5 and 0.1 MMU does not affect the total forest area estimates (Table 3), it does influence estimates of change in forest area, i.e., deforestation or forest degradation, underestimating by as much as 40% due to the omission of large number of small disturbances. Third, the use of models based on proxy variables rather than direct measurements may underestimate forest degradation because it does not capture all forms of forest degradation, is limited in geographic scope, and is based on only the wood removals rather than stand disturbance.

2.6. Conclusions

This study demonstrates the importance of measuring forest disturbances due to forest degradation, rather than deforestation alone. Further, I have demonstrated the value of a landscape approach, considering tree cover in both forested and agricultural landscapes. Climate change mitigation policies and measures require a whole landscape approach that includes customary land and other non-gazetted areas. The implications for carbon management are clear: efforts to reduce deforestation and forest degradation as well as active restoration must include agricultural land and rural communities. This strengthens the argument that REDD+ should be more Agriculture Forestry and Other Land Use (AFoLU) centered, rather than focused on Land Use, Land Use Change and Forestry (LULUCF) even in a country like Malawi in which most emissions are related to forests.

Furthermore, this study was based on complete national coverage at high spatial resolution (0.1 ha MMU), which provided direct measurements of deforestation and forest degradation, thus avoiding past confusion over rates when forest degradation is omitted or both types of disturbances are co-mingled. A mapping approach may appear to be difficult to implement in many African countries, particularly for forest degradation measurements, so many countries opt-out of including forest degradation in their national REDD+ scope. But this study demonstrates a practical and accurate modality for implementing direct measurements of forest degradation. The mapping also enhances the utility of the results to proscribe specific local interventions under national polies and measures (PAMs) and for identifying locations and opportunities for forest landscape restoration.

Previous mapping work has been done in Malawi by various partner organizations. However, these datasets and the technical methods have been limited in meeting the requirements and national needs for REDD+ measurement and monitoring. For example, most of previous products and approaches do not provide measures of forest degradation, which is a critical characteristic of forest cover change in Malawi, where charcoal and fuelwood removals are important drivers of forest degradation. Moreover, most mitigation interventions will be implemented through local-scale changes in forest management, and thus coarse-scale land cover classification maps that do not provide fine scale local information for forest management and planning are inadequate. Detailed, fine-scale maps of forest cover over large areas are needed to identify hot spots of forest degradation where interventions would be most cost-effective. Such detailed maps are also needed to identify hot spots for deploying detailed ground surveys to understand drivers of deforestation and forest degradation. Fine-scale mapping of forest cover change is needed to align with the spatial variation in carbon stocks from ground measurements for accurate GHG emissions and removals estimation.

This study produces new estimates for the total area deforested between 2000-2009 (201,688) and 2009-2015 (233,624 ha), and new estimates of the rate of deforestation between 2000-2009 (22,410 ha yr-^{1}) and 2009-20015 (38,937 ha yr^{-1}). I further produce new and separate estimates of the total forest degradation between 2000-2009 (386,648 ha) and 2009-2015 (431,266 ha), and new estimates of the rate of forest degradation between 2000-2009 (42,961 ha yr^{-1}) and 2009-2015 (71,878 ha yr^{-1}). The implications of these new estimates for calculating carbon emissions are important. They are approximately 3-fold higher than reported by the GoM, with forest degradation accounting for a large fraction (See Appendix G for the updated 2016-2021 estimates). These new estimates and the associated maps should be of interest to the national REDD community in Malawi and others for both science and policy use.

The current reporting from the GoM of carbon emissions for its national forest reference emission level (FREL) estimation is likely to be insufficient for use in the National REDD program. Based on our study, current national estimates which have been produced without published accuracy assessment are low, perhaps due to methodological issues and use of proxy estimators rather than direct measurements. Its selection of a MMU has an important impact on measurement, resulting in underestimates due to the high level of small clearings and disturbances.

These results have implications for National REDD Programs in Malawi. The UNFCCC advises countries that are Parties to the Convention (COP) and are aiming to undertake REDD+ activities to follow specific methodologies for estimating greenhouse gas (GHG) emissions and removals developed by the International Panel on Climate Change (IPCC). These methodologies require a system for estimating forest stocks and fluxes using a national forest monitoring and measurement system (NFMS). Further, the UNFCCC recommend national programs consider their scope of REDD activities from a list of five elements: 1) reducing emissions from deforestation, 2) reducing emissions from forest degradation, 3) conservation of forest carbon, 4) enhancements of forest carbon, and 5) sustainable forest carbon. Determination of the national scope is important because it sets the agenda for national policies and measures (PAMs). All countries participating in REDD+ actions and programs need to have a basic level of "readiness" for implementing a NFMS to produce the data needed for REDD+ measurement, reporting, and verification (MRV). In this study I demonstrate potential for implementing in Malawi four of these scope elements and provide a model for operational components of Malawi's NFMS.

As with many countries in Africa the establishment of a National Forest Monitoring System (NFMS) is a key challenge in developing its reporting stream under REDD+ and its NDC efforts. Following COP decisions and guidance a NFMS includes three parts, or pillars as sometimes called: 1) a satellite land change monitoring system (SLMS), which includes a national land classification schema and mapping of changes in forest cover due to deforestation and forest degradation, 2) a national forest inventory (NFI) that focuses on carbon stocks from a system of field plots, using standardized methods and field measurement protocols, and 3) routine quantitative estimation of GHG emissions and removals from plot data and forest cover monitoring data over time, benchmarked to reference emission levels (RELs). This study demonstrates how Malawi can bring its NFMS efforts to an operational readiness level with respect to the SLMS and its ability to produce detailed, spatially explicit Activity Data.

As Malawi expands its response to climate change through forest management, it will increase its deployment of the National Forest Landscape Restoration programs. Low carbon forest management is an essential component of low emissions development strategies aimed at enhancing livelihoods for millions of Malawians, and thus is an essential climate change adaptation measure as well as mitigation strategy.

As with many developing countries, the Government of Malawi (GoM) recognizes the general importance of expanding its national capacities to measure and manage its forest resources even without the predicate of REDD+. Indeed, national interests are best met by developing MRV capacities that satisfy carbon requirements of REDD+ and basic national forest management needs, with as much utilization of capacities already in place or existing elsewhere that could be readily transferred. This strategy is often referred to as a “no regrets REDD” strategy (GoM, 2016). For most countries in Africa, there is a recognized immediate challenge to increase data collection, improve forest monitoring, develop measurement standards and protocols, define appropriate mitigation measures, and expand overall technical means. An optimal approach would be one that uses current capacities or readily available and tested best practices for making measurements compatible with IPCC guidelines and protocols. This study demonstrates that countries like Malawi do not have to go elsewhere to acquire their measurements but can readily develop and own the necessary national technical capacity to deliver robust MRV functions from a National Forest Monitoring System.

CHAPTER 3: ANALYSIS OF TREE GROWTH FROM HARVESTED DOMINANT NATURAL TREES FROM LIWONDE FOREST RESERVE

3.1 Introduction

Tree rings provide a wealth of valuable information about a tree's growth patterns and development over time. By examining the width and characteristics of the individual rings, scientists and researchers can gain insights into a variety of important factors related to the tree's growth (Klesse et al., 2016; Worbes, 1989). While tree growth focuses on the physical development of the tree itself, biomass accumulation incorporates the total organic matter stored within the tree or forest ecosystem (Hyvonen et al., 2007; Fahey et al., 2010). Tree growth contributes to biomass accumulation as trees increase in size and add more organic material to their structure over time (Hilty et al., 2021). Understanding both individual tree growth and biomass accumulation is essential for assessing forest productivity and carbon storage capacity (Bowman et al., 2013). Dendrochronology can be used to estimate tree growth and retrospective biomass accumulation in forests (Frank et al., 2022).

When researchers analyze the width and characteristics of the annual growth rings, they gain information about a tree’s age and timeline, environmental conditions that have influenced its growth and its growth rates (Peters et al., 2015). Additionally, they can quantify annual and long-term growth trends, identify periods of stress or favorable conditions, reconstruct past environmental conditions and establish historical timelines and age estimates (George, 2014). Most of the tropical regions have at least a minimum of 2-3 months of dry conditions which allows the use of dendrochronological methods developed for temperate zones (Schweingruber, 2012). It is this seasonality that affects the formation of growth rings (Hughes et al., 2002). Research on tree ring analysis is extensive and keeps going on in the African with reviews compiled of tree species with proven annual ring formation from different tropical biomes (Mbow et al., 2013; David et al., 2014; Quesada-Roman et al., 2022).

However, the limiting factor for conducting dendrochronology research in the tropics of Africa has been the lack of suitable tree species that form distinct annual growth rings (Worbes, 2002). This is due to the relatively uniform climatic conditions in the tropics, which lack the distinct seasonal changes that drive the formation of clear annual growth patterns in temperate regions (Frank et al., 2022; Hughes 2002). Many tropical African tree species exhibit continuous growth rather than distinct growth periods, making it challenging to identify and count annual rings (Groenendjik, 2015). Additionally, the dense and inaccessible nature of the tropical forests, as well as the large size of the trees, makes it difficult to collect the necessary tree core samples. The scarcity of long-lived tree species in the tropics further limits the ability to obtain the long-term records required for dendrochronological studies. (Rozendaal and Zuidema, 2011; Groenendjik, 2015).

The importance and interest in tree growth characteristics and forest carrying carbon capacities has also increased with climate change research (Nunes et al., 2020). The Food and Agricultural Organization (FAO) global forests report (2020) estimates that there is about 605 Gt C stored in forest ecosystems, with regions with tropical forests having the highest biomass stock per hectare with values above 200 tons per ha in South America and Western and Central Africa. Forest ecosystems have a vital role in the carbon cycling in terrestrial ecosystems and account for 76% of biomass carbon and 42% of the annual net primary productivity of terrestrial vegetation (FAO, 2020; Fan et al., 2008). The global biomass stock decreased by about 8 Gt between 1990 and 2020 with the largest decrease registered in Africa and South America due to the decline in forest area in these regions. Which brings us to consider tree growth and biomass accumulation in the forests of Malawi.

Biomass can be measured by using destructive and non-destructive methods. The destructive/harvest method is the most direct method for estimation of above-ground biomass and the carbon stocks stored in the forest ecosystems (Burt et al., 2021; Brown, 1997). However, the disadvantages of the destructive method are that it is time-consuming, resource-intensive, strenuous, and expensive, making it impractical for large-scale analyses. In contrast, the non-destructive method offers a more feasible alternative, especially for ecosystems with rare or protected tree species where harvesting is not viable. Estimating the biomass of a tree without felling it, utilizing allometric equations and biomass estimation techniques, provides a practical solution for situations where the harvesting of vegetation is not an option, allowing for the assessment of biomass and carbon stocks in a manner that is less disruptive to the ecosystem. (Siddiq et al., 2021; Brown 1997).

Productivity and biomass are interconnected aspects of ecosystem dynamics, with productivity influencing biomass accumulation and vice versa. Higher productivity leads to increased biomass accumulation as more organic matter is produced and stored within an ecosystem (Prommer et al., 2020). Ecosystems with high productivity levels tend to have higher biomass due to the efficient conversion of energy into biomass by plants (Keeling and Phillips, 2007).

Two approaches have been used to establish the relationship between productivity and biomass. The first one uses a direct relationship between productivity and biomass based on the assumption that productivity is the source of biomass (Keeling and Phillips, 2007). Studies in China and the US by Whittaker and Likens (1973) and Ni et al. (2001) have reported linear relationship between aboveground net primary productivity and the aboveground biomass. The second one is based on the metabolic theory of ecology, (e.g., West et al., 1999, Niklas and Enquist, 2001, Brown et al., 2004, Cheng et al., 2009), it states that, "If tree productivity is a reasonable surrogate for metabolic rate, the rate of production P and biomass M can be described by a power function": P = aMb, where a is a normalization constant and b represents an allometric scaling exponent. Whether or not the value of the scaling exponent b is a constant is still debatable, the form of the allometric relationship has been widely accepted (Hui et al., 2012).

I used a destructive sample approach in this study. I collected discs from randomly sampled trees using information from permanent plots that were established in Liwonde forest reserve. In this study I analyze tree ring width increment using dendrochronology techniques (Frank et al., 2022; Worbes and Schongart, 2019). Previous work by Mbow, et al., (2012) and David et al., (2014) demonstrated the potential to extrapolate historical patterns of diameter growth to understand annual aboveground biomass and carbon dynamics in the dry savannah and Kenya. The data set I created allowed us to make inferences about tree growth in the reserve on the assumption that tree productivity and biomass were not much influenced by other derivative information such as elevation within the Liwonde forest reserve. I set out to develop an overall relationship between tree age (forest productivity) and biomass using a linear regression model.

Growth is most strongly influenced by tree size and yet growing conditions can affect tree growth patterns which is why foresters include site quality in their models of tree growth (Hilty et al., 2021; David et al., 2014). Additionally, I developed a set of equations for estimating tree age from knowledge of diameter at breast height (DBH) and used it to develop a DBH and age relationship. I also explore whether the increment I effected on the inventory data had influence on the size class distribution. Our motivation to use tree-ring analysis is based on the ability it provides foresters to obtain local and species-specific growth data and tree ages (Pommerening et al., 2021) that can be used to plan and evaluate forest management.

3.2 Materials and methods

3.3 Study site

Liwonde Forest Reserve is in Machinga district in Southern Malawi. It is one of the many forest reserves that are threatened due to collection of firewood, timber, curios, pit-sawing, and charcoal production. Encroachment and illegal settlements are common in the reserve due to the need for more Agriculture land from the rural communities surrounding it even though parts of it had been protected by a Eucalyptus plantation which acts as a buffer zone. The 26,472-hectare forest reserve is in a district that has the highest population density and smallest household farm size and the communities' dependence on the forest reserve for firewood is highest and, consequently, so is its food insecurity (GoM, 2018).

The forest vegetation in Liwonde Forest Reserve fits the description of Miombo woodlands as described by Frost, (1996) as characterized by open, dry deciduous forests dominated by tree species from the *Brachystegia, Julbernardia,* and *Isoberlinia* genera. Chidumayo (1997) further described them as a continuous canopy of trees, which can reach heights of 15-20 meters and shed their leaves during the dry season. Liwonde, which is in Machinga district, is characterized by distinct wet and dry seasons with almost no rainfall in the months of June-October and about 80-90% of the annual precipitation falls in December–March. The average rainfall data covering the last 30 years (1984–2014) indicates that the area receives an average annual precipitation of 1031.21 ± 246.93 mm. The mean annual temperature is 22.28°C.

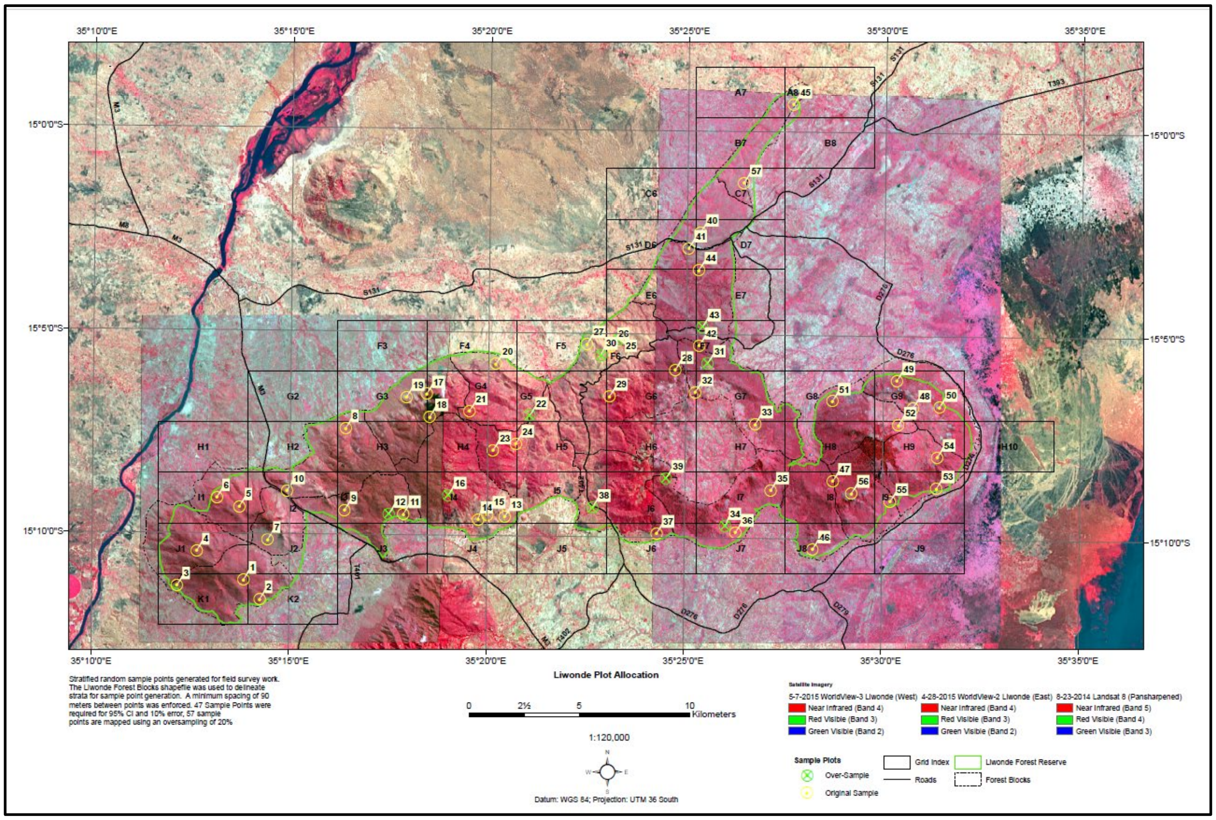

Figure 11: A map showing the location of Liwonde forest reserve and permanent plot information from the 2016 forestry inventory.

3.4 Study procedure

This study used dendrochronological analysis results to estimate biomass increment per individual tree from destructively sampled trees from Liwonde forest. The trees included in the analysis were purposively sampled from existing permanent plots. The choice to collect discs from already existing sample plots was systematic as the permanent plots were also randomly generated. The permanent sample plots were established in Liwonde Forest Reserve 2016 as part of a national forest inventory effort nationwide (See inventory protocol appendix A). National Forestry Inventories (NFI) come in two primary forms: periodic and continuous. Periodic NFIs occur at regular intervals, typically every five to ten years, while continuous NFIs involve ongoing monitoring, providing frequent updates as required by the forestry sector or other stakeholders. NFIs play a crucial role by offering current and specific data on a country's forests (Mandallaz, 2007). The NFI sampling is used as a process to obtain information by surveying only a portion of the whole to draw inferences overall (Köhl et al. 2007), this motivated us to use the permanent sample plots as disc collection points.

Permanent sample plots (PSP) are established and measured at intervals of two to five years to get improved estimates of successive volumes through inventory (Poso, 2006; Synott, 1975). The purposive sampling technique is a non-probability sampling method where the researcher selects specific individuals or groups that meet certain criteria or characteristics relevant to the research question (Palinkas et al., 2016). Our intention for collecting tree discs was to establish growth rates across different species within the reserve, and I was mindful of the importance of selecting individual trees that are critical to understanding a species' growth according to our objective. As Morse and Niehaus (2009) observed, sampling methods are intended to maximize the efficiency and validity of subjects under investigation whether the methodology employed is quantitative or qualitative.

The discs were collected at 1.3 m above the base of the tree as a routinely applied silvicultural measurement, which is tree diameter at breast height (DBH) except in cases where there was a knot, then discs were collected below the 1.3 m level. This was the case as taking measurements as this height allows tree-ring width measurements to be more readily compared, and integrated, with periodic surveys of tree size (Evans et al. 2017). Additionally, when collecting discs at this height one mitigates growth irregularities at the same time it allows for the collection of most tree rings and is mostly convenient for the physical collection of the sample (Altman, 2020; Frank et al., 2022).

The tree disc collection was done by randomly selecting trees from a size class range of 5cm to a maximum of 35cm in the established permanent plots see figure 12 below showing the plots where trees were collected from. I collected a total of 60 discs from 30 established permanents plots. Tree-ring information provides size class species-specific ring width increment data that can be used to improve the projections of how much biomass an individual tree accumulates in each period.

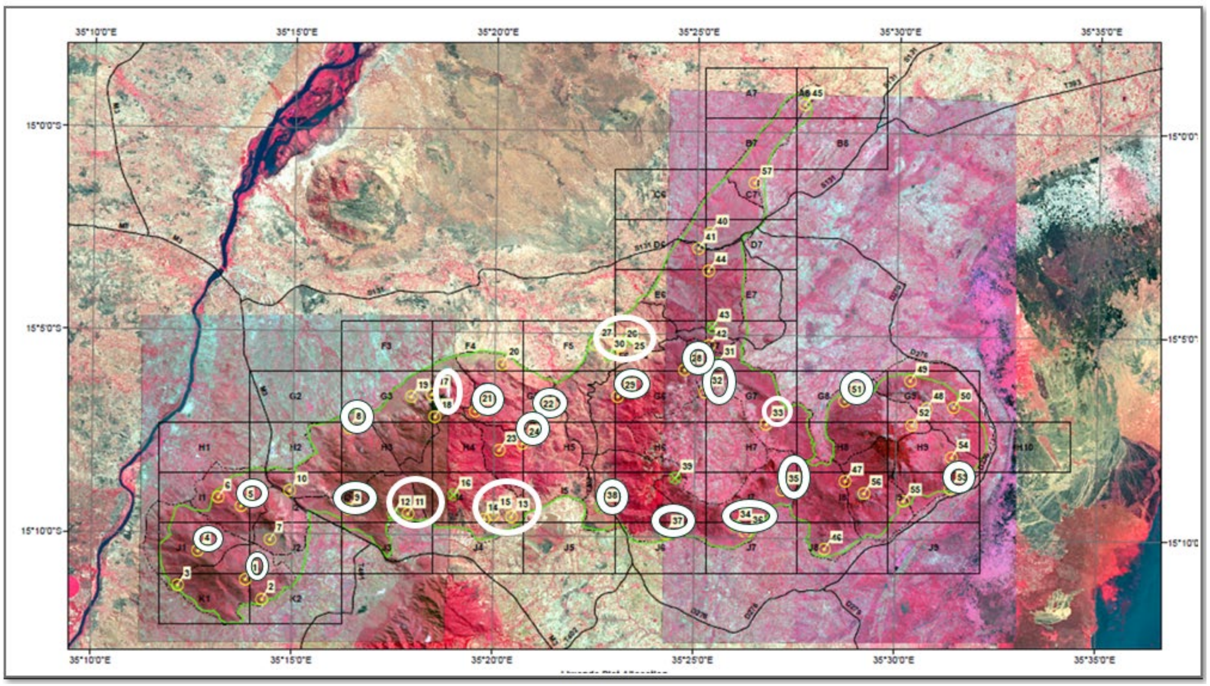

Figure 12: Points of field collection from where the dendrochronology discs were collected using destructive sampling.

This study aimed at determining growth rates of dominant species in Liwonde forest reserve using dendrochronological analysis which will be an important input in the development of a future harvesting or strategic plan for the reserve. Knowledge of these species' annual increment is important in that it will also inform management on their biomass accumulation over time.

3.4.1 Tree identification and disc collection procedure at each plot

Information about the species and size class composition of each permanent sample plot was collected from Forest Research Institute of Malawi and the Protecting Forestry Ecosystems in Malawi (PERFORM) project archives. The project focused on sustainable land management, biodiversity conservation, and climate change mitigation in Malawi and commissioned the inventory process which was designed and guided by Michigan State University (Skole and Samek, 2016). The knowledge of size and species composition guided the process of deciding which of the permanent sample plots would potentially provide discs for inclusion in the study. For example, in the plots that were recorded to be dominated by smaller size diameters<10cm, they were automatically assigned to be sampled for the small size class (see Appendix F-Size class per plot). Additionally, I considered abundance of species within a permanent plot in deciding whether it qualified to collect samples from. For example, if a plot had less than 10 smaller diameter trees in total., I didn't collect any samples from it within this size class. I did not collect any tree discs from Plot 29 since it showed on the data sheets it only had 7 trees in total, one being above 30cm. Small size diameters are prone to dying and mortality could be linked to the size and health of neighboring trees, especially concerning biotic factors, which implies that the response to neighboring tree mortality doesn't always result in increased growth at the individual scale (Chin et al., 2023).

Once at the plot, I randomly selected a tree from the inventoried data, from which a desired size class was purposefully selected for inclusion in the disc sample. Since the priority was to build a generalized growth rate for the reserve, the collection of discs was more informed by size class than species. The GPS coordinates were recorded for each sample plot where a tree was felled. Measurements taken for each tree prior to felling included tree height (m) and diameter at breast height (cm). The trees were felled using a chain saw and in some cases the tree split, samples were not collected from trees that split during felling or had a heart rot after drying. The remainder of the tree after disc sample collection was given to the community members who were part of the team.

Each of the sampled trees was felled at the thickest part of the trunk to ensure that maximum growth was accounted for, thus the height and width of each sample varied. A single disc was collected from each of the sampled trees. The discs I sampled varied in width between 50-350 mm. Discs were wrapped in newspaper to absorb moisture, labelled, and packed in containers for storage and transported back to the laboratory at Malawi College of Forestry and Wildlife (MCFW) in Dedza after the field work.

3.4.2 Number of discs analyzed, and challenges encountered in samples collection.

Representative samples of trees were predetermined from examination of the 2016 Malawi national inventory plots datasets for Liwonde reserve. I sub sampled 30 plot locations (out of 47 in the inventory) as shown in figure 12 based on the information I had and pre-selected them for tree harvest. Once I got to each plot location, I collected two trees with stem 5< diameter <35 selected and harvested those. I collected 60 discs in total., but our analysis only considers usable discs (45 out of 60) which is more than the 20 trees that had initially been recommended by Fritts (1967) or two dozen trees sampled from a location of interest (Frank et al., 2022). During the disc collection process as explained in the section above. Some of the reasons I was not able to analyze all the discs I collected during field collection and after bringing them to the lab as listed below.

1. Heart rot observed after felling, e.g., most of the *Brachystegia boehmii* species.

2. Improper tree splitting during felling affecting the collection of the samples.
3. Loss of the center of the sample disc after drying, mostly in *Brachystegia boehmii* and
4. Failure to read or tell most of the growth in some of the *Brachystegia spiciformis* and *bussei* discs.

Where there is more than one species as was the case in this study, David et al., (2014), suggested categorizing the species' sample in terms of difficulty in determining the rings. Since these trees belonged to the same geographic locality, the assumption is that they were influenced by similar climatic conditions. This is recommended by Frank et al., (2022) who explain that where trees are hypothesized to be in the same ecological setting, they are typically cross dated and analyzed together.

3.4.3 Disc preparation before analysis

Upon getting the discs to the laboratory, the specimens were prepared for analysis after they had been sun and air dried for 6-8 weeks. A belt sander (Makita 40Japan) was then used to prepare them for analysis by starting with a coarse 400-grit paper, and progressively to a finer 600-grit. Discs were polished with increasingly finer sandpaper to ensure they could be easily analyzed (Gartner & Nievergelt, 2010). After clearing and cleaning the sanded part of the disc, then for each disc I started by identifying and dating the innermost to the outermost ring, and then measured and recorded each growth in the same sequence, each increment signifying a year's growth as explained by Fritts (1976).

3.4.4 Tree ring width analysis

Tree-ring width measurements are often done under a stereomicroscope except in cases where rings can be sufficiently resolved with flatbed scanners, digital cameras, or imaged from thin sections (Frank et al., 2022). As a first step on the disc surface, I evaluated whether continuous tree rings could be identified around the stem circumference. I followed the anatomical features that define ring boundaries. Concentric growth rings around the entire cross-section of sample discs were detected and marked. The evaluation process, as laid out by Worbes and Fichtler (2010), is meant to assist in the detection of phenomena that can obscure ring detection e.g., wedging rings, and intra-annual growth variations. There are different software packages that can be used in the identification of rings e.g, WinDENDRO™, CDendro & CooRecorder, LignoVision™ (Fabijańska & Danek 2018). The discs in this study were analyzed with a flatbed scanner and where rings seemed not too clear, a magnifying glass was used.

3.4.5 Total tree ring width (radius)

The ring width determination was estimated by direct measurement on the surface of each disc from the pith (center) towards the bark using a magnifying hand lens over a calibrated transparent ruler. The measurement of the length of the radius was done at the end, which was the sum of the ring width points that had been established on a chosen radial direction. The radius (ring width) was then converted to a diameter. I calculated for each species average diameter growth rates (in mm/year) per tree age as it allowed us to do a comparison of patterns in growth rates between species whose samples I had collected. Since I did not have any growth rates on record for Malawi species to compare them with, I then compared these average growth rates with the rates used in some Miombo forests (Varmola et al., 2008, Mugasha et al., 2014, Chidumayo 2013, Kuyah et al., 2014).

3.4.6 Biomass ring width percentage increment

The process involved recording tree ring values in Microsoft Excel and calculating the total radius from the various ring widths and converting it to a diameter. Biomass increments were determined using the Kachamba (2016) model, with area growth calculated using the circle area formula for each year. The ring width increments started from the earliest years to the end of the disc (chosen radius) or last year when I cut the tree. After labelling the starting value as V_a (first value) and labelling the final value as *Vz* (final value) or any difference between any identified ring width, this difference gave us the length of the radius. The second step was recording the increments in years as observed on the identified radius for each disc. For example, a *B. bussei* disc with 11 recorded increments that added up to a 4.5cm radius. Each of these 11 was treated and recorded separately. That meant that this disc would have 11 separate entries of its own in a row in excel. I then proceeded converting the radius (ring width) to a diameter. I did so by calculating the biomass of the increment using the Kachamba (2016) allometric model. Essentially, the formula for the area of a circle was used to calculate the current (t) and previous (t-1) years' area growth.

The third step was then to determine the percentage change, which I calculated by subtracting V_2-V_1, then dividing it by V_1 to get the total percentage change. This was our biomass ring width percentage increment for that particular year, and the difference between these two areas is a representation of annual biomass area for each increment in ring width, it meant I had a calculated percentage change. For example, for a 72-year-old tree, I calculated 71 growth percentage points.

Each disc had percentage points equivalent to its age as identified by its rings. The next step was grouping these acquired percentage points by species and size class. This allowed us to come up with percentage growths rates for species as well as the various size classes. I arranged the biomass increment curves by species to get annual growth rates, by species and size class.

From these data I started creating the regression relationship between age and biomass, as shown below. I did this for each disc and further did the average biomass (for a given age) by genus, or for all discs. The example in figure 12 below is just disc 2, one of the 45 trees. The regression relationship is very tight, with R^2 of 99.

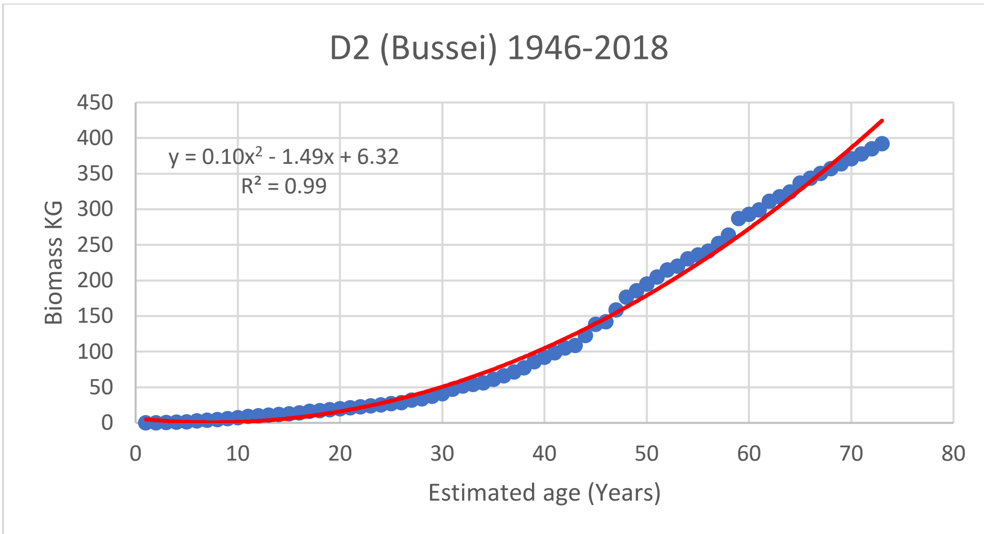

Figure 13 Disc number 2 of Brachystegia *bussei* showing the relationship between biomass increment to tree age.

By taking these same data I was then able to construct a similar age-related increment relationship. This is the biomass at time t minus the biomass at time t-1. I expressed it as a percentage growth per year of age, which is biomass at t minus biomass at t-1 divided by biomass at t. This is shown in figure 13 below for disc 2.

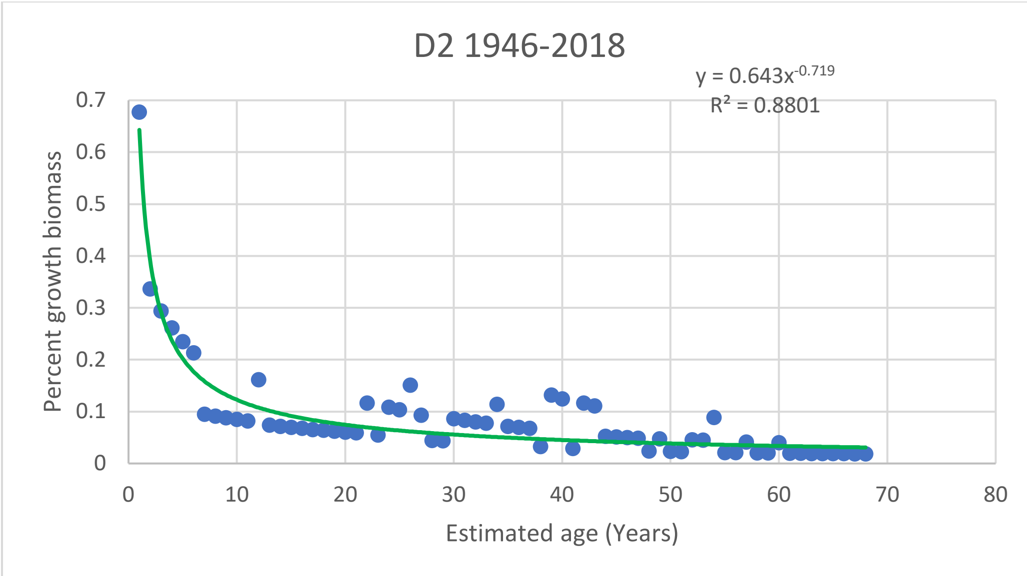

Figure 14: Disc number 2 of Brachystegia *bussei* showing the relationship between percentage growth increment and tree age.

I also observed that the relationship in percentage biomass growth and age was better in older trees discs, unlike in the younger ones as shown in the figure below.

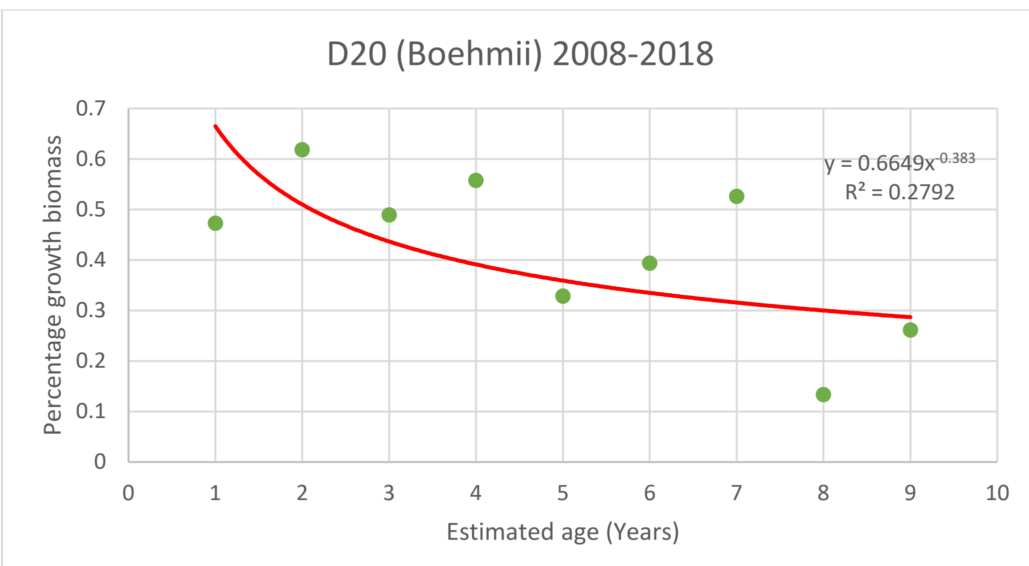

Figure 15: Disc number 20 of Brachystegia *boehmii* showing the relationship between biomass increment to tree age.

From the presentation in the figures above (13,14 and 15) I came up with two models. The first is the absolute biomass by age. The second is the relative growth rate by age. But I do not have the relationship between age and DBH. This is important because it will be more likely to be able to measure a tree DBH than its age; indeed, it will be impossible to measure tree ages for all trees in a landscape or for any tree not harvested.

So, since I needed a relationship between DBH and age. Below is an example where I plotted the 45-tree discs. I plotted age on the X axis and the dependent variable is DBH – i.e., which is what I wanted to predict. Overall, based on R^2, there is a very strong correlation between age and DBH growth. I further show the breakout by younger (smaller) vs older (larger) trees, and the R^2 is lower in the smaller tree discs than from the older tree discs.

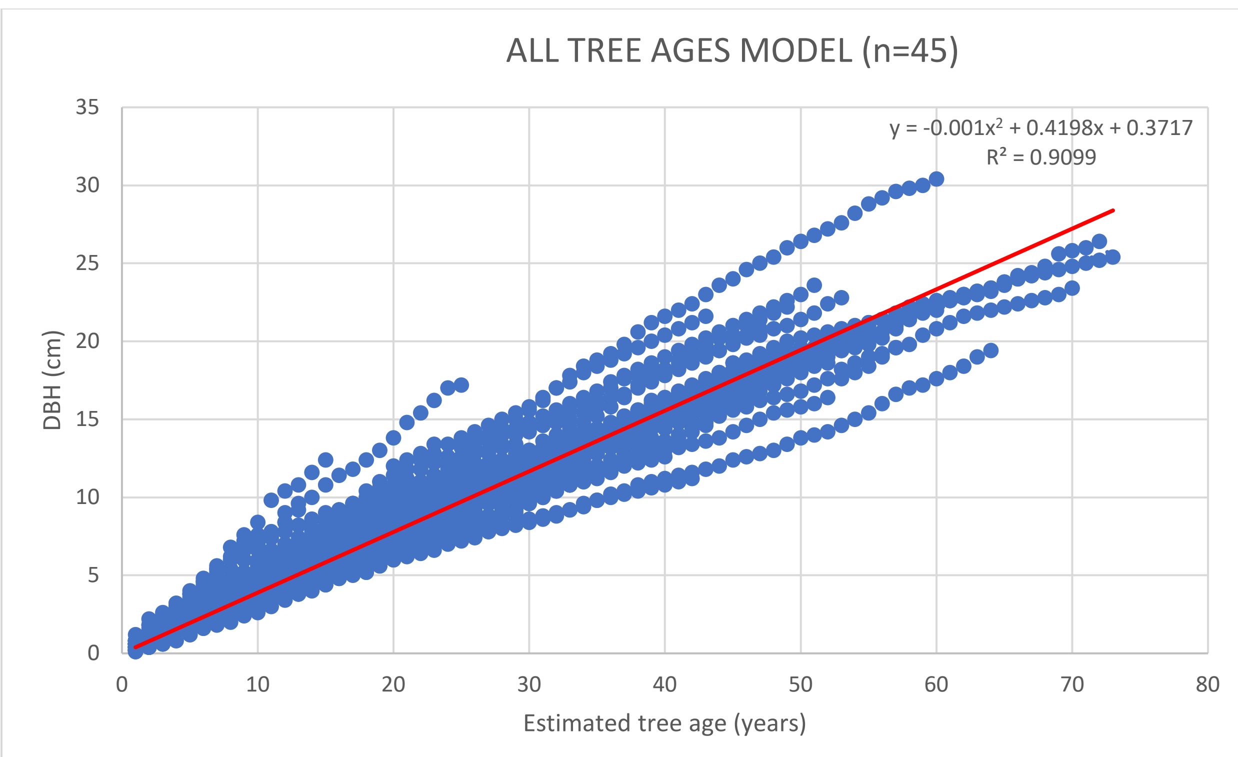

Figure 16: The relationship between DBH and age for all the discs.

I also show the breakout by younger (smaller) vs older (larger) trees, and the R^2 is lower, especially for older trees but the models may be better.

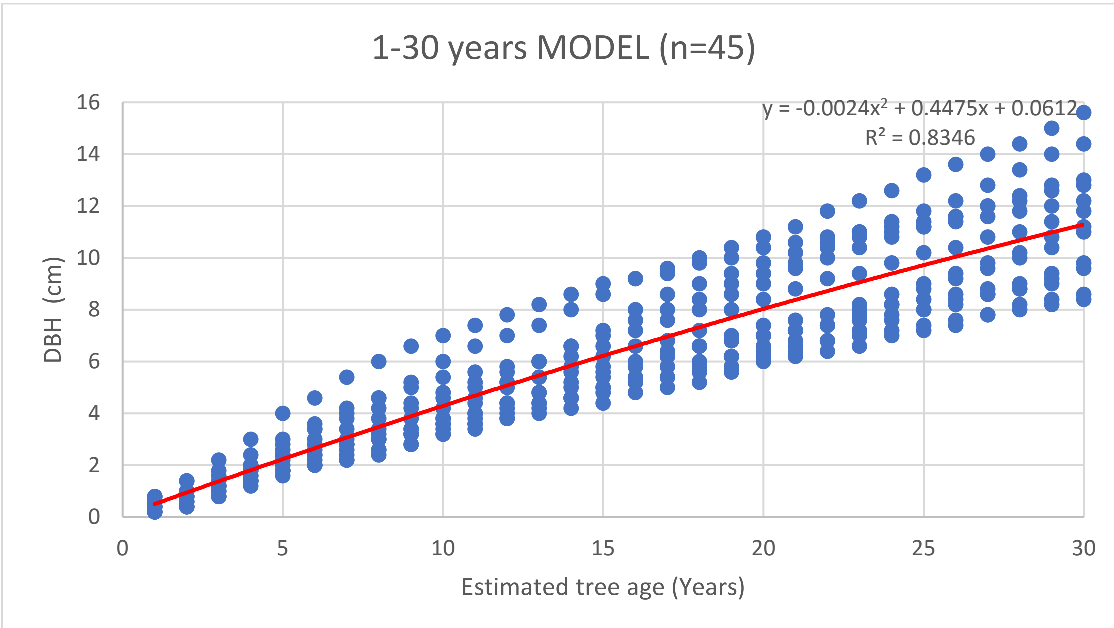

Figure 17: The 1–30-year relationship between DBH-Age.

The R^2 is lower for the 1–30-year relationship as compared to the greater than 30 years but improves greatly as shown in Figure 18 (below for the >30cm DBH).

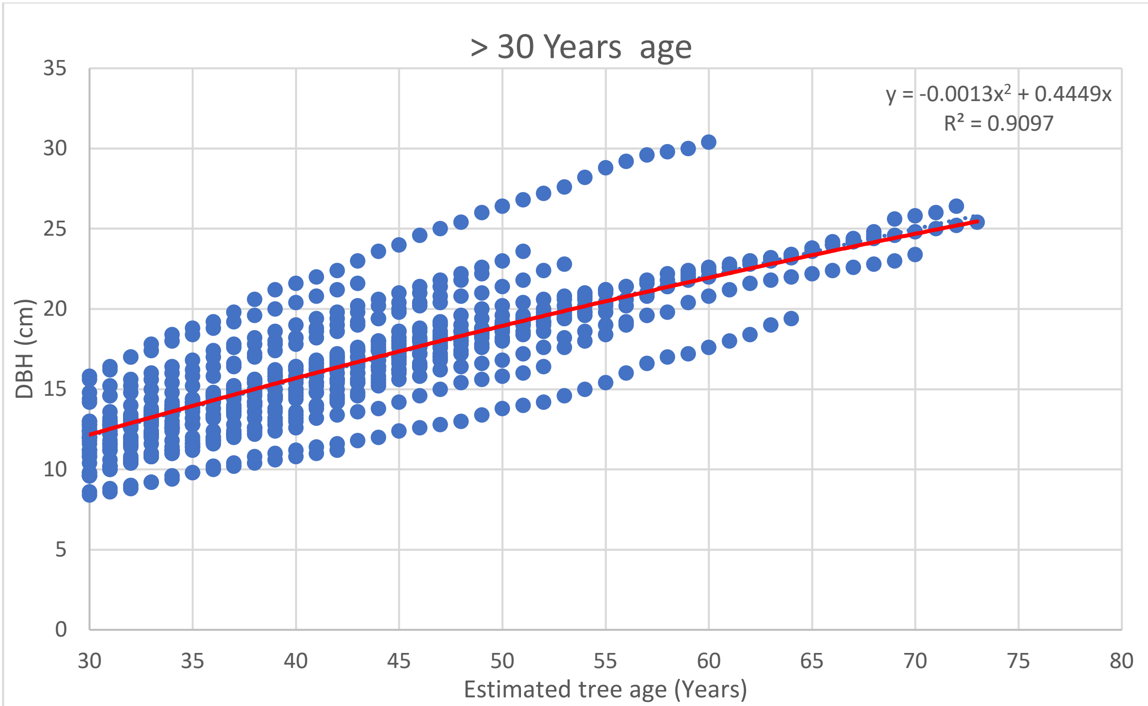

Figure 18: The relationship between DBH-AGE for Discs >30 Years.

3.5 Results

This section presents the results according to the laid-out methodology and then links them to the study objectives. It presents an in-depth view of the results and further explains how the process resulted in the choice of the preferred model and use of the combined species and size class values for estimating biomass and disc increment respectively.

3.5.1 Ring width and percentage increment on discs.

Table 4 below shows the combination of the species and size class biomass ring width percentage increments. I used the size class and species combination to create a third option of the averages of the two. I then proceeded to use the table to guide us in deciding what percentage I was going to apply for the individual trees from the forest inventory, to estimate the new size for the trees in 2017. Averages were used for all the species and size class I did not have information on from the dendrochronology analysis.

Table 4: Biomass ring width percentage table for species and size class calculations

	Tree Size class (diameter)	5-9.99cm	10-14.9cm	15-19.9cm	20-24.99cm	25cm above
Species		17%	8%	6%	4%	3%
Brachystegia *boehmii*	13%	15%	11%	10%	9%	8%
Brachystegia *bussei*	15%	16%	12%	11%	10%	9%
Brachystegia *utilis*	18%	18%	13%	12%	11%	11%
Brachystegia *spiciformis*	11%	14%	10%	9%	8%	7%

Table 4 (cont'd).

Uapaca *kirkiana*	18%	18%	13%	12%	11%	11%
Julbernardia *globiflora*	18%	18%	13%	12%	11%	11%
Diplorrhynchus *condylocarpon*	18%	18%	13%	12%	11%	11%
Brachystegia genus	16%	17%	12%	11%	10%	10%

By looking at the table on average the younger (5-15cm size class) discs have substantially higher biomass ring width percentage increment than the older (>25cm size class).

3.5.2 Analysis of size class

For each plot I compared the size classes from the collected inventory data (Appendix C) and compared it with the increment factor from species and size class. The figures below show how the smaller and older size class trees experience the most change in numbers when I factor the growth increment.

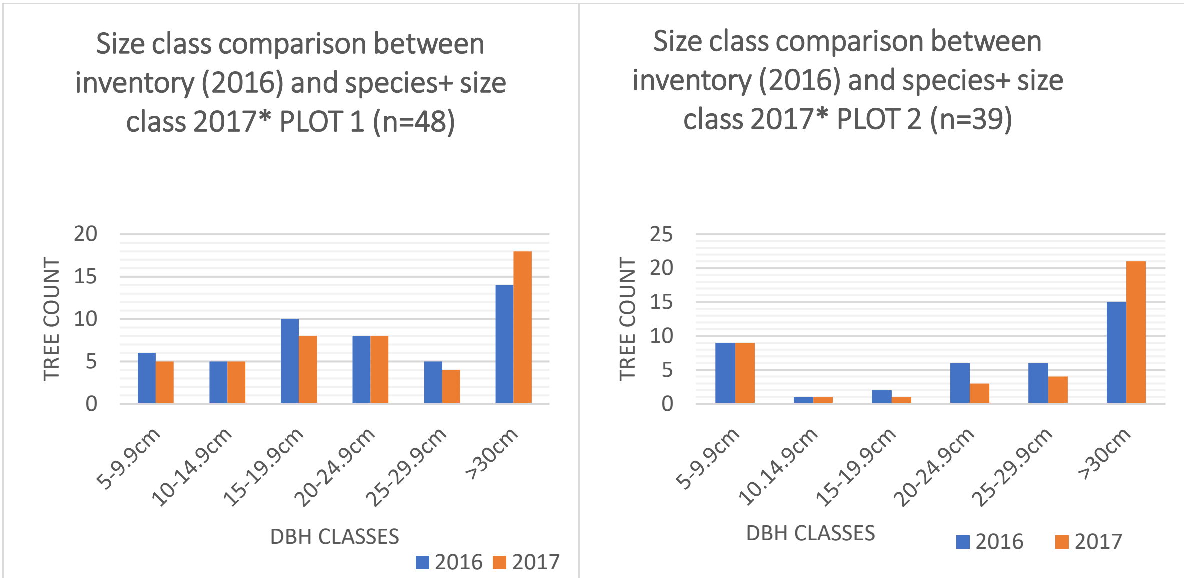

Figure 19: A comparison of size class between the inventory and growth increment in the subsequent year (Plot 1 and 2 examples).

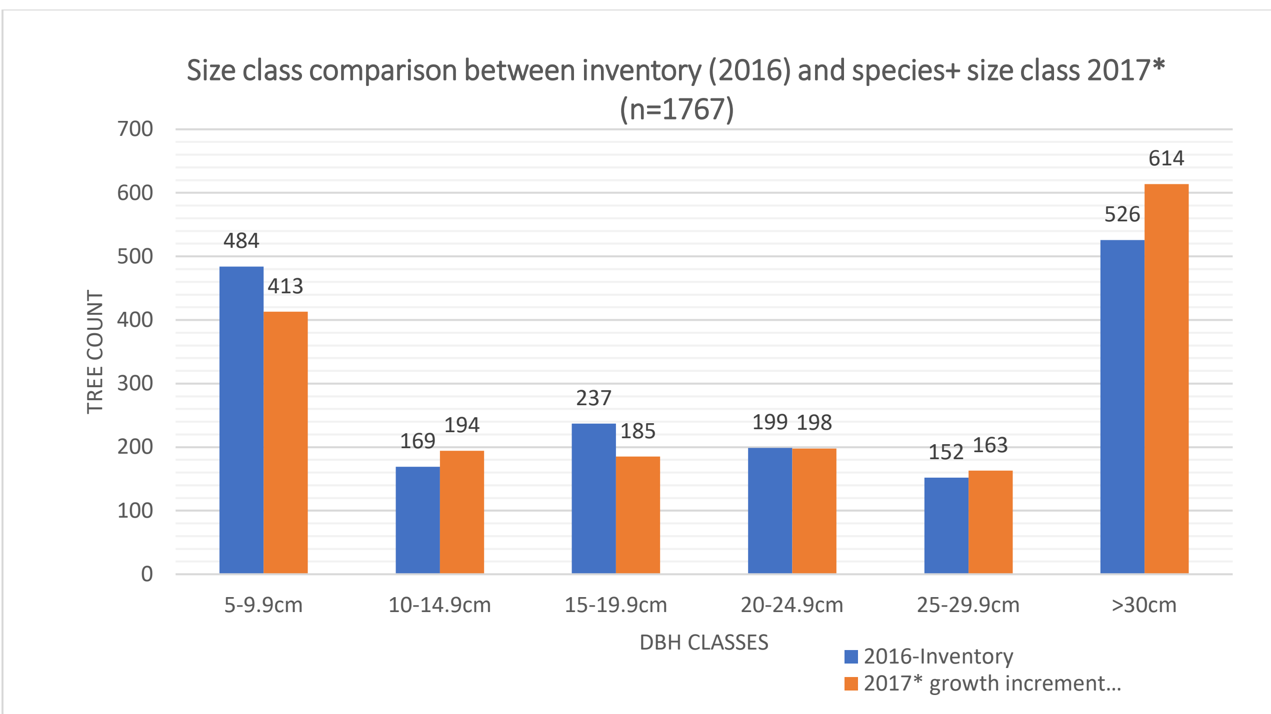

Figure 20: A comparison of size class between the inventory and growth increment in the subsequent year for all trees.

When you combine all plots as per the figure above the size class between 10cm -30cm do not seem to experience significant growth change to warrant a shift in classes compared to the above 30cm and below 5cm.

3.5.3 Species growth averages from tree ring width measurements

The growth rate of the Miombo tree species in Liwonde was on average 1.98±0.02 mm, with an average range between species from 1.85 mm to 2.97 mm (Table 7).

Table 5: Table of species average growth rates from the dendrochronological analysis

Species	Sample size (n)	Growth ring width (mm)	
Brachystegia bussei	11	1.94	± 0.05[cde]
Brachystegia boehmii	11	1.89	± 0.05[de]
Brachystegia utilis	2	2.14	± 0.13[c]
Brachystegia spiciformis	12	1.85	± 0.04[e]
Julbernardia globiflora	3	2.97	± 0.16[a]
Uapaca kirkiana	2	2.04	± 0.08[cd]
Diplorrhynchus condylocarpon	3	2.60	± 0.11[b]
Pterocarpus angolensis	1	2.00	± 0.16[cde]
Mean		1.98	± 0.02

Mean values are followed by standard errors.

Means with different superscript within a column in the same category significantly differ ($P \leq 0.05$)

3.5.4 Allometric model comparison for estimating biomass.

In this section I present results showing the difference in biomass estimation per disc from 4 allometric models developed for the Miombo in sub–Saharan Africa. The Kachamba (2016), Mugasha (2013), Kuyah (2014) and Chidumayo (2014) allometric models are shown in the figures below and the rest are shown in Appendix B. The Kachamba showed it gave higher estimates compared to the other 3 allometric models.

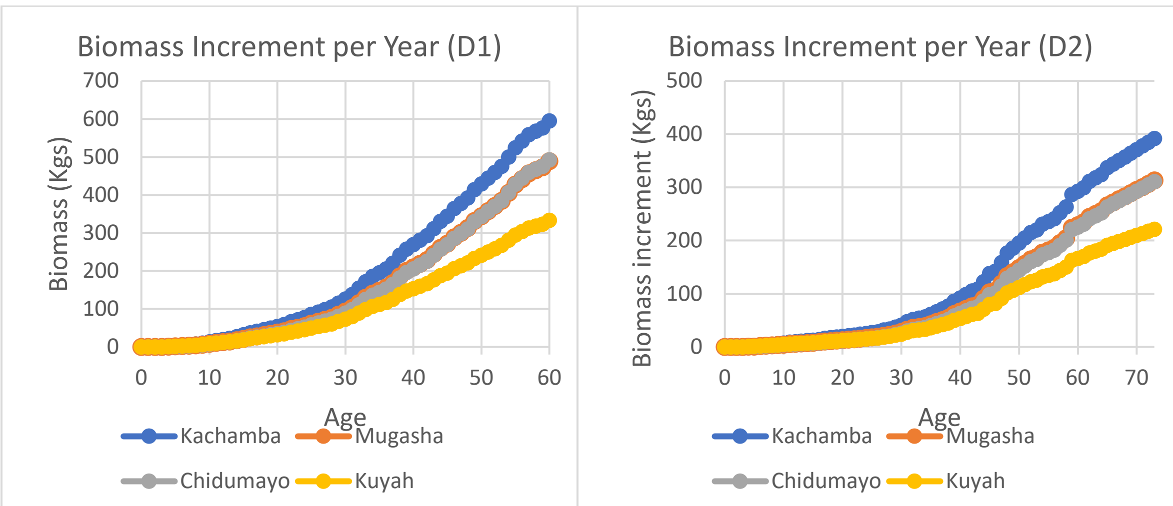

Figure 21: A comparison of models in estimating biomass for discs 1 and 2.

The same pattern is depicted in all the discs (see Appendix B), which supported our decision to run our calculations with the country specific allometry model by Kachamba (2016).

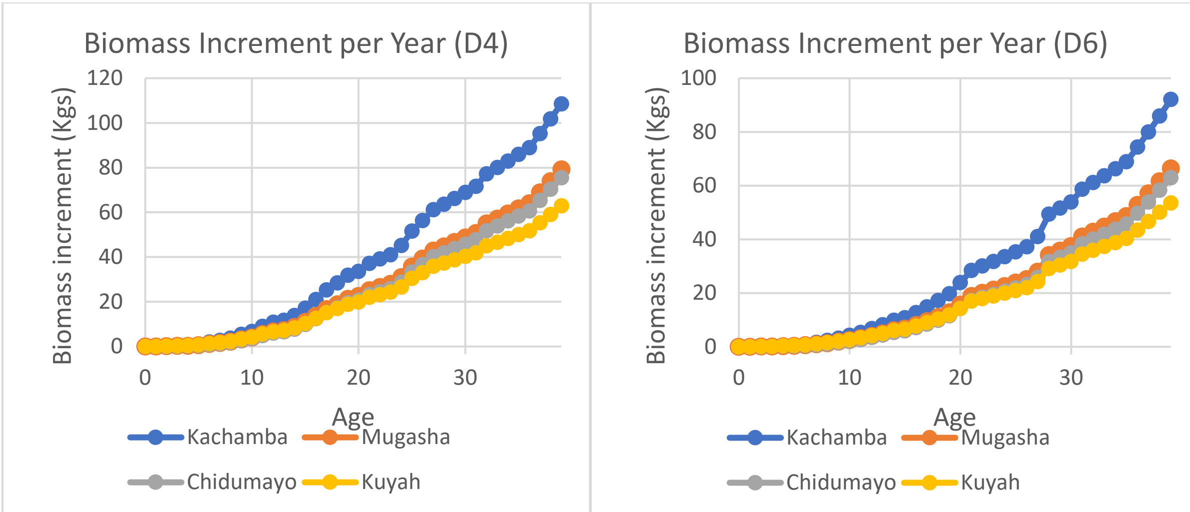

Figure 22: A comparison of models in estimating biomass for discs 4 and 6.

3.6 Discussion

Tree sampling in this study was carried out following an even distribution of diameter classes. The size class distribution was between 5cm-30cm which indicates that most of the trees (84%, n=45) were between the diameters of 10 and 30 cm. This agrees with Saint-André *et al*. (2004) as well as Samalca (2007) who recommended that an even distribution of diameter classes where small and big diameter trees should be included in biomass studies to maximize the representation of models. There were few tree species observed in the above 50cm diameter class during the forestry inventory which could be attributed to limited number of species that naturally grow up to larger diameter (Hadi et al.,2009) but in the case of Liwonde, with illegal charcoal and timber production being rampant, the diameter class is desirable for charcoal making and hence easily prone to being cut or utilized.

Most of the identified Miombo species are characterized by slow growth rates (Chidumayo, 2019). The growth rates average 1.85 mm to 2.97 mm/yr. in our study. This is close to what was reported in Tanzania by Varmola (2008) 1.8 mm to 7.0 mm/yr. Miombo trees across various studies in Tanzania. These low growth rates require that Liwonde forest reserve should have long term, adaptable plans targeted at successful tree management and succession. Similarly, species in the dry Miombo of Zambia are reported by Chidumayo, (2019) to grow at an average rate of 1.5mm/yr. in uneven-aged old-growth stands, with no significant annual differences although they observed variations among specific species were significantly large. Schwartz et al., (2022) suggested that the slow and episodic growth of smaller sizes influences overall growth patterns. They observed a slow growth of about 1 mm/yr. in *Pterocarpus angolensis* in Tanzanian forests. From our results I was able to observe a notable shift in size classes in the DBH < 10 cm and DBH ≥ 30 cm size classes (Appendix C).

Based on the large database of inventory data and biomass for Liwonde Forest Reserve we derived the relationship between DBH and tree age using both linear regression and allometric equations. I found both the linear regression model and the power function provided statistically significant fits (Appendix B) which is in line with studies by Chengetal., (2009) and Hui et al., (2012), who developed the relationships between forest productivity and biomass with both a linear regression model and an allometric equation.

An interesting finding was that when splitting the whole data base into different tree-age, the larger tree R^2 was better in prediction than the smaller trees (using a cutoff point of 1-30 years for the smaller trees ages and any above 30 ears considered old). The regression relationships assisted in coming up with the Age predictor equations for the species under investigation (Figure 17: Section 3.1.6). Using these and by substitution, one can easily predict the age of a tree, its diameter and carbon content at any given time (t). Tree age is important for understanding tree growth and forest dynamics (Worbes and Schongart, 2020). I am mindful of how results from empirical studies can differ significantly from the predictions of terrestrial biosphere models as discussed by Moorcroft (2006) but still encourages their development.

The analysis of the disc data provides evidence of a substantial biomass carbon sink in the young and old-growth forests of Liwonde Forest Reserve. There is continued increment in size of all the trees that were used in the analysis regardless of how small the increment was (3%) from the larger tree diameter (size class >25cm from our sample). Our observation and results on the size class increment agree with Hoover and Smith (2023) that while tree carbon increases in absolute terms, it decreases as a percentage of the previous stock.

By using long-term inventory plots in tropical forests (Clark, 2004) observed that some tree measurements can produce inflated estimates of biomass and biomass change. Our panel data shows that the trees keep accumulating carbon over time as their diameter increases which shows a high potential for carbon sequestration. This supports work by Bombelli et al., (2009) whose observation was that African forests have a high potential for carbon sequestration and had called for further investigations on this potential (Jindall et al., 2008; Bombelli et al., 2009). The forest reserve, if left undisturbed, would be suitable for involvement in Payment for Ecosystem Services (PES) and REDD+ as it has been suggested by the government to engage projects at a subnational and local level. Our results have begun to generate accurate data on carbon stocks and carbon stock change over time which is of particular interest to many for developing countries that are interested in taking part in REDD+.

The comparison of calculating biomass from the discs clearly shows (Section 3.5.4) that the Kachamba (2016) equation is the most suitable for Miombo in Malawi from a sink and carbon perspective since the forests are stocking high carbon numbers as it gives a better return of biomass prediction than the other 3 allometric models it is compared to. The biomass yields are comparable to the national average for Miombo woodlands in Malawi at 45.9 ± 3.9 t C ha^{-1} (GoM, 2022). Our results align closely with figures reported for Zambia (41.2 t C ha^{-1}) and Tanzania (33.6 t C ha^{-1}) but lower than what Missanjo et al., (2015) reported for Dzalanyama forest reserve at 50.8 t C ha. These results are important as continued measurement will help bring attention and correct estimates as Openshaw (1977) reported that the Miombo were underestimated in their growth and biomass increment. This supports the need to have a country specific model as suggested by IPCC (2008) when calculating biomass/carbon under programs such as REDD+ is the best way forward considering the discrepancies in data collection and results that might be produced.

I am also mindful of the difficulty in the description of tree populations as well as their modelling due to fundamental demographic processes driving forest dynamics as reported by Lamonica et al., (2020). This is evidenced by a low disc count for species I collected such *Pterocarpus angolensis* in our study, but I recognize other factors such as recruitment and mortality that influence spatial arrangement and size structure of neighboring trees.

Since natural regeneration is a key pillar for the sustainable management of the Miombo woodlands , if communities have plans to harvest insist on doing so, I recommend they adopt the method of coppice-with-standards systems (CWS) which entails harvesting whilst leaving a few valuable tree species behind as it has been proven to be best when compared to any other especially for the Miombo forests (Chirwa et al., 2009; Missanjo et al. 2014).

3.7 Conclusion

Our assessment of biomass growth in the 45 tropical forest stems (8 species) showed that individual biomass growth patterns often plateau for extended periods, with no significant difference in the growth increment. I can state that individual and aggregate patterns of biomass growth with size are distinct for each species whilst recognizing the need to collect and test more species. I understand that a good model is one that can satisfy the requirements of reliability, universal applicability, ease of use with minimum data and comprehensiveness in terms of the factors required to input (Morgan, 1995). However, no single model can satisfy all these requirements or is the “best” for all applications (Merritt et al., 2003). The choices of models thus generally depend upon the purpose for which they are needed, the accuracy and validity of the model, resources available and the scale and detail of application.

I recommend continued collection of tree discs from the additional permanent plots during the National Forestry Inventory. The continuous collection of these measurements allows for better documentation and this dataset provide a more robust basis for evaluating the biomass trends in Malawi’s forests.

3.8 Limitations

I am mindful that our use of growth percentage increments may be a satisfactory tool for forecasting tree growth over short periods, Aitken et al., (2008) point out that they might be unsafe for long periods due to uncertainty in extrapolating growth percent curves. Should there be continued data collection on growth from established plots, then that would supplement our proposed rates since forests capture and store different amounts of carbon at different speeds and depending on the average age of the trees in the stand and the number of trees in the stand, growth percentage increments may not be a good way to estimate biomass increase.

CHAPTER 4: ESTIMATING MAXIMUM SUSTAINABLE (BIOMASS) YIELD (MSY) FOR LIWONDE FOREST RESERVE.

4.1 Introduction

Fuelwood (firewood and charcoal) is one of the forest resources that is preferred by most rural people and many urban dwellers for cooking globally (Abanikannda & Abdulmalik, 2021). The 5th integrated household survey (GoM, 2020), a comprehensive socio-economic survey of living standards in Malawi, reported that 98.8% percent of the households were using solid fuels as the main fuel used for cooking and only 1.2 % of the remaining households used electricity. This heavy reliance on fuelwood has led to unsustainable utilization of forest resources and has led to the increase of deforestation rates, environmental degradation, loss of biodiversity and climatic problems in most countries (GoM, 2017). Fuelwood is mostly preferred because of its affordability and availability, compared with other sources of energy (GoM, 2018).

Fuelwood use as described above has been linked to poverty and the cost and availability of alternative fuels. Although there have been proven linkages between fuelwood use and income, to the rural masses the distances they cover and trouble they go through to meet their energy needs are not seen as priority problems as their concerns are more to do with income, health, and food security (Bandyopadhyay et al., 2011; Arnold et al. 2003). This necessitates a sector-wide approach to assess fuelwood and the most cost-effective options for improving access to modern energy, including efficiency and conservation (Chamdimba et al.,2021).

Sustainability in forestry management refers to management practices that ensure the long-term health, productivity, and resilience of forest ecosystems while meeting the needs of present and future generations (Kumar et al., 2021; Sample and Sedjo,1996). Sustainable forestry management aims to balance environmental, economic, and social considerations to promote the sustainable use of forest resources. Malawi, like all other countries the world over continues to explore ways of successfully managing its forests as they face enormous pressure from the ever-increasing population and a matching consumption for wood energy (Drigo, 2019).

There is a consensus that the Energy and Forestry sector policies in Malawi do not distinguish between rural household consumption and specific market demands, e.g. (wood fuel for tobacco curing) (Dewees 1995; Kambewa and Chiwaula, 2010; Bandyopadhyay et al., 2011; Schuneman et al., 2018). Each one of these, when treated differently, would have a separate and known impact which would require specific interventions to address (Zulu, 2010). What is also clear from most studies is the greater dependence on biomass energy for rural households than urban households. It is estimated that 90.9 % of households in the rural areas use firewood as fuel for cooking compared to 18.9 % of the households in urban areas. In urban areas 75% of the households in the urban areas use charcoal as their main fuel for cooking compared to 7.5% households in the rural areas (GoM, 2020) the population in rural areas was reported to be 14,929,187 whilst urban areas population was 2,634,562 (GoM, 2018).

The government has been trying to fast track the implementation of a substantial rural household electrification program. What is of concern is that the newly electrified households continue to use firewood or charcoal because of the high cost of appliances and the erratic supply of electricity by the service provider (GoM, 2018). The variety of cooking devices available to households in both rural and urban areas range in use from a combination of wood/charcoal coal stoves, open fires with three-legged pots, liquefied petroleum gas (LPG) stoves and electric stoves (GoM, 2020). The percentage of households using electricity and LPG for cooking are high in urban areas and very low in rural areas as reported by Coley et al., (2020) that 12% of the people connected to electricity do not cook with it. The report further says that despite challenges with adequate supply and reliability of electricity, it remains a highly desirable cooking fuel than charcoal and firewood that they use. Several studies have summarized the biomass production and supply situation in Malawi (Drigo, 2019; Zulu, 2010, Kambewa and Chiwaula, 2010), citing an increasing population causing supply–demand imbalances and calling on policies targeting sustainable biomass energy. Despite these studies, there has been comparatively limited interest in examining available sustainable biomass supply in terms of wood volumes, management implications, and options associated with it in Malawi.

Forests are essential carbon sinks, absorbing and storing large amounts of CO_2 from the atmosphere (IPCC, 2007). However, deforestation and degradation release this stored carbon, contributing significantly to global greenhouse gas emissions and climate change. Protecting and restoring forests is a crucial climate change mitigation strategy, given their fundamental role in regulating the earth's climate and ecosystems (Epple et al., 2016). It is important to determine how much biomass is available for use (Parresol, 1999; Zheng et al., 2004), as biomass assessment is additionally central to carbon sequestration estimates. The two main reasons for the assessment are to guide decision making on resource use and sound environmental management. For this purpose, one needs to know how much biomass has accumulated over time. The Kyoto protocol requires transparent reporting of forest removal and accumulation (biomass change), which translates to precision in the procedures of quantifying forest biomass and all its uncertainties (Samalca, 2007).

The concept of Maximum Sustainable Yield (MSY) is relevant in biology and economics, although its application and interpretation often differ in each field. The biological maximum sustainable yield refers to the highest amount or volume of a natural resource, such as timber, that can be harvested without depleting the population's ability to replenish itself (Hyatt and

Ridell, 2020). This is commonly used in fisheries management and forestry to ensure the long-term sustainability of natural resources. When applied in natural resource economics, MSY is used to denote the optimal extraction level or resource use over time. This concept considers the interplay between resource extraction, regeneration, and market dynamics to identify the level of resource use that maximizes economic benefits over the long term (Garlock et al., 2022). The goal is to achieve the maximum long-term economic benefit from the resource, which may not necessarily coincide with the biological sustainability of the resource. By calculating and implementing the maximum sustainable yield, foresters can ensure that the forest remains healthy, productive, and ecologically balanced for future generations. It is the intention of the government of Malawi through its forestry policy (GoM, 2016) to see to it that its forest reserves continue to be sustainably managed as they focus on maintaining a balance between harvesting activities and conservation efforts to promote long-term forest health and resilience.

I apply in principle this MSY concept to Liwonde Forest Reserve in southern Malawi (see figures 12 and 13) using forestry inventory data and our own calculated growth rate percentages, bearing in mind that forestry management practices aim to find the optimal harvest level that allows for sustainable timber/wood harvesting while preserving the health and biodiversity of the forest ecosystem. The forestry inventory data allows us to know the stock (total estimated biomass) in the reserve. The growth curves and percentage increments assist in predicting stocks in the subsequent year. I took this approach because Liwonde forest reserve was engaged in a co-management agreement with the government. The definitions of co-management vary, but it generally involves the shared rights and responsibilities over a resource between governments and private users/communities (Zulu, 2013). The balance of power can range from predominantly private to predominantly government-run. In developing countries, co-management is typically government-driven and pre-designed, with only partial devolution of authority and resource rights to the users (Kamoto et al., 2023). The communities that went into the co-management agreements, did so with the option to harvest even though there was no readily available information on growth rates guided by the Department of Forestry locally or centrally to guide in making management decisions. The approved co-management plans merely suggest periods of regeneration after clearing an area (GoM, 2008).

The closest estimates used for biomass estimates are headload counts (the maximum amount of firewood an individual can carry on their head) which can be used as volume proxies. The closest estimates used to come up with biomass equivalent during coupe harvesting, which was an area-based approach allowing communities to clear any amount of biomass within a 2-hectare area (Turner et al., 2002, GoM, 2004). This has potential problems such as, (1) under and over estimation of the biomass to be removed from a given area, (2) the error of the set growth rates to calculate future timber yields (i.e., too high or too low), potentially leading to incorrect regulations on logging intensity or length of cutting cycle, and (3) persistent differences in growth between individuals trees are ignored if one species average value is used.

This study’s objective is to assess the sustainability of utilization of the reserve by estimating biomass stocks using forestry inventory data and growth rates to project biomass increments within the reserve. Calculating MSY requires a population growth rate and reproductive capacity which I estimated from growth percentages derived from dendrochronological analysis and estimated total biomass of the reserve from the inventory data. In estimating MSY, I also consider subtractive effect of mortality and fire as they are inevitable in the Miombo woodlands. In the third step, I calculated the maximum sustainable yield (biological stock) that would be expected to be harvested from the entire forest reserve. I then remove the area of the reserve that is degraded and deforested before estimating the productive area of the reserve to estimate its biomass stock.

The importance of data from permanent sample plots is critical in sustainable forest management as it provides basic information on growth, ages, and survival of exploited tree species (Groenendijk et al., 2016) and this study took advantage of the available inventory data for Liwonde forest reserve (GoM, 2016), and protocols used in the inventory are outlined below.

4.2 Materials and methods

4.3 Forest carbon inventory protocol

The inventory methodology was based on the guidelines and Standard Operating Procedures (SOPs) designed by Michigan State University (Skole and Samek, 2016) and tested during the (2016) Malawi National Forest Inventories (NFI). The primary objective of the inventory was to assess the forest's carbon sequestration contribution and in the process the species composition and stand structure.

In setting up a baseline for carbon stock estimates, there is a need to follow standard steps for annual reporting of carbon sequestration for carbon offset projects that meet the compliance standards of different compliant and voluntary carbon markets (GOFC-GOLD,2016) as outlined in the Guidelines for National Greenhouse Gas Inventories by IPCC (2007). These procedures include quality assurance and quality control protocols for small-scale biotic agroforestry carbon offset projects. The standard operating procedures were set up in collaboration with Forestry Research Institute of Malawi (FRIM) and supplemented with protocols from Michigan State University (Skole and Samek, 2016) which were revised to ensure adherence to IPCC guidelines and from Winrock (Walker et al. 2012).

The sample allocation was determined using standard IPCC methods, deployed by the MRV Toolbox (Skole and Samek, 2016), which is derived from the Winrock sample estimator tool (https://globalclimateactionpartnership.org/app/uploads/2016/01/Winrock_SamplePlot_Calculator_2014.xlsx). The Toolbox was used to ascertain the number of samples and their location. A random unstratified sample allocation was prescribed across the forest reserve area. 47 T plots were generated (141 random sample plots) to meet a 95% Confidence Interval (CI) and 10% error. In total 57 sample points were mapped giving an oversampling cushion of 20%. A detailed description of the protocol is provided in Appendix A, with plot outlay and data collection procedures and field considerations and the planning process.

4.4 Tree ring analysis and growth percentage calculations

The methods described in Chapter 3; sections 3.4.1 to 3.4.6 employed a destructive sampling approach. This involved the collection and analysis of 45 discs from the Liwonde forest reserve. The collected discs were then assessed and analyzed, and I recorded the radial growth of the discs, then determined their diameter growth increment by size and species using ring analysis methods as described by Groenedijk et al., (2016), Frank et al., (2022), David et al., (2014) where I directly measured the surface of each disc from the pith (center) towards the bark using a magnifying hand lens over a calibrated transparent ruler. The percentage growth increases observed in the sampled discs were then applied to the plot inventory results. This allowed me to estimate the biomass growth value for the plot in the subsequent year regardless of species. The destructive sampling approach provided the necessary data to quantify the radial growth (converted to diameter) and growth increments of the trees in the plot. By applying the observed growth rates to the plot inventory, I was able to project the biomass growth for the plot in the following year.

4.5 Population and wood energy consumption and production

Harvest and population data are important in the calculation of a Biological Maximum sustainable yield (BMSY). I use household data values as reported in the Protecting Ecosystems and Restoring Forests in Malawi (PERFORM) project baseline report (2017). The project focused on sustainable land management, biodiversity conservation, and climate change mitigation in Malawi. The report estimated the total annual firewood consumption per household at 2518.11Kg/ year and indicated that 90% of the firewood that survey respondents used is extracted from Liwonde Forest Reserve. The remaining 10% is from woodlots and trees around homestead. They estimated that 50% of the wood extracted was acquired through illegal means (theft) whilst 40% was through legal means which is receipts issued by the District Forestry Office. All the firewood these communities use comes from the forest reserve. This means that on average the forest reserve supplies every household 2,266.3 Kg (2.27 tons) of wood per year. According to the 2018 Malawi population census report, there were 164,176 households and 735,438 persons in Machinga district where ethe reserve is located. The forest reserve is also under immense pressure as it is a source of illegally produced charcoal which is in high demand in Zomba and Blantyre cities, on top of supplying the district's energy needs.

Household firewood needs are important as they are core to the provision of day-to-day energy services for preparation of food to maintain the quality of life in rural and urban Malawi (Drigo, 2019). The results obtained from this study can inform policy about the potential of the Miombo woodlands in Machinga district to meet the needs for energy and other wood products. It can help the Department of Forestry in strategizing how best to engage with communities around the forest reserve as they embark on initiatives such as reducing emissions from deforestation, forest degradation, and forest management (REDD+) and forest landscape restoration (GoM, 2016; GoM, 2017).

4.6 Results

Data was collected from 140 concentric (T) plots across Liwonde Forest Reserve. A total of 1767 individual trees and 99 species were identified, recorded, and included in the analysis (Appendix C). The mean stem density in the plots was 100 ± 38 stems per plot, ranging from 19 to 183 stems across sample plots (Appendix D). The estimates are done from plot level before being extrapolated at plot level.

4.6.1 Ring width and percentage increase on size class and species

Table 6 presents a combination of size class and species percentage increase. I used the size class and species combination to create a third option of the averages of the two. I then proceeded to use the table to guide us in deciding what percentage I was going to apply for the individual trees from the forest inventory. What is clear from the table is the high percentage growth increase in the <10cm size class compared to the >25cm diameter trees.

Table 6: Biomass ring width percentage table for species and size class calculations

	Tree Size class (diameter)	5-9.99cm	10-14.9cm	15-19.9cm	20-24.99cm	25cm above
Species		17%	8%	6%	4%	3%
Brachystegia *boehmii*	13%	15%	11%	10%	9%	8%
Brachystegia *bussei*	15%	16%	12%	11%	10%	9%

Table 6 (cont'd)

Brachystegia *utilis*	18%	18%	13%	12%	11%	11%
Brachystegia *spiciformis*	11%	14%	10%	9%	8%	7%
Uapaca kirkiana	18%	18%	13%	12%	11%	11%
Julbernardia *globiflora*	18%	18%	13%	12%	11%	11%
Diplorrhynchus *condylocarpon*	18%	18%	13%	12%	11%	11%
Brachystegia genus	16%	17%	12%	11%	10%	10%

4.6.2 Inventory results and predicted ring width percentage increase applied.

Table 7 below presents the calculated results from the forest inventory as described in the methodology outlined in the previous section. The Kachamba (2016) allometric model was used in estimating biomass for each plot as presented in columns 2 and 3 which presents the same values in tons of carbon per ha. Plots 19 and 47 had the highest biomass per ha whilst Plots 29, 34, and 38 had the least amount of carbon per ha.

Table 7: Inventory results per plot and subsequent year from effected growth increments.

Inventory Plot no.	2016 tons C Ha $^{-1}$	2017 tons C Ha $^{-1}$
Plot 1	40.84	47.97
Plot 2	34.83	38.95
Plot 3	9.97	12.1

Table 7 (cont'd)

Plot 4	49.46	60.25
Plot 5	40.46	49.85
Plot 6	44.27	49.80
Plot 7	31.50	38.27
Plot 8	10.41	14.52
Plot 9	12.75	17.15
Plot 10	10.4	14.5
Plot 11	30.54	35.54
Plot 12	32.39	41.06
Plot 13	66.16	80.20
Plot 14	12.4	16.55
Plot 15	30.51	38.56
Plot 16	40.22	68.08
Plot 17	51.58	61.54
Plot 18	49.71	64.53
Plot 19	60.48	69.46
Plot 20	28.75	35.58
Plot 21	19.40	24.40

Table 7 (cont'd)

Plot 22	26.87	29.73
Plot 23	17.41	23.04
Plot 24	62.36	77.51
Plot 25	49.27	53.49
Plot 26	23.55	27.17
Plot 27	48.14	56.71
Plot 28	52.54	59.05
Plot 29	2.7	3.7
Plot 30	27.06	30.2
Plot 31	46.65	54.67
Plot 32	56.70	68.13
Plot 33	39.2	48.73
Plot 34	6.6	9.15
Plot 35	29.95	36.45
Plot 36	47.02	56.55
Plot 37	29.02	36.47
Plot 38	6.72	9.27
Plot 39	43.66	49.01

Table 7 (cont'd)

Plot 40	11.6	14.8
Plot 41	36.89	44.01
Plot 42	22.85	25.74
Plot 43	29.16	34.44
Plot 44	15.96	17.39
Plot 45	49.57	57.62
Plot 46	6.6	7.65
Plot 47	67.71	79.48

From the 140 plots across Liwonde Forest Reserve, the inventory estimated the biomass in the reserve at 33.77 t/C ha^{-1}. The sample plots ranged from as low as 2.7 t/C ha^{-1} to as high as 80.2 t C ha^{-1} in the highest increase in sample plots (see plot 13). The combination of the averages of species and size classes would give a projected biomass increment in 2017 of 40.19 t/C ha^{1}.

4.6.3 Deforested and Degraded area in Liwonde

An analysis by Skole et al., (2021) reported deforestation rates within forest reserve areas in Malawi (Appendix E). For Liwonde Forest reserve, 9,885 ha is the total amount of deforestation and degradation for the period under investigation, 2016-2021. This leaves only 16,487.8 ha out of the total 26,472.8 ha which can be considered productive or intact in the forest reserve. I then proceed to factor in mortality and fire effect.

4.6.4 Mortality and fire effect

In table 8 (below) I use 7.3%, which is the total of the fire mortality figure (5%) [plus the PSP mortality of 2.3%, together representing mortality rates in the reserve. I then proceed to factor in the mortality in the plot biomass estimate. As indicated by Hofstad and Araya (2014), the effect of fire must be considered after the estimate of each plot's increase. Using the 2016 year as a base year, I then proceed to calculate the total increment of the whole reserve per tree and plot.

Table 8: Inventory results per plot with a consideration for mortality and fire effect.

Inventory Plot no.	2016 tons C Ha^{-1}	2017 tons C Ha^{-1}	2017 tons C Ha^{-1} (Mortality and fire effect)
Plot 1	40.84	47.97	44.5
Plot 2	34.83	38.95	36.1
Plot 3	9.97	12.1	11.2
Plot 4	49.46	60.25	55.8
Plot 5	40.46	49.85	46.2
Plot 6	44.27	49.80	46.2
Plot 7	31.50	38.27	35.5
Plot 8	10.41	14.52	13.5
Plot 9	12.75	17.15	15.9
Plot 10	10.4	14.5	13.4

Table 8 (cont'd)

Plot 11	30.54	35.54	32.9
Plot 12	32.39	41.06	38.1
Plot 13	66.16	80.20	74.3
Plot 14	12.4	16.55	15.3
Plot 15	30.51	38.56	35.7
Plot 16	40.22	68.08	63.1
Plot 17	51.58	61.54	57.0
Plot 18	49.71	64.53	59.8
Plot 19	60.48	69.46	64.4
Plot 20	28.75	35.58	33.0
Plot 21	19.40	24.40	22.6
Plot 22	26.87	29.73	27.6
Plot 23	17.41	23.04	21.4
Plot 24	62.36	77.51	71.9
Plot 25	49.27	53.49	49.6
Plot 26	23.55	27.17	25.2
Plot 27	48.14	56.71	52.6
Plot 28	52.54	59.05	54.7

Table 8 (cont'd)

Plot 29	2.7	3.7	3.4
Plot 30	27.06	30.2	28.0
Plot 31	46.65	54.67	50.7
Plot 32	56.70	68.13	63.2
Plot 33	39.2	48.73	45.2
Plot 34	6.6	9.15	8.5
Plot 35	29.95	36.45	33.8
Plot 36	47.02	56.55	52.4
Plot 37	29.02	36.47	33.8
Plot 38	6.72	9.27	8.6
Plot 39	43.66	49.01	45.4
Plot 40	11.6	14.8	13.7
Plot 41	36.89	44.01	40.8
Plot 42	22.85	25.74	23.9
Plot 43	29.16	34.44	31.9
Plot 44	15.96	17.39	16.1
Plot 45	49.57	57.62	53.4
Plot 46	6.6	7.65	7.1

Table 8 (cont'd)

Plot 47	67.71	79.48	73.7

The average across the plots drops to 37.3 t C ha^{-1}, from the 40.19 t C ha^{-1} estimated before factoring in the fire and mortality effect on the plot carbon estimates.

4.6.5 Maximum yield compared to community fuel wood consumption

I calculated the forest stock (maximum yield) based on the difference between the total forest area and the degraded and deforested parts (section 4.6.3). The estimated stock available from the forest is 57,707 t C ha from the 16,487.8 ha of intact forest. The average carbon per hectare increment is 3.5 t C ha^{1}, which is the difference between the average sample plot values between 2016 and 2017 carbon estimates in Liwonde Forest Reserve.

Machinga district population's fuel wood consumption is 185,519 t C and yet the forest reserve can provide only 57,707 t (31% of the household's consumption). This leaves a deficit of almost 127,812 t C (69 % of the households' consumption) for the district per year. My calculations do not consider other wood sources but focused solely on the reserve. I did not consider recruitment as some tree stems might have reached the minimum 5cm DBH to be accounted for in a forest inventory and this might have resulted in underestimating the carbon per hectare at plot level

4.7 Discussion

The maximum sustainable biomass yield (MSY) from the reserve is 57,707 t C (Table 10). However, this biomass increment within the forest reserve is insufficient to meet the annual household fuelwood consumption, which amounts to 185,519 t C. Consequently, there is a deficit of 127,812 t C, representing 69% of the total household consumption. This significant shortfall underscores the unsustainable pressure currently placed on the reserve, as also noted by Nerfa et al., (2020) and Greene et al., (2017). The high consumption, particularly for charcoal, is having a particularly damaging impact on the natural Miombo woodlands, leading to a reduction in forest resources, biodiversity, and opportunities for rural livelihoods. Given the strong link between the economic activities of the local population and deforestation, there is a need to improve forest governance to ensure the sustainable management of the Miombo woodland ecosystem (Chilongo, 2014; Zulu, 2013).

This analysis of size class shows us that large trees (DBH $\geq$ 30 cm) contributed a large portion of all biomass stocks whereas small trees (DBH < 10 cm) typically did not contribute much across all plots. Small trees contributed more to aboveground woody productivity (AWP) than to above ground biomass. This was similarly observed by (Piponiot et al., 2022) whose global study on the distribution of biomass dynamics in relation to tree size suggested that whereas large trees dominate forest biomass, small trees are proportionally more important for productivity of the forest. This calls for longer and continuous measuring of the small tree components, and studying their dynamics as they have influence on biomass accumulation in stands in the long term.

The plot structure distribution was very complex in species and tree size and distribution. Liwonde forest seems to be dominated by *Brachystegia* species ($\geq$ 40% of inventoried trees) currently, which might also explain why it's the most utilized in terms of tree extraction. *Brachystegia* are also desirable especially for charcoal, although the current need for firewood trees shows that communities will use any species without exception. Kamangadazi et al., (2020) analyzed different descriptors that characterize the reserve's regeneration capacity, observing a typical reverse J-shaped. This patter indicates increased seedling population, active regeneration, and recruitment across the reserves. Such findings suggest that there is steady and expanding recruitment within the Miombo woodlands communities.

The findings of mean carbon storage ranging between 33.77 t C ha^{-1} and 37.3 t C ha^{-1} are similar to findings from previous studies within sub-Saharan (Luoga et al., 2002, Jew et al., 2016). The wet miombo woodlands have greater tree density and size, leading to higher aboveground carbon storage in the vegetation unlike the dry miombo woodlands have a more open canopy structure with smaller trees, and lower soil carbon content, resulting in lower total ecosystem carbon storage compared to the wet miombo (Chirwa et al, 2013; Ryan et al, 2011). Sakala and Vinya (2020) concur with (FAO, 2017b) that eastern, southern, and northern sub-regions of Africa which are covered by the dry forests and woodlands, have less above ground living woody biomass hence their biomass stock may not significantly differ (McNicol, 2014).

Additionally, these findings might support REDD+ plans if there is a clear understanding of expectations between the local communities and government on the modalities of meeting their needs and carbon project expectations. The younger (5-15 cm size class) tree discs have substantially higher biomass ring width percentage increment than the older (>25cm size class, see Table 6). In other words, the trees do not gain as much biomass percentage per increment as they grow older. This could have broader implications on carbon management of the forest reserve, especially if the big diameter or older trees have been removed or lost to deforestation.

The study explored the sustainability of utilizing forests from tree growth and biomass increment side, using inventory data to help make smarter managerial decisions. This approach parallels the work of Miapia et al., (2021) in Huambo district in Angola. Acknowledging the household consumption of the forest prior to considering carbon needs is important for planning purposes.

Once consumption is quantified, it becomes clearer how to maintain carbon levels in the forests and whether this goal is attainable.

4.8 Long term sustainable yield

Forestry plays a crucial role in many economies, providing valuable resources, ecological services, and economic opportunities. As economies evolve, the economic considerations surrounding forestry also undergo change. In the Malawian context, the Forestry Act (GoM, 1997; GoM, 2019) defines gazetted forestry reserves like Liwonde as designated areas of land that are protected and managed by the government for the purpose of conservation and sustainable use of forest resources established through a legal process known as gazettement; which involves the publication of a notice in the government gazette, a legal document that announces official government actions. The same Act further spells out the duties of the Director of Forestry in Part 2 section 5 (b) as being for responsible for (a) planning, promoting, conducting and assisting in the activities required to maintain, restore and develop the forest cover necessary for soil and water conservation, maintenance of biological diversity and the supply of forest produce. This section focuses on the Director's role outlined in Part 2, sections 5(g) and 5(j), which entails promoting appropriate harvesting systems, transportation, marketing, and sustainable use of forest products. Additionally, the Director is responsible for overseeing the control and management of forest reserves and protected forest areas in compliance with the regulations of the same Act (GoM, 1997; 2019).

From this background I posit a harvesting plan based on FORest Simulation-Optimization Model (Leefers, 1991) spreadsheet model initially developed for long term sustainable yield of timber developed for two state forests in Michigan. Simulation provides a powerful technique of testing and applying harvesting systems and management regimes to virtual environments without the costly need to implement them in ‘real life’. Harvesting simulation has the potential to produce results that would be representative of real systems (Hogg et al. 2010) and can be used to tweak current and potential systems to determine the effects of these in terms of productivity. Although Miombo woodlands are characterized by slow growth rates (Chidumayo, 2019), evidence supports their robust capacity to regenerate, with studies by Missanjo et al., (2013) and Syampungani et al., (2010) documenting substantial Miombo resilience to disturbance and harvesting. Furthermore, managed appropriately, resprouting stumps in these woodlands can achieve high regrowth rates of up to 1.4 cm per year (Syampungani, et al., 2010).

It is important to acknowledge the divergence of interests between development and conservation. This does not mean that the different balances between the two results are less or more ‘sustainable’ than the other. Rather it is the recognition that sustainability has several different dimensions (Arnold and Perez, 2001). The objective of this simulation is to show the possibility of incorporating harvesting whilst maintaining ecological sustainability and forest cover. The goal of sustainable forest management is maintaining a continuous flow of stated outputs, while retaining the productive capacity of the forest intact (Morgan et al., 2021). I am mindful however of the economists’ tendency to focus only on the sustainability of economic benefits. As the benefits people seek to obtain from the forests change over time, pursuit of this objective is likely to entail changes to the resource base. Local management systems that modify the structure of the forest resource in favor of outputs can be seen to be giving priority to this economic objective. Below is a brief description of the FORest Simulation-Optimization Model (FORSOM) which I chose due to its ability to run simulations, create tables and charts of model variables and simulation results based on an envisioned problem (Leefers, 1991).

4.8.1 FORest Simulation-Optimization Model (FORSOM)

The model was constructed in Microsoft software package designed to facilitate the construction of a dynamic systems model. The model provides a simple set of building blocks that can be used to visually represent components of the system. The model components are visually linked in a hierarchical environment which allows for easy use. The model allows the user to tweak and parameterize it according to their preference. This allowed us to calibrate the model to fit Liwonde forest reserve. Using the biomass results of the plots inventory data's weighted averages to denote the "age class" based on the estimated carbon content I proceeded to allocate each block, the average age based on the amount of carbon estimated in that zone. Trees in each diameter class (Age class in our case) grow in diameter at breast height (DBH) and height over the course of the simulation. The equations that determine both DBH and height growth were from the Kachamba model (2016) and the per ha yield values used are from the forestry inventory data (GoM, 2016) conducted in Liwonde forest reserve.

The schedule assumes a harvest every decade or an annual harvest of 10% of the long-term sustainable yield (LTSY) value. There is no succession, and the schedule assumes trees simply grow older (70+). I additionally factored current values for deforestation and degradation (Skole et al., 2021) in the schedule which are 14% and 24% of the total forest reserve area respectively. The planned harvesting schedule is based on a 30-year-old rotation, but I know the reality is that people in Machinga district need firewood right now. Also, the model considers that areas older than 30 years maybe be left intact and be added to areas left for watershed management and protection. By manipulating various management assumptions and simulated harvesting patterns, different forest management projections can be created. These management options typically identify key factors such as the forest type being modeled, rotation ages, species composition, the area allocated for different uses, as well as the status of deforestation and degradation.

The ability to adjust these management assumptions allows for the exploration of different scenarios and their potential impacts on the forest ecosystem. Through this iterative process of modifying management inputs and evaluating the resulting projections, forest managers and decision-makers can gain valuable insights. These insights inform sustainable forest management strategies that balance economic, ecological, and social considerations. The flexibility to adjust the modeling parameters enables the testing of various management approaches and the identification of the most suitable options for Liwonde forest reserve. I simulated the potential long term sustainable harvest in 26,473 ha of Liwonde forest reserve with different age classes.

Since there is a huge demand for firewood, the model is scheduled such that harvesting starts with the available 10–20-year-old age class, and later in the 20-29 and 30-39 Age classes ensuring there is time for regrowth after clear cutting and not removing the entire class.

By feeding the model with the information of the Age class and the amount of hectares they approximately cover and not adding anymore constraints and running the model. The model proceeds to calculate Long-term sustainable yield (LTSY) for Liwonde for the next 50 years on the managed hectares of intact and degraded forest. The model estimates that an average of 123,563 m^3 be harvested every decade based on yields from a 30-year rotation given the current biomass estimates from the forestry inventory (GoM, 2016). The current levels of forest degradation in Liwonde play a major role in the amount of area that could be harvested and hence harvest options available. The LTSY would tremendously increase with less forest degradation. The model estimates that a minimum of 205-440ha (1.9-3.2%) of the forest reserve area) per year be clear felled following a management plan.

Important questions about forest management strategies and resource allocation can often be answered more efficiently with the help of decision support systems as has been shown by running the FORSOM model in Liwonde forest. The model is only the first step towards the development of a robust decision support tool. To create a comprehensive decision support system, these results need to be integrated with other complementary models and data sources such as ecosystem models that may help capture the broader ecological relationships and interdependencies within the forest. Economic models can be used to assess the financial implications of different management strategies, including timber harvesting, non-timber forest product utilization, and ecosystem service valuation with some spatial analysis tools. All this would involve stakeholder engagement tools to help gain insight from various stakeholders, including local communities, policymakers, and industry representatives, in the decision-making process.

By integrating these diverse components, the decision support system can provide a more comprehensive and holistic view of the forest management alternatives. This allows for better-informed decisions that balance economic, ecological and social considerations, ultimately leading to more sustainable forest management practices. The development of such a robust decision support system requires a collaborative effort involving experts from various disciplines, including forestry, ecology, economics, and information technology in Machinga district.

4.9 Management proscriptions for Liwonde forest reserve

Forestry proscriptions are a set of rules, regulations, and guidelines that govern the management and use of forest resources (McGinley et al., 2012; Cerutti et al., 2008). These proscriptions are aimed at the sustainable and responsible utilization of forests while protecting the environment and biodiversity. The specific details of any forestry proscriptions mostly vary depending on the country, region, or jurisdiction, as they are typically tailored to the local environment economic, and social conditions (Baral and Vacik, 2018). The adherence to these proscriptions is essential for the sustainable management and conservation of forest resources.

To the question can Liwonde Forest reserve in its current condition be sustainably harvested? There are several considerations that management ought to make before answering the question. It's not only the resource status but relationship with guardians of the resource or communities that matter in coming up with a utilization plan. Makungwa and Kayambazinthu (1999) acknowledged at the time that there was observable friction between communities and the government (Forestry Department) which might explain increased numbers of illegal logging and charcoal production presently.

I identify 7 distinct zones (as shown in figure 26) based on the average carbon that was calculated during the forestry inventory in 2016 and each has its own proscription. What is critical is the need to put a comprehensive monitoring program in place to keep monitoring the levels of utilization impacts on the woodlands, otherwise a gloomy projection is that the reserve might end up deforested. This calls for stronger law enforcement to ensure there are fewer illegal activities reported in the reserve and its surrounding area.

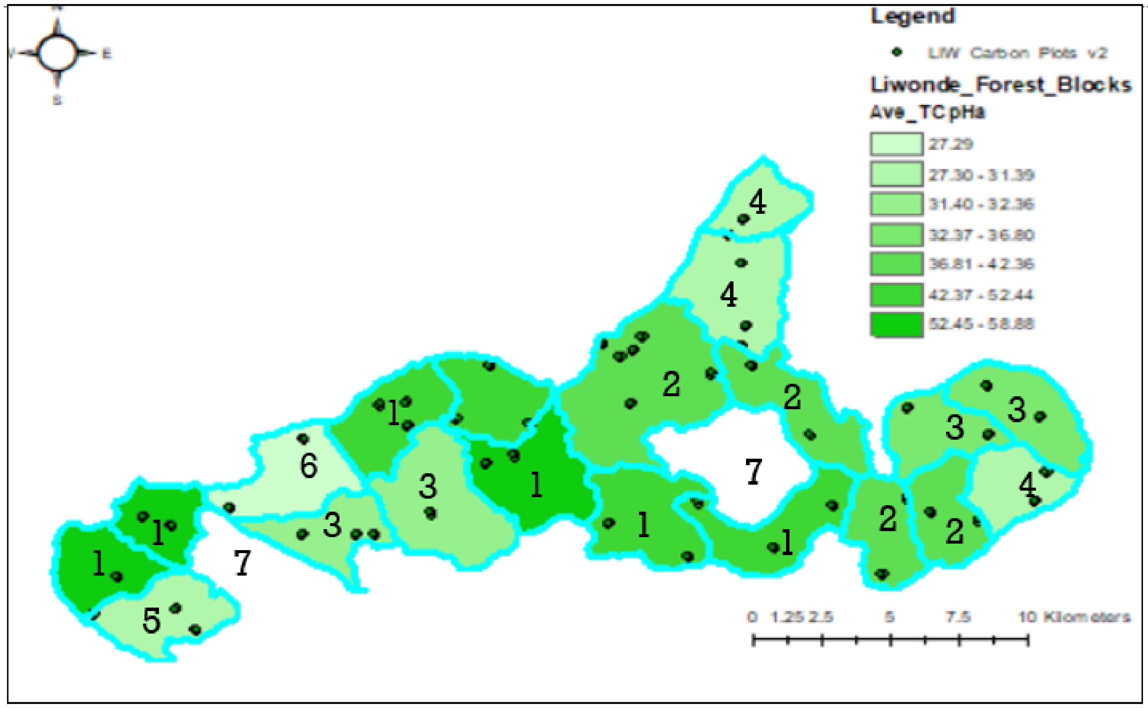

Figure 23: Identified areas (blocks) and their proscriptions in Liwonde forest reserve.

Zone 1. Harvesting can be allowed but must be under supervision.

Zone 2. Must have a management plan in place before any harvesting is decided on.

Zone 3. Needs continued management to allow for small trees to grow.

Zone 4. Must be guarded to allow for small trees to grow since they are prone to degradation.

Zone 5. Must be under protection and needs involvement in FLR activities to allow regrowth.

Zone 6. Needs community policing and protection since it is prone to deforestation and degradation.

Zone 7. Reforest and replant and protect the tree seedlings as there has been a total land use change.

Previous inventory participants allude to the reserve having an even more diverse species base, compared to this inventory results. Though I cannot verify this information, there is certainly a need to ensure restrictions of harvesting endangered or threatened species. A more pragmatic approach to achieve more sustainable woodland management requires strengthening of the capacity of communities and staff so that they can coordinate the regulation and utilization of the woodland.

It is important to acknowledge the divergence of interests between development and conservation in the woodlands (Angelsen, 2010). This does not mean that one is less or more 'sustainable' than the other. Rather it is the recognition that sustainability has several different dimensions. Whilst the objective of ecological sustainability is usually expressed in terms of maintaining forest cover and biodiversity, the goal of sustainable forest management has usually focused on maintaining a continuous flow of stated outputs (community biomass needs), while retaining the productive capacity of the forest intact. As the benefits people seek to obtain from the forests change over time, pursuit of this objective is likely to entail changes to the resource base (Zulu, 2013). Local management systems that modify the structure of the forest resource in favor of outputs can be seen to be giving priority to this economic objective (Arnold and Perez, 2001).

To be able to manage the reserve for carbon projects, such as involvement in REDD+ projects, the district must find ways of restricting utilization that might result in the decline of carbon stored across the study area or set in place robust and reliable methods for estimating forest degradation (UNFCCC 2007). This calls for collaborative efforts not limited to the department of forestry or energy department. A multisectoral approach is a must in ensuring the reserve continues to provide the ecosystem services it provides.

The findings suggest that though there is availability of biomass in the immediate short term, if the management of the reserve is not well managed the long-term sustainability of forest resource may be compromised due to forest degradation as presented in the analysis through the years. A multisectoral approach is a must in ensuring the reserve continues to provide the ecosystem services it provides. Policymakers should aim for sustainable forest management that carefully balances the protection of forests with their use, particularly considering the needs of vulnerable households (Chilongo, 2014). This involves creating policies that ensure forests are preserved for environmental benefits such as biodiversity and climate regulation while also allowing for responsible and equitable use of forest resources. Such an approach supports the livelihoods of communities that depend on forests, helps alleviate poverty, and promotes social equity.

I therefore recommend that interventions to curb the loss of forest areas should be put in place through strategies, for example apart from land zoning (blocking) of woodlands by Group village Head (GVH) as is with the current format. The government departments (Land, Water) led by the Forestry team would have to work on the enforcement/sensitization of land and water use laws and policies which are vital. This will be followed by institutional strengthening to enhance coordination and optimization of resources for effective management.

4.10 Conclusion

Our findings suggest several policy implications for the Malawi government, particularly regarding its participation in the REDD+ program, which is results-based. Given the high rates of forest degradation (Skole et al., 2021) from various drivers beyond wood energy, charcoal production, and agriculture the country risks failing to receive payments as stipulated in the design of the program. In our analysis, the removal of wood from Liwonde forest reserve to meet household energy needs was accounted for without considering the extent of degraded or deforested areas. If Machinga were to participate in a local REDD+ program, it would need to substantially reduce both legal and illegal carbon removals, which I estimated at 2.3 tons per household annually from the PERFORM survey. The purpose would be to demonstrate that the district has achieved a net positive impact, or 'additionality, from its REDD+ program involvement over a set period, such as 5 years. The household usage of fuelwood and its heavy reliance on the forest reserve as only source calls for a multisectoral approach with the forestry and energy sectors playing key roles in the development of a management plan that includes alternatives to fuel other than wood.

The results of this study suggest that sustainable utilization of Liwonde forest is possible especially when considering biomass composition of the entire reserve which could prove beneficial to both the government and communities when considering REDD+ and any other payment for ecosystem services scheme. Further studies are required to examine potential proscriptions against effects of no extraction on other communities and their energy use habits. There is a need for controlled and planned extraction of wood from the Miombo woodlands to allow them to grow and provide and meet community needs in the long term. This requires a shift in longstanding tradition in Malawi Forestry of forest reserves which has been that reserves are primarily there for indigenous tree preservation. The reserves can serve as a sustainable wood fuel source and preservation area if communities are convinced of the need for preservation as they are already beneficiaries of the wood fuel. Planned and systematic exploitation at Block management level might have the potential to succeed as some parts of the reserve are better managed than others and this is a direction that district and national forest managers might want to pursue as one way of shifting pressure away from these forest reserves.

CHAPTER 5: CONCLUSIONS AND IMPLICATIONS

The aim of this dissertation was to investigate tree growth and biomass accumulation using dendrochronological analysis and explore how tree growth rates can offset degradation and could positively influence the availability of biomass for wood energy in Liwonde Forest Reserve through sustainable harvest management. Forest reserves in Malawi, though owned by government, are surrounded by communities with needs for wood for energy. The continued vulnerability of the reserves to deforestation and degradation is a complex issue tied to the communities' reliance on fuel wood for energy requirements. A multi-faceted approach is necessary. First, sustainable forest management practices must be implemented to directly protect the reserves from further deforestation and degradation. Second, alternative energy sources are needed so that the communities can reduce their dependence on fuel wood harvesting, alleviating pressure on the reserves. Third, with knowledge of growth rates and biomass yield a sustainable management plan must be deployed to allow spatially and quantitatively regulated wood removals. By addressing the root causes through these three key strategies sustainable forestry, alternative energy, and community development the vulnerability of the reserves can be mitigated, and their long-term protection can be better ensured.

I utilized tree-ring analysis to estimate growth increments of the trees, which in turn enabled me to reliably estimate the biomass accumulation within the Liwonde forest reserve in Malawi. Analysis of growth rates from dendrochronological analysis of tree species that had been destructively sampled revealed particularly low radial increments, ranging from 1.85mm to 2.97mm per year. I calculated the annual disc increment percentage biomass whole tree growth values for different tree size classes, which ranged from an impressive 17% growth experienced in the 5cm-9.99cm diameter size class to a more modest 3% growth rate for the above 25cm diameter size class. The average above ground carbon accumulation estimated in this Miombo forest inventory was 33.77 t C/ha per year, increasing to 37.3 t C ha over the one-year period 2016-2017. There is high aboveground woody productivity (AWP) in the tree species that are in the smaller size classes (DBH < 10 cm) even though their carbon accumulation is lower compared to the older/larger trees >30cm. These results call for more studies in Miombo in Malawi to make projections on the life span of the Miombo especially recognizing that the older trees are the ones that are easily targeted for cutting or charcoal production by communities.

The development of policy and interventions that effectively reduce deforestation and forest degradation should be tailored to specific locations in Malawi. As Ryan et al., (2014) suggest, countries considering REDD+ engagement should begin by quantifying the specific drivers of deforestation. Similarly, Yin (2024) supports this approach, emphasizing the importance of establishing a results-based scheme grounded in well-defined causes of forest loss. In our study, I was able to quantify removals through wood energy consumption, but a suite of deforestation drivers was identified for Liwonde. Therefore, it is critical to understand the historical rates and drivers of land-use change in this area. The management proscriptions I propose are designed to ensure sustainable utilization of the forest reserve.

One of the most important findings of this dissertation is the demonstration of continuing current growth across all samples in the studied species. These findings lend support to the notion that these woodlands are currently experiencing growth increases. The publication of these results would support a call by Rozendaal et al., (2010) and Nock et al., (2011) for more comprehensive analyses and documentation of long-term growth trends in these ecosystems. Thus, this dissertation strongly supports the conclusion that these Miombo woodlands are carbon sinks, with biomass accumulation continuing over time. This observation suggests that national accounting for greenhouse gas emissions in its national inventories, reporting, and reference emissions levels is missing a removals term that offsets some of the current emissions. This research did not have the scope to determine quantitatively the significance of these sinks, but such an analysis could be the basis for future research. Given the ongoing deforestation and forest degradation, there lies a significant opportunity to greatly increase conservation of these forests and expand the area of protection through restoration efforts as a means to including forest sinks in the national accounting.

Natural, demographic and climatic tree mortality is an important process of forest dynamics that needs to be included when determining net yield of biomass or carbon sink strength, but mortality is a poorly understood quantitatively and in terms of the processes that influence or control it in the Miombo (Chidumayo, 1998). Thus, an essential area of further research that needs to be addressed is the examination of processes leading to mortality in Miombo species, processes that might not be related to natural stand senescence.

This dissertation examined tree growth and biomass accumulation in Liwonde forest to assess whether annual increments of biomass were significant enough to meet wood energy consumption levels by communities in Machinga district surrounding the forest reserve based on historical data derived from dendrochronology. However, the study did not consider the growth rate response of trees to climate variables such as temperature and rainfall. Climatic factors are known to influence increments in growth-ring width (Zuidema, 2016; IPCC 2007). Therefore, incorporating the effects of climatic variables on the growth of Miombo trees could improve the precision of any forest models developed in the region.

This study also highlights a critical issue of the lack of quantitative data on forest degradation rates across Africa. This research demonstrates an innovative use of a remote sensing fractional cover tool to map the broad landscape of forests and trees outside of forests, allowing for comprehensive and precise quantitative analysis, which could be applied elsewhere. This study presents a detailed forest map for Malawi, which provides spatial and quantitative measurements of both forest degradation and deforestation. This analysis included new estimates of landscape-wide deforestation rates between 2000 and 2009 (22,410 ha yr-^{1}), 2009 and2015 (38,937 ha yr^{-1}), and between 2016 and 2021 (22,640 yr-^{1}). I further produce new estimates of the rate of forest degradation for the periods 2000-2009 (42,961 ha yr-^{1}), 2009-2015 (71,878 ha yr^{-1}) and 2015-2021 (43,454yr-^{1}). The new estimates are significant because they enhance Malawi's prospects for achieving full REDD+ readiness.

Addressing the drivers of deforestation and degradation requires a multisectoral approach beyond just the Forestry sector. Effective strategies will need to involve the departments of forestry, agriculture and energy at least, to ensure communities adjacent to forest reserves can achieve the intended benefits. Hofstad et al., (2009) note that while reducing wood harvesting in miombo would increase above-ground biomass, it would also heighten demand for alternative fossil-fuel based energy sources and could adversely affect rural economies. Thus, careful planning and coordinated action across sectors are essential to balance environmental objectives with socio-economic impacts.

The dissertation suggests that the current management practices within Liwonde forest reserve, particularly unregulated allowance of harvest, jeopardize the sustainability of Miombo woodlands' biomass provision, even in the near term, based on projections of degradation and deforestation observed over the 20-year period from 2000 to 2021. It advocates for the implementation of comprehensive, science-based planning needs to address these challenges and ensure the long-term sustainability of the Miombo woodlands' biomass composition.

Particularly, with the ongoing high consumption of fuelwood, the lack of alternative sources of energy for cooking poses a continuous threat to forests.

This study relied on forest carbon inventory sampling as a basis to calculate biomass increments by species and size class, which is new and novel. I used dendrochronological analysis techniques to determine biomass growth increment rates. The choice of the appropriate model for biomass estimation in the Miombo woodlands involved comparing various allometric models from Malawi and the region. Of the 3 models I compared, the Kachamba (2016) allometric. The Kachamba allometric model proved to be superior in projecting higher carbon values and is recommended for estimating tree biomass within the Miombo woodlands nationwide.

As Malawi transitions from the IPCC's Tier 1 to Tier 3 for its greenhouse gas emissions inventory, the use of country-specific emission factors and more detailed activity data, as outlined in Chapters 2 and 4, allows for more precise reporting across a range of reporting categories, from the national forest reference emission levels (FREL), its national correspondences, and its stocktaking on its nationally determined contributions (NDCs). For example, evidence from mapping degradation suggests that the current FREL is incorrect and includes double counting from fuelwood and charcoal impacts on forest carbon loss. Also, the analysis suggests that important sink terms are being excluded from the inventories and reporting. Tier 1, which uses default emission factors and simple activity data, provides only basic estimations and is used when more detailed data are unavailable. In contrast, Tier 3 enhances accuracy of greenhouse gas emissions, and can be foundational data for analysis of growth rates and biomass removals.

The ability to distinctly identify and count tree rings from collected discs facilitated this study's estimation of biomass accumulation. This study adds to the body of research indicating that tropical and sub-tropical species do produce annual rings, as evidenced by Zuidema et al., (2012), David et al (2014), Mbow et al. (2013) and Syampungani et al., (2014). Future research could explore biomass accumulation by investigating the DBH-Age relationship, thereby allowing the use of non-destructive field measured DBH in forest inventories to be used as proxies for growth rates. While this analysis has begun to explore such relationship, but I recognize there is room towards the fuller development and parameterizations, there is substantial potential for further development and parameterization of growth and yield models for Miombo woodlands, which could aid in their sustainable management.

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APPENDIX A: FOREST CARBON INVENTORY PROTOCOL AND DATA COLLECTION

Carbon pools

The inventory team measured specific pools of carbon, but not all pools shall be included in the measurement protocol. The definition of each pool is specified below and the pools that are measured (included) are specifically identified and presented in table 8 below.

Table 9: Carbon pools and their definition

Carbon Pool	Description
Above ground biomass (AGB)	Woody and herbaceous biomass of living vegetation above the soil surface that includes trees, shrubs, palms, bamboo, vines, and other living plants.
Below ground biomass (BGB)	The biomass of live roots >2 mm diameter that includes the coarse roots of trees, shrubs and other living plants.
Dead wood	Non-living woody biomass that is larger than the litter pool. Deadwood includes both standing dead wood and down dead wood lying on the surface ≥15 cm diameter.
Litter	Non-living biomass on the soil surface that is larger than soil organic matter (>2 mm) and smaller than the dead wood (<15 cm).
Soil organic carbon (SOC)	The organic carbon in mineral or organic soils to a specified depth (30 cm is the default depth but sometimes measured up to 1 m deep).

There following are the Carbon pools directly measured at each site:

- Aboveground Biomass

- Dead Wood, both standing and down.
- Herbaceous and woody seedlings for regeneration assessment
- The default values for the Belowground Biomass pool were applied in lieu of measurement.

Estimates for pools that were not measured (default values can be used in this instance I did not use them in our calculations):

- Soil organic carbon
- Litter and small debris

Delineation of the boundary of the inventoried area

The boundary was delineated using GIS files from official government sources which are verified. These layers were then used inside the Measurement, Reporting, and Verification (MRV) Toolbox mapping tool developed at MSU by Skole and Samek, (2016). The delineation of the inventory area followed the same protocol as the delineation of the Forest Reserve. Similarly, the delineation of the forest management blocks were included and used to subdivide the Forest Reserve. The coordinate systems used were the standard Universal Transverse Mercator (UTM Zone 36 South) and Geographic (latitude/longitude) and all areas were reported in hectares.

Land covers to be delineated and mapped.

The assessment process requires delineation of various land cover types in each of the inventoried areas. These were determined based on remote sensing analysis and field reconnaissance. A map of the pilot landscapes was prepared by Michigan State University and provided to inventory teams before field work commenced.

Forest land area.

Malawi has since adopted a formal definition of forest area that is aligned with the IPCC conventions but customized to the Malawi context. The geographic area of forest land covers must be determined through a GIS, remote sensing (RS), or by field measurements with a GPS device. GPS devices used to determine area and location should have a minimum accuracy of 5 meters, but sub-meter accuracy is preferred. The area should be reported in hectares. Forest land must be determined according to an agreed upon definition of forest land. The UNFCCC allows for a range of values for three parameters where a forest is land with tree canopy cover between 10 and 30%, the trees at maturity must be between 2 and 5 m tall, and the land area is a minimum of 0.05 to 1 ha.

Non-forest land area.

The geographic area of non-forest land cover must be determined through a geographic information system (GIS), remote sensing (RS), or by field measurements with a geographic positioning system (GPS) device. The area should be reported in hectares. Non-forest land includes cropland, grassland, wetlands, settlements, and other land where the land cover does not meet the above definition of forest land.

Deforested and degraded land area.

The geographic area of deforested land was determined through geographic remote sensing (RS) analysis. By using a fractional cover tool that maps across a broad landscape of forests and trees outside of forests, a quantitative analysis was used to come up with figures for deforested and degraded areas (Skole et al., 2021). The area was reported in hectares. Deforested land includes land that was previously classified as forest land but underwent land cover change to non-forest land covers. Degraded forest land is forest land with decreased carbon density due to human activities yet remains forest land according to the definition above (Gao et al., 2020; IPCC, 2007).

Stratification of the inventoried forest area

Stratification of the forest land inside the delineated area may reduce the variance of the plot measurements and reduce the number of assessment plots needed. However, it was decided at this time not to include stratification within the Forest Reserve inventory areas due to time unavailability of shape files for the reserve showing various forest stratum. The only other option in our case was to plan for at least one plot for every Forest Management Block, which is what I did in spreading inventory plots across the reserve.

Determination of sample frame, number of plots, and their location

The sample allocation was determined using standard IPCC methods, deployed by the MRV Toolbox (Skole and Samek, 2016), which is derived from the Winrock sample estimator tool (https://winrock.org/wpcontent/uploads/2016/03/Winrock_SamplePlot_Calculator_2014_0.xlsx). . The Toolbox was used to ascertain the number of samples and their location. A random unstratified sample allocation was prescribed.

Sample plots adherence conditions:

1. A minimum of 50 m from a road or forest edge
2. Had to be on land that is preferable flat, but not more than 30-degree slope.
3. Must not be located too near or include certain geographic features such as cliffs, ravines, and large rivers.
4. Not located across two strata

The number of plots for each stratum met a defined minimum error (5%) and confidence level (95%) based on the size of the plots, the mean carbon value (t C-ha) of the strata, the standard deviation of the carbon within the strata, and the size (ha) of the strata. This was calculated using the MSU-MRV Toolbox (Skole and Samek, 2016).

Establishing cluster plots.

The starting point for establishing the cluster was taken from the random location generated by the Toolbox sample frame allocation provided by MSU to each inventory team (Skole and Samek, 2016). Clustering of plots within one area allowed field crews to sample a large area while reducing travel time between plots. This is often recommended for natural forest areas and areas that have been selectively logged as was the case with the forests being inventoried. A cluster sample using 3 center points for 3 nested circular plots is recommended as the most suitable design to cope with access issues and ease of implementation. The layout of the nested plot cluster is shown below.

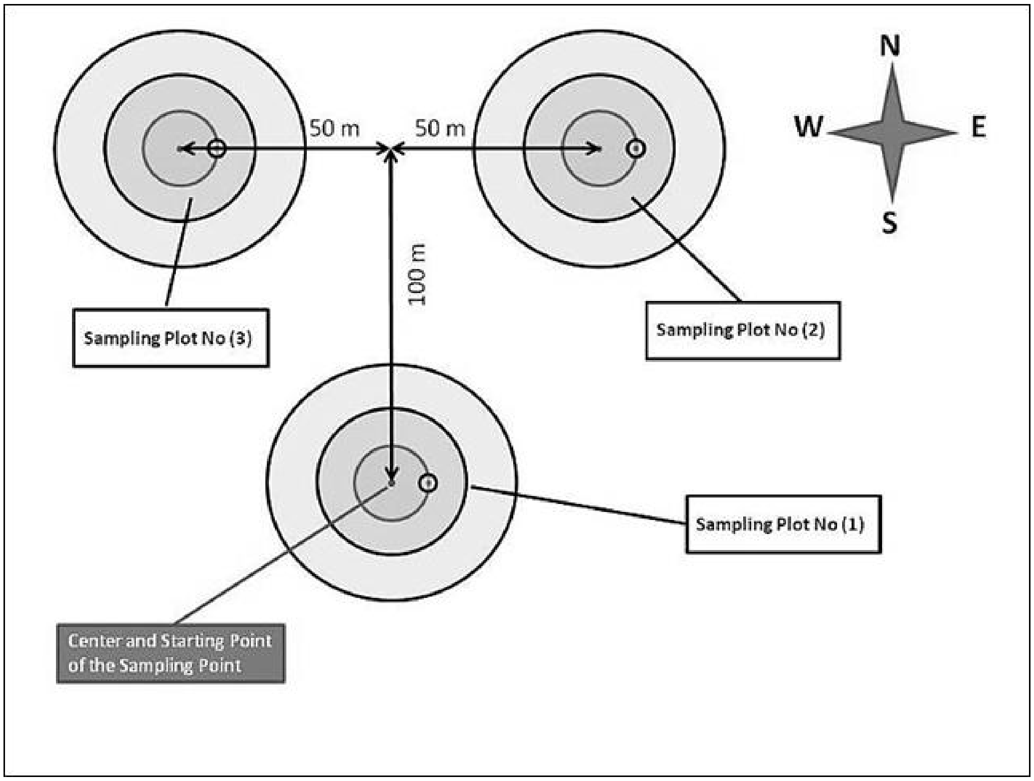


Figure 24: The layout of the nested plot cluster.

Each center point was monumented by taking its GPS reading, for each center point and driving a piece of rebar iron rod into the ground.

Establishing sample plot areas.

The selection of sample trees was done in fixed radius nested circular plots, which are easy to establish in the field and can be demarcated with simple tools and procedures. The three nested plots for each cluster are described above. In each of these plots in the cluster, trees were measured for aboveground biomass, and deadwood shall be measured.

The sampling point design applied in the field inventory follows this scheme for a nest plots design to capture both large and small trees. The fixed radius circular plots had concentric plots at the following radii:

1. 6 m Radius Circular Plot – small trees 5 – 15 cm DBH
2. 12 m Radius Circular Plot – medium trees 15 – 30 cm DBH
3. 20 m Radius Circular Plot – big trees > 30 cm DBH

In addition, there was a one 2m radius clip plot used to collect seedlings for regeneration estimates. This plot was placed due East with a center at 6 m radius. The design of each nested fixed radius plot is shown below.

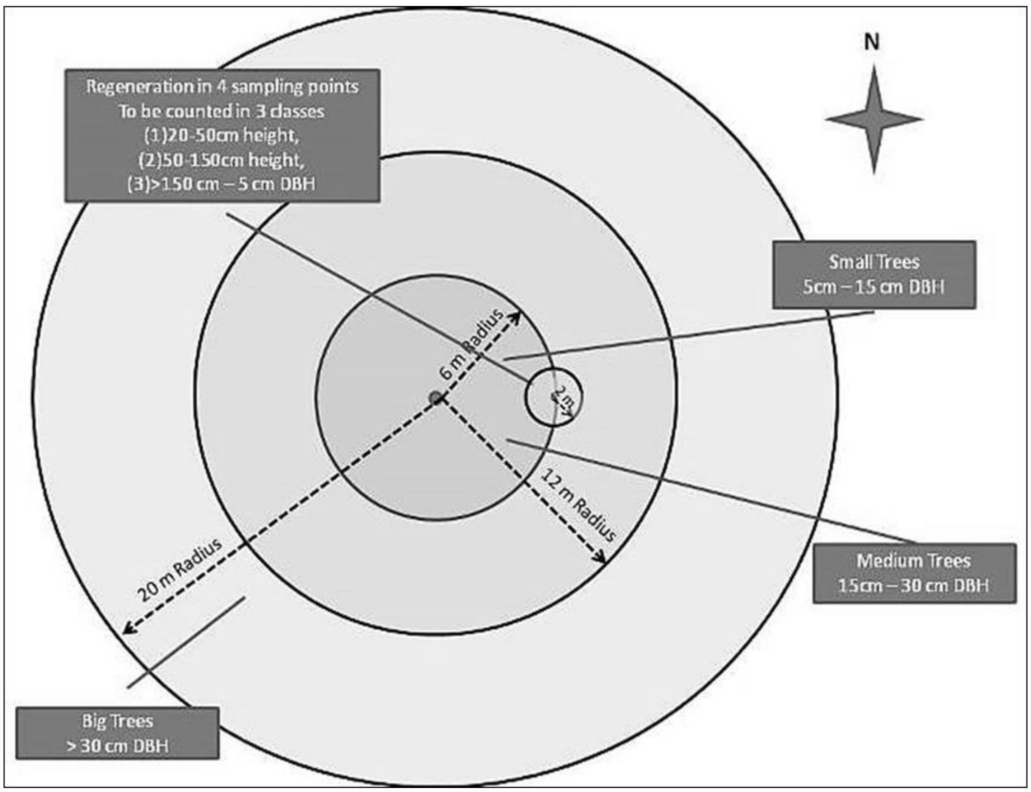


Figure 25: The design of each nested fixed radius plot.

Tree measurements.

The estimation of forest biomass (and timber volume) was based on tree characteristics that were measured and assessed from the sampled trees:

1. Species – all trees

2. Diameter at breast height – all trees

3. Canopy height – all trees > 15 cm (only measured at the primary plot)

4. Canopy projected area – all trees > 15 cm (only measured at the primary plot)

Deadwood assessment.

The dead wood assessment covered two types of dead wood that occur in the sample plots. The standing dead wood and dead wood lying on the ground. The plot layout for assessing dead wood is shown below. The aim was to measure tree/wood length inside the largest plot circle, and the mid-diameter. I do not consider deadwood in our calculations for biomass.

Plot area correction when plots are on sloping ground.

If the plot was located on sloping land, a slope correction factor was applied to the layout of the plot. The distance between two points, measured along one slope (d1) is always longer than an equivalent horizontal distance (h1). On slope terrain, the horizontal distance was multiplied by a factor that corresponds to the inclination to obtain a corrected distance.

For simplicity, a table was used to give the slope correction factor and corrected distance. For horizontal distances not included in the table, the corrected distance can be calculated by multiplying the slope correction factor of the known slope by the horizontal distance.

Since carbon measurements are reported on a horizontal-projection basis, I used a correction factor for plots established on sloping lands. This correction factor accounted for the fact that when distances measured along a slope are projected to the horizontal plane, they will be smaller. If the plot falls on a slope that is greater than 10%, then slope angle should be measured using a clinometer so that an adjustment can be made to the plot area at the time of analysis. If the slope is less than 10%, correction is not required. The calculation of area correction was done during data analysis. In the field, only the average slope measurement was taken.

Following data collection, the slope was used to estimate the projected horizontal area of the plot (see Figure below). It is recommended this be done as part of data analysis within a computer spreadsheet.

$L_{horizontal} = L_{field} * \cos(slope)$

Where:

$L_{horizontal}$ True horizontal length; m (for circular plots, this will be the radius)

L_{field} Length measured in the field, parallel with the slope; m (for circular plots, this will be the radius)

Slope Slope, measured in degrees.

Cos The cosine of the angle

Procedure for labeling plots

A standardized and hierarchical schema was established for labeling the cluster plots. Each plot was identified by the following code scheme and all data for the plot as a label is associated with it. A metadata record for each code corresponding to the basic data collected at the site is available.

CPPP-gggg-NN-rr

Code scheme followed the syntax as shown in table 10 below:

Table 10: Coding syntax for recording metadata

Code	Description	Notes	Valids
C	Campaign number	The campaign or inventory number, not likely more than 3	Integer, 1-3
PPP	The pilot landscape	This is the name of the forest reserve	LIW, NTZ, PER
gggg	The initial random point	The location of first plot in cluster, the Master Plot, that has a GPS from the Toolbox	Integer, 0001-1000, 999 reserved for "no data"
NN	The Master (1st), East (2nd) or West (3rd) plot in the cluster	Will always be 01 for Master, 02 for East and 03 for West Cluster	Integer, 01, 02 or 03
rr	The radius of the nested plot	Will aways be 20, 12 or 06	Integer, 20, 12, 06

Example for the 30th random cluster from the Toolbox assignment, the East plot, 20-meter radius, in Liwonde:

1LIW-0030-02-20

In addition to tagging the monument, three metal tags were fixed to three trees in each of the sub plots. All other ancillary and measurement data for the plots are kept in a database with the specific plot label associated with it.

Establishment of plots in the field

Field crews were deployed to the field using a separate Deployment Management Plan that showed a calendar of activities and locations. This was done between June 9th to July 20th, 2016. To establish the cluster plot in the field, the following protocol was followed by each team:

1. Navigate to predetermined latitude and longitude using a GPS based on the report provided by the Toolkit from MSU.
2. Walk an additional 10 steps in the direction of travel. These additional steps reduce bias in choosing the plot center. For circular plots, this will be the plot center.
3. At the plot center/corner, mark a 'waypoint' on GPS and record GPS coordinates, accuracy, elevation, and waypoint number on data sheet.
4. Label the plot based on SOP Labeling Plots described above.
5. Measure the slope using a clinometer. If the slope is greater than 10% record the exact slope for later correction of plot area.
6. Describe land and vegetation conditions of plot and if there is anything unique or unusual in the plot or directly surrounding the plot. This could include things such as small streams, trails, large boulders or termite nests, and proximity to a paved road.
7. For permanent plots only: write detailed instructions on how to access the plot in the future. Note any hazards encountered on the route to the plot.
8. Mark the center of the plot with a wooden stake wrapped with flagging tape. This plot center mark will be used to identify the plot center during any third-party verification or quality checks.

Monumenting the cluster plots.

At the plot center / corners, the team hammered a ~30 cm section of metal pipe/rebar into the ground. The metal pipe/bar was hammered until it was completely in the ground. If there were rocks or other obstructions in the soil, the metal pipe/bar was moved to another spot (within 2 m of the original location). The monumenting is important so that the plot be identified permanently for future monitoring.

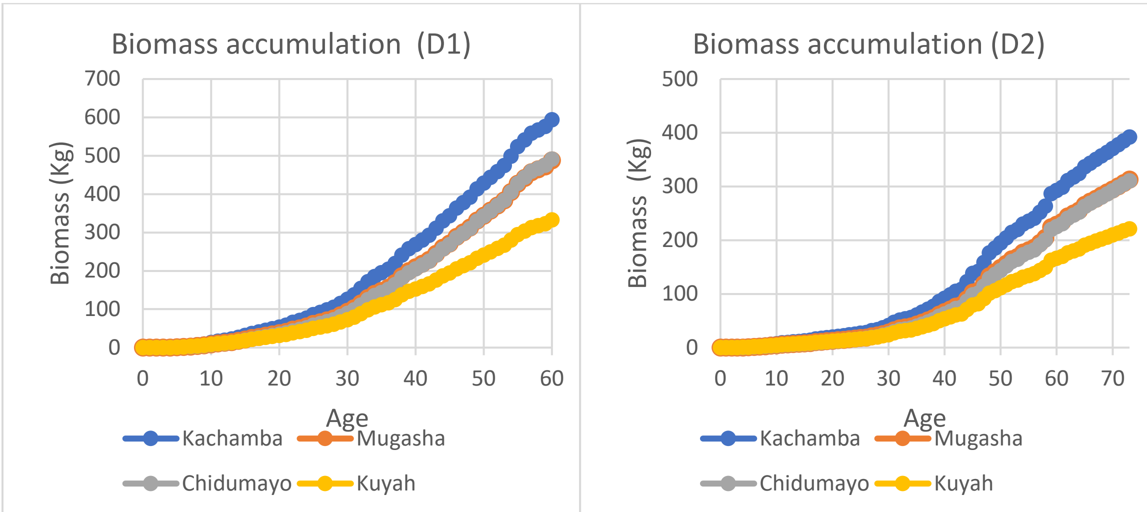
Alternative plots

If the initial location was not appropriate for the establishment of the primary plot. The team following the SOP guidance would move north 50 meters and record that the plot location had been shifted. If either one of the secondary plots was not suitable, for instance lying on a road, then they would continue another 50 meters to the first available location and make note.

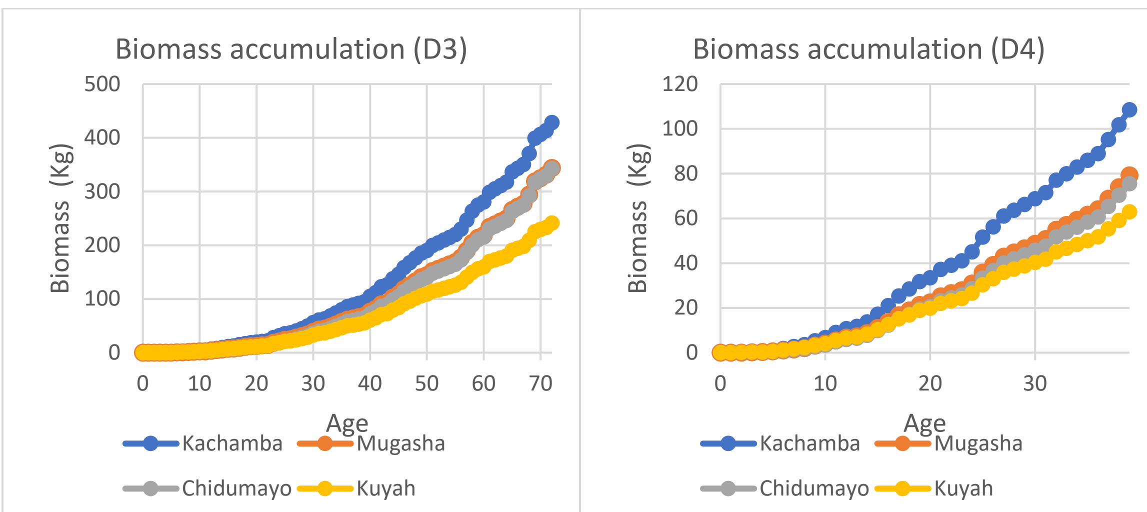
Field safety measures

The Winrock guide (Walker et al. 2012) spelled out all safety measures that needed to be adhered to during the inventory. No matter what activities are engaged in or where they are carried out, safety is the priority, and all precautions must be well thought out in advance and then strictly adhered to. Planned field activities must remain flexible and allow for adjustments in response to on-the-ground assessments of hazards and safety conditions. Accordingly, field personnel must be vigilant and always avoid unnecessary risks

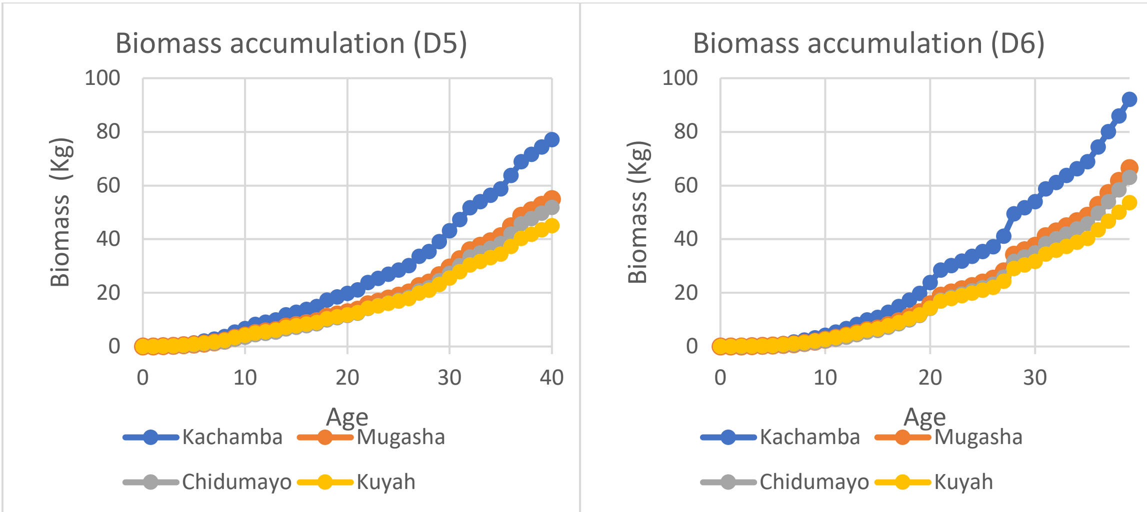
APPENDIX B: MODEL COMPARISON OF BIOMASS INCREASE PER DISC



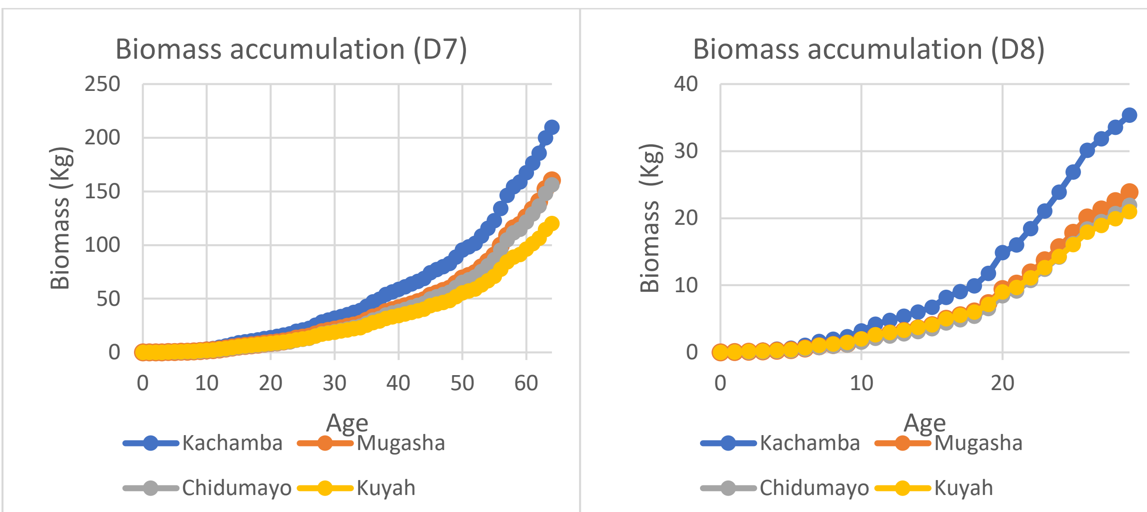
Figures 26 and 27: Discs 1 and 2 showing Biomass accumulation



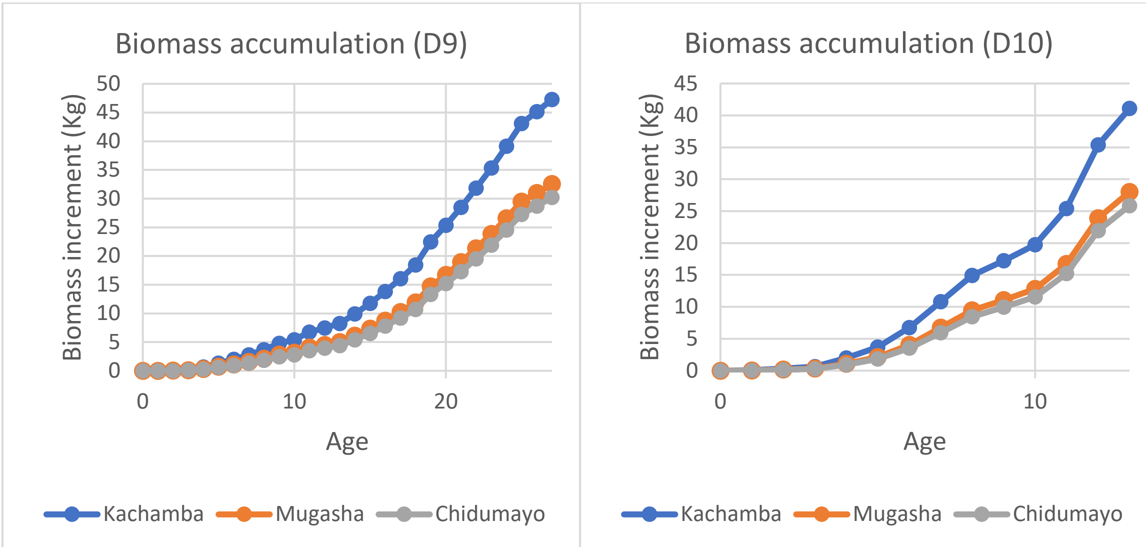
Figures 28 and 29: Discs 3 and 4 showing Biomass accumulation



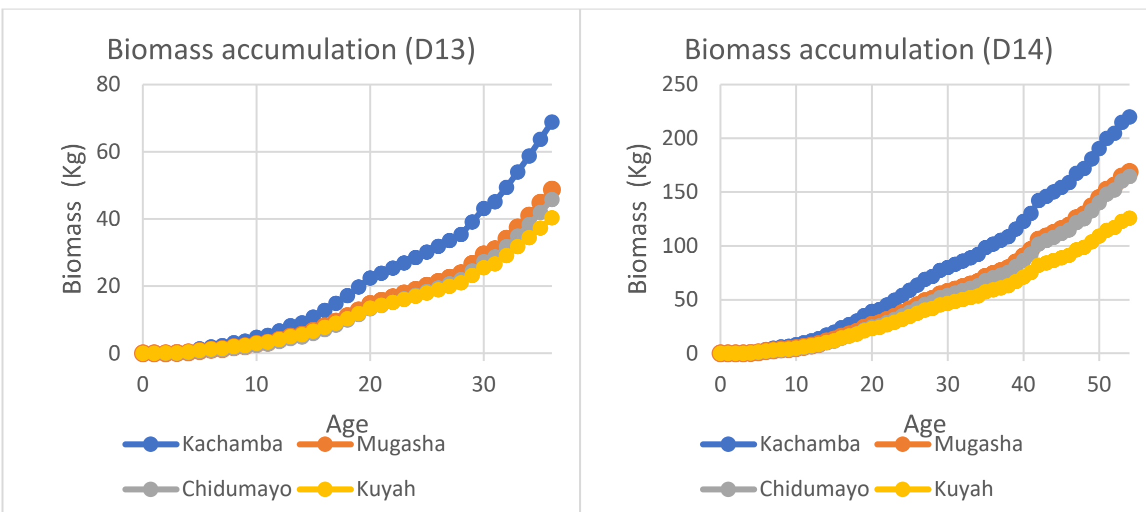
Figures 30 and 31: Discs 5 and 6 showing Biomass accumulation



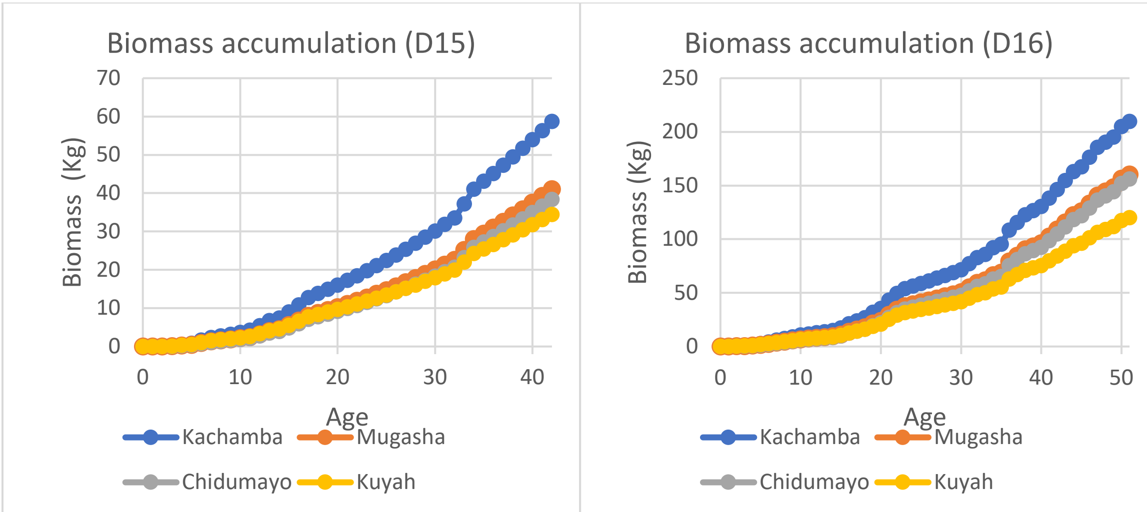
Figures 32 and 33: Discs 7 and 8 showing Biomass accumulation



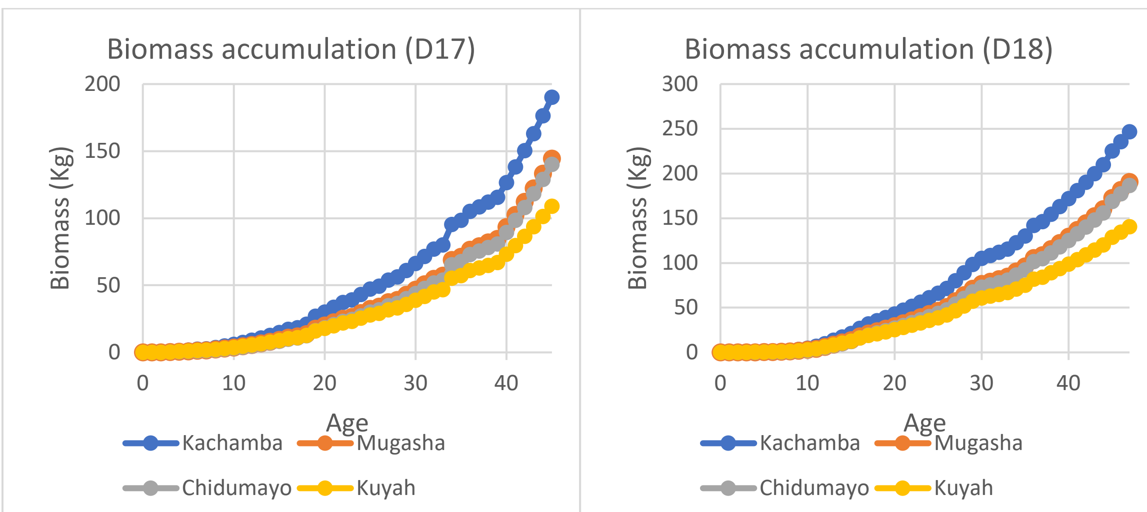
Figures 34 and 35: Discs 9 and 10 showing Biomass accumulation



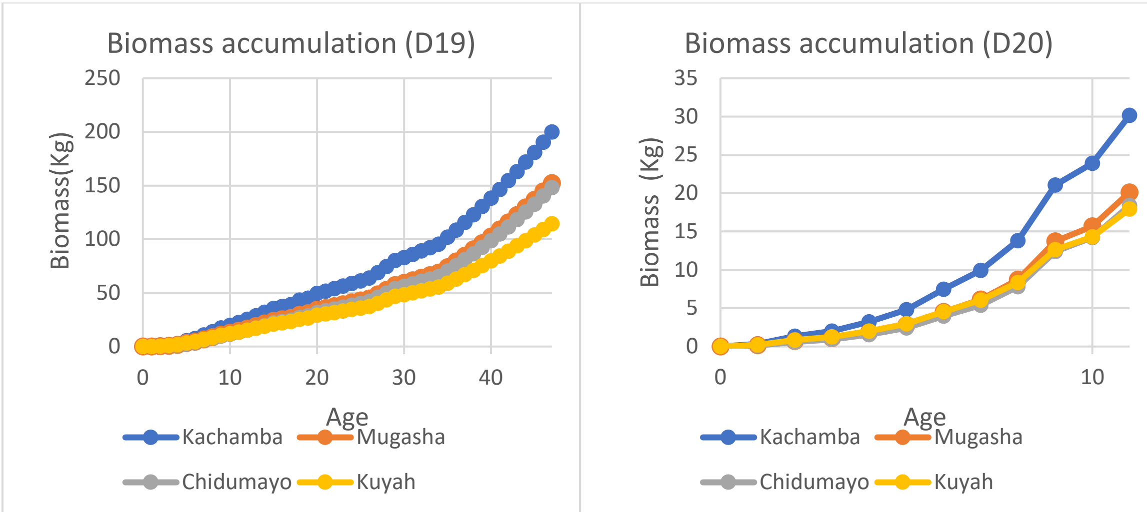
Figures 36 and 37: Discs13 and 14 showing Biomass accumulation



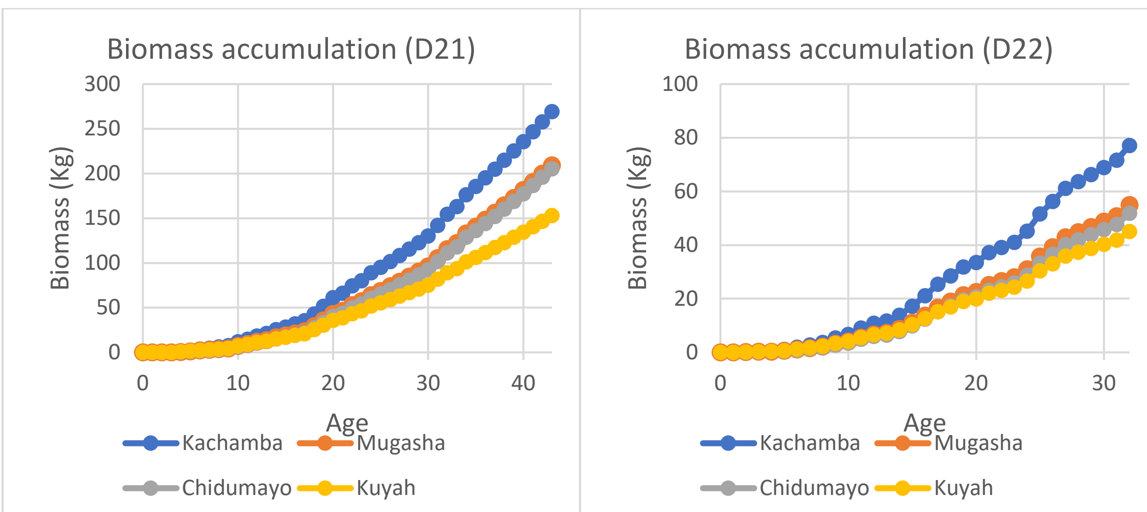
Figures 38 and 39: Discs 15 and 16 showing Biomass accumulation



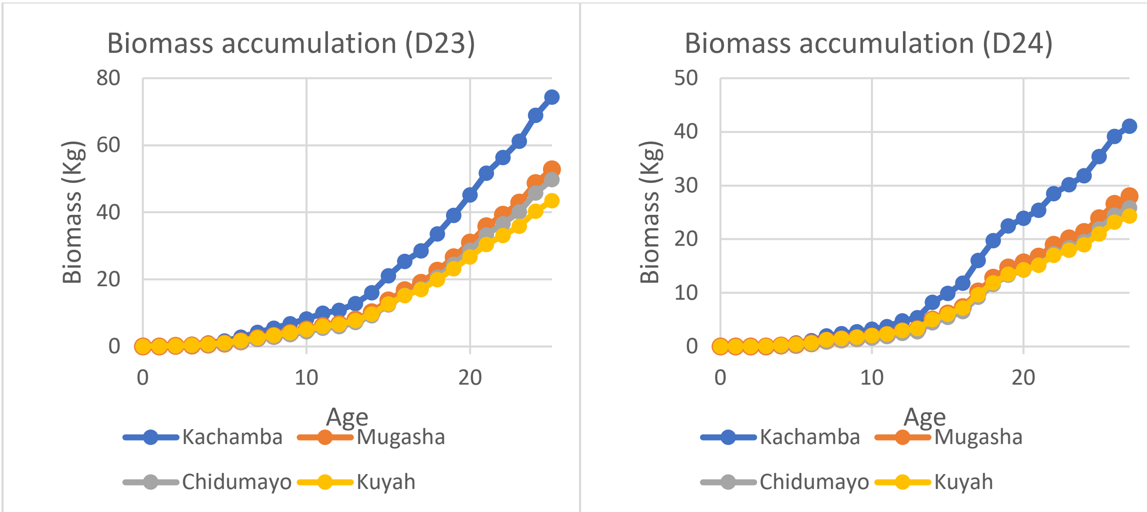
Figures 40 and 41: Discs 17 and 18 showing Biomass accumulation



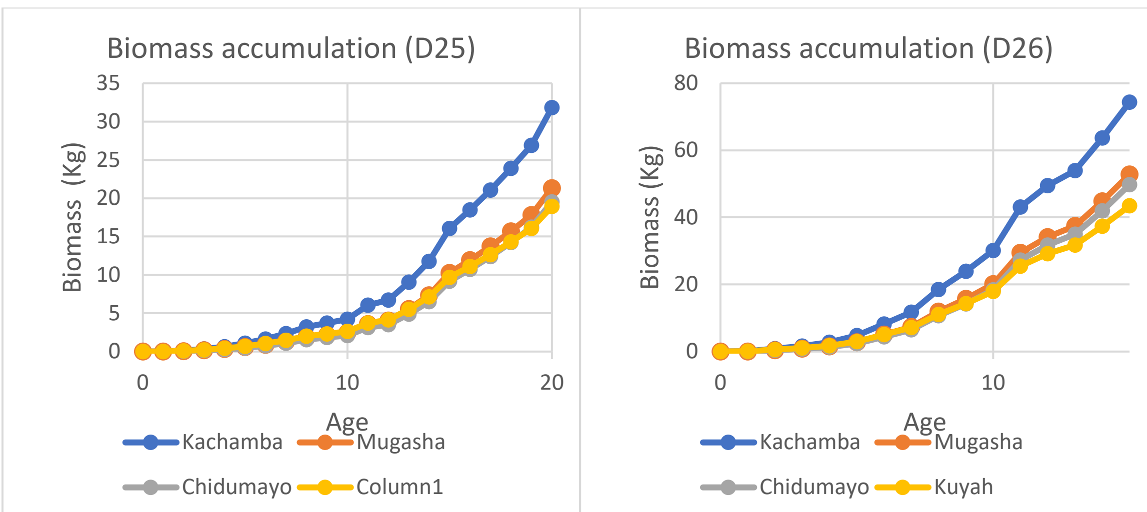
Figures 42 and 43: Discs 19 and 20 showing Biomass accumulation



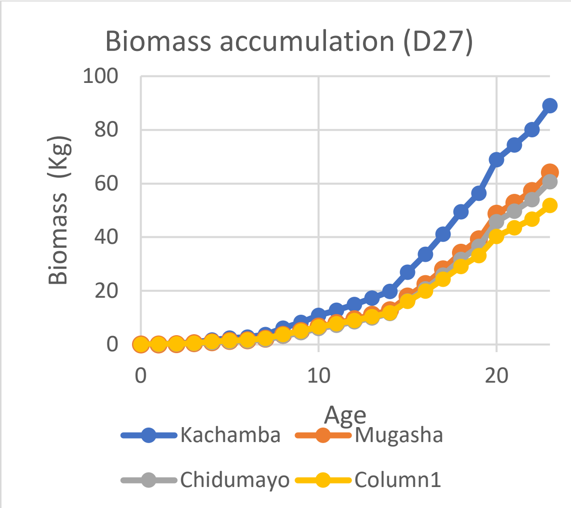
Figures 44 and 45: Discs 21 and 22 showing Biomass accumulation

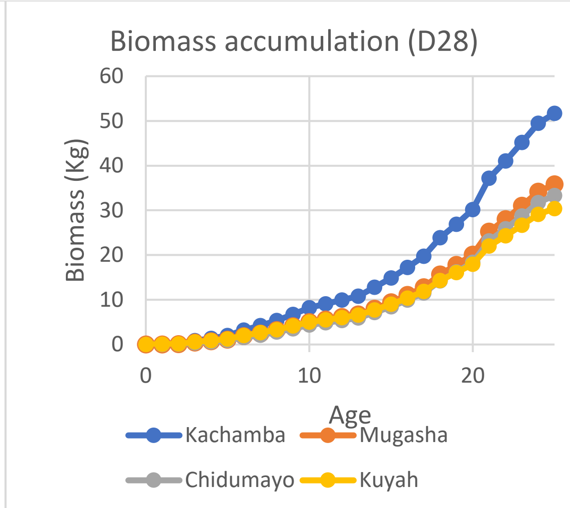


Figures 46 and 47: Discs 23 and 24 showing Biomass accumulation

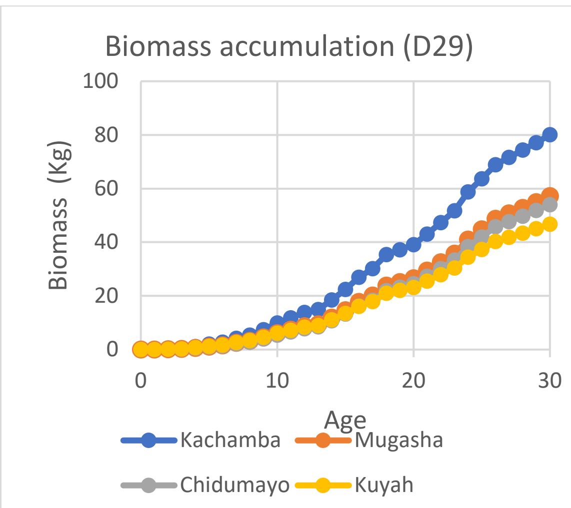


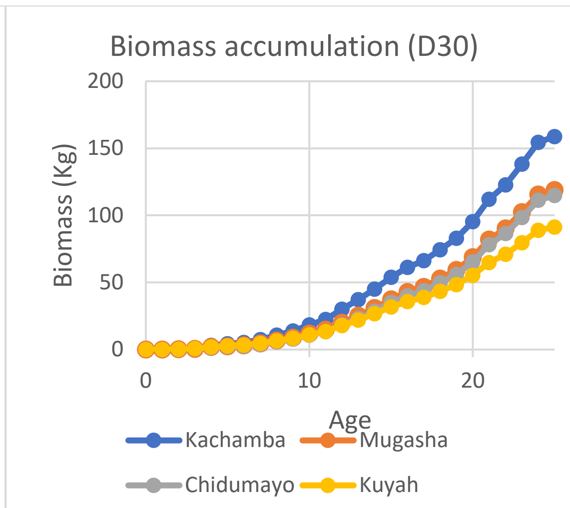
Figures 48 and 49: Discs 25 and 26 showing Biomass accumulation



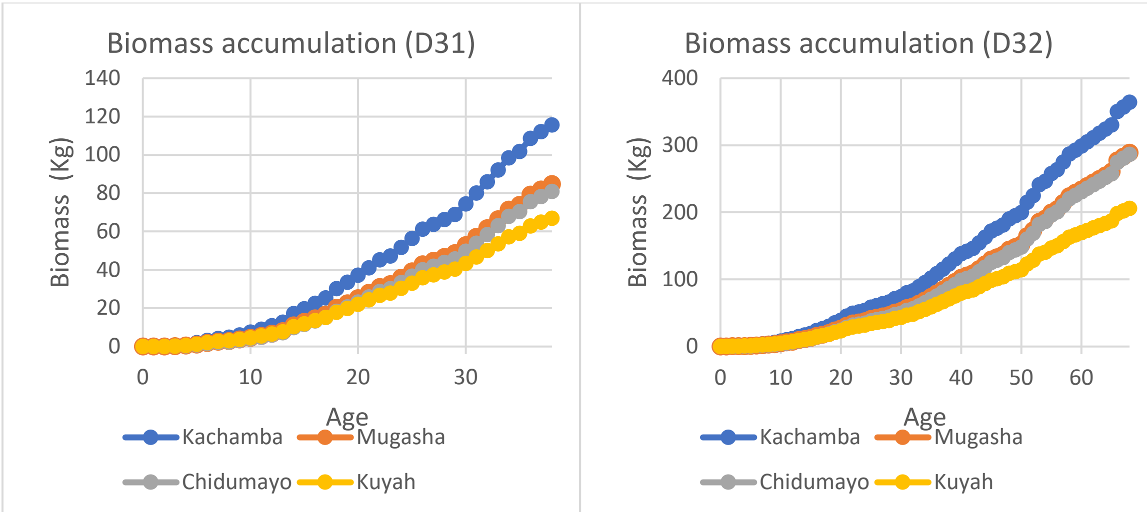


Figures 50 and 51: Discs 27 and 28 showing Biomass accumulation





Figures 52 and 53: Discs 29 and 30 showing Biomass accumulation



Figures 54 and 55: Discs 31 and 32 showing Biomass accumulation

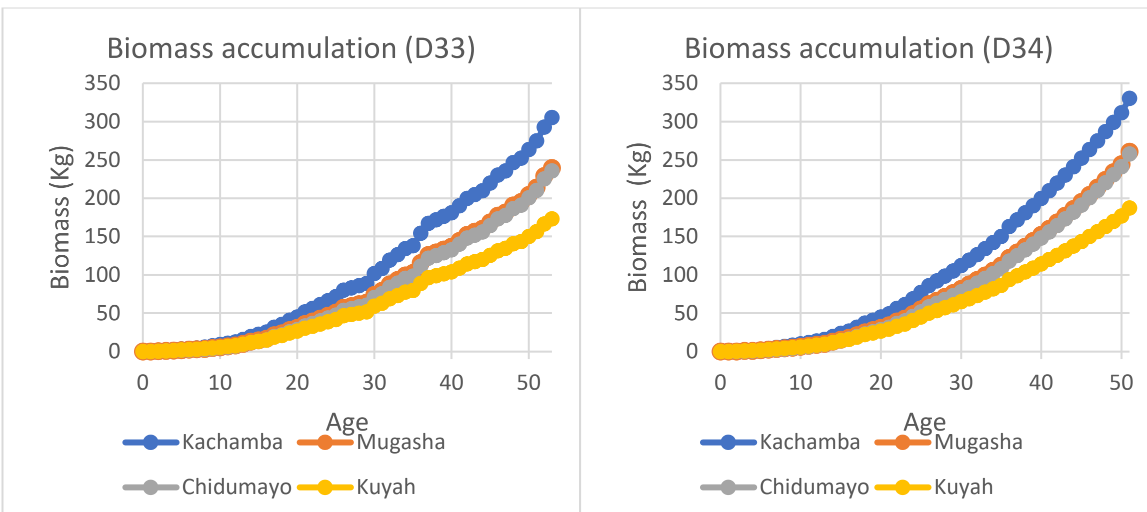
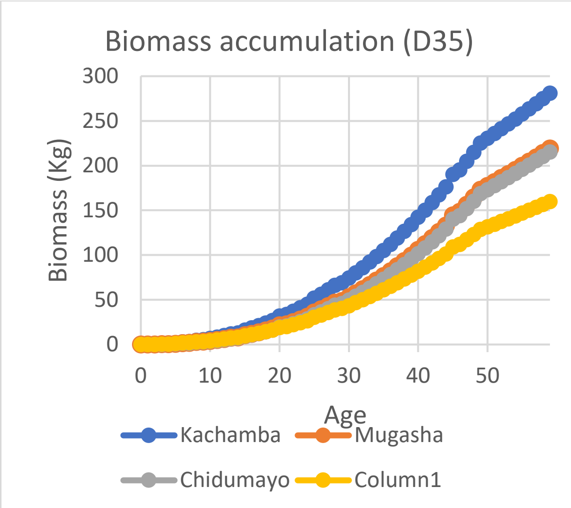
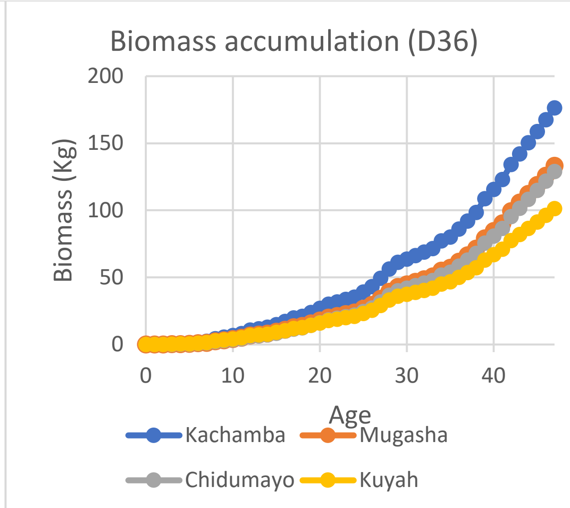
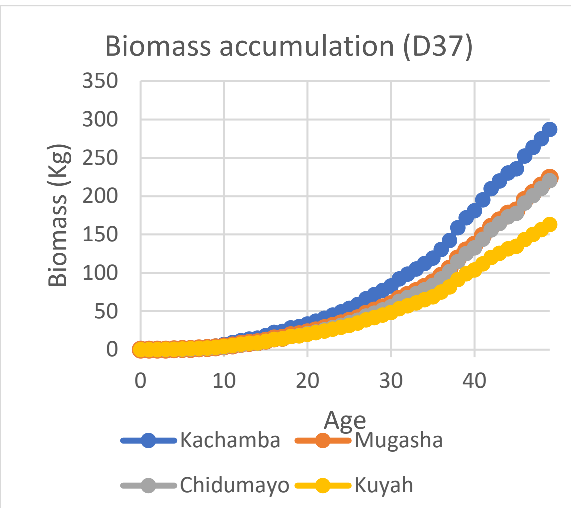


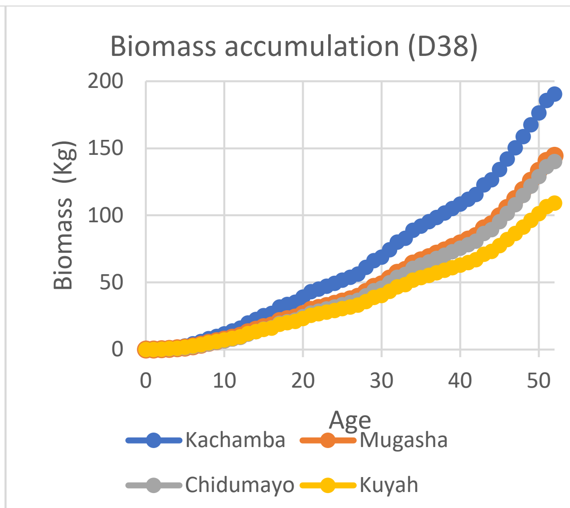
Figure 56 and 57: Discs 33 and 34 showing Biomass accumulation



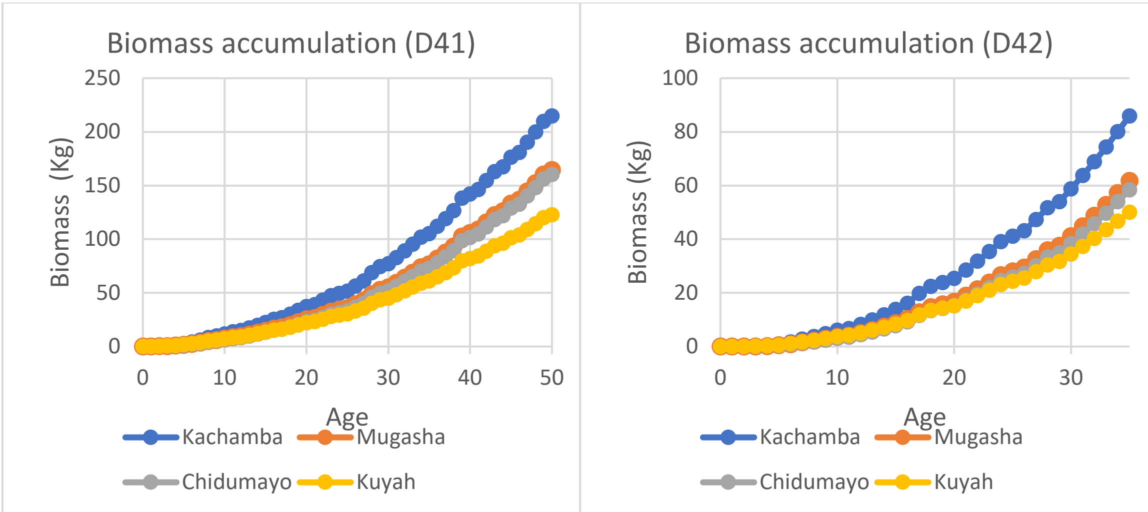


Figures 57 and 58: Discs 35 and 36 showing Biomass accumulation

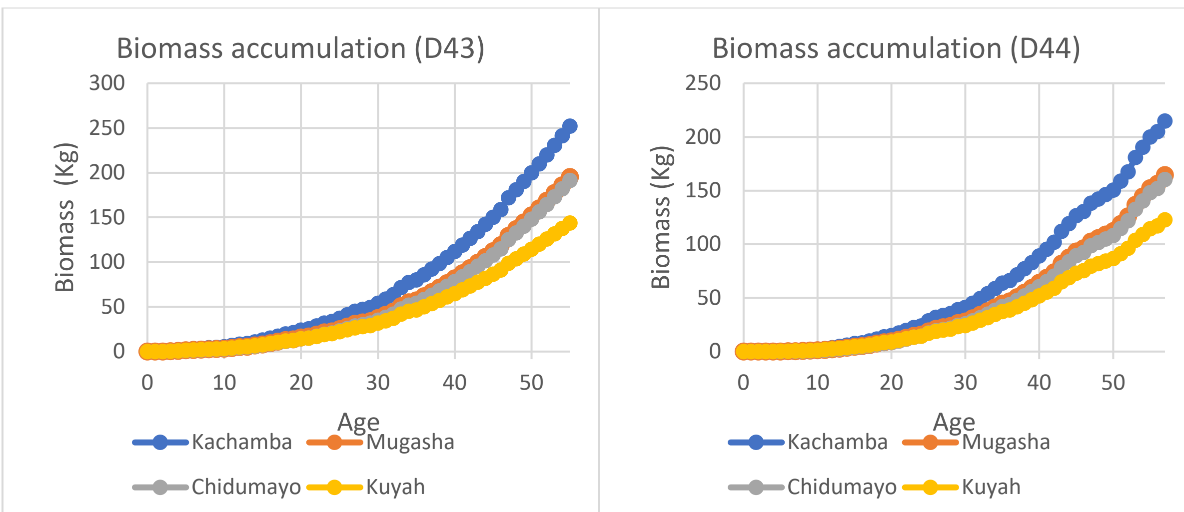




Figures 59 and 60: Discs 37 and 38 showing Biomass accumulation



Figures 61 and 62: Discs 41 and 42 showing Biomass accumulation



Figures 63 and 64: Discs 43 and 44 showing Biomass accumulation

APPENDIX C: SIZE CLASS NUMBERS PER PLOT

Table 11 Summarized table of trees per size class in each plot

	Size Class	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9	30-34.9	35-39.9	40-44.9	45-49.9	>50
Plot 1	2016	6	5	10	8	5	8	4	2		
	2017	5	5	8	8	4	7	7	3	1	
Plot 2	2016	9	1	2	6	6	9	6			
	2017	9	1	1	3	4	10	5	5		
Plot 3	2016	6	1	2	1	1		3	1		
	2017	4	3	2	1	1		3	1		
Plot 4	2016	5	6	6	13	2	4	11	3	1	
	2017	5	4	7	11	4	3	5	8	3	1
Plot 5	2016	0	1	4	4	3	12	4	4	3	2
	2017	0	1	1	5	4	2	13	2	2	4
Plot 6	2016	1	5	7	3	3	3	8		5	1
	2017	0	3	6	4	2	4	2	8		6
Plot 7	2016	15	4	6	2	2	2		2		3
	2017	14	4	6	2	2	1	2		2	3
Plot 8	2016	9	3	5	2	1			1		
	2017	6	6	3	2	3			1		
Plot 9	2016	20	6	1	0	0	0				
	2017	16	10	1	0	0	0				
Plot 10	2016	10	2	0	2	2	3	4	2		3
	2017	9	3	0	0	2	2	4	4	1	3
11	2016	2	2	2	11	6	7	3			
	2017	2	0	2	7	8	8	3	2		
12	2016	7	1	5	1	1	5	5	3		2
	2017	4	4	5	0	2	1	4	6	2	2
13	2016	17	4	3	4	4	3	3		3	
	2017	17	4	3	1	5	3	1	3		3
14	2016	10	8	6	2	6	10	5	4	4	4
	2017	8	10	3	4	4	7	7	4	4	8
15	2016	9	7	0	1	0	0				1
	2017	9	7	0	1	0	0				1
16	2016	17	8	4	0	1	4	6	1	0	1
	2017	15	10	3	1	0	3	4	4	1	1
17	2016	24	3	13	11	2	8	3	2	1	2
	2017	21	5	6	13	6	6	5	2	1	4
18	2016	6	4	9	9	7	7	6	1	1	1
	2017	4	4	7	9	4	8	8	4	1	2
19	2016	15	3	15	6	6	10	4			2
	2017	14	3	8	11	5	7	8	3	1	2
20	2016	3	3	4	10	7	7	9	1	1	4

Table 11 (cont'd)

	Size Class	5-9.9	10-14.9	15-19.9	20-24.9	25-29.9	30-34.9	35-39.9	40-44.9	45-49.9	>50
29	2016	5	0	0	1	0	1				
	2017	5	0	0	1	0	1				
30	2016	6	5	1	3	5	2	3	1	1	
	2017	6	3	2	3	5	1	3	2	2	1
31	2016	11	0	0	5	11	7	7	1	1	1
	2017	9	2	0	2	9	6	7	6	1	2
32	2016	11	1	5	4	4	9	12	3	2	2
	2017	6	6	2	4	4	4	8	12	2	4
33	2016	5	1	3	3	1			1	2	7
	2017	4	2	2	3	1	1		1		8
34	2016	12	1	0	1	0		1			
	2017	9	4	0	1	0			1		
35	2016	10	4	4	1	3	5	3	2		2
	2017	9	4	4	2	3	2	3	3	2	2
36	2016	7	5	8	12	5	9	4	2		1
	2017	7	5	6	9	7	4	10	2	2	1
37	2016	21	3	6	2	2	2	1	1		3
	2017	20	3	7	0	3	1	2	1	1	3
38	2016	10	2	3	0	0	0				
	2017	9	4	0	1	1	0				
39	2016	8	2	1	0	0	1	1			
	2017	6	4	1	0	0	1		1		
40	2016	12	8	7	6	4	7	8	2	4	2
	2017	9	8	6	8	2	10	2	7	2	6
41	2016	11	7	12	5	2	7	3	3	1	
	2017	8	7	7	11	2	6	3	3	3	1
42	2016	15	2	0	0	0	2	1	2		
	2017	13	4	0	0	0	2	1	1	1	
43	2016	6	4	3	3	4	4	5	3	1	1
	2017	6	2	3	3	5	2	3	5	3	2
44	2016	14	3	7	4	3			2		
	2017	14	2	5	5	3	2			2	
45	2016	11	8	4	1	1	5	2	3		
	2017	6	10	5	3	0	2	5	1	3	
46	2016	28	1	2	1	3	0				
	2017	26	2	3	1	1	2				
47	2016	1	3	12	6	6	12	6	1		1

APPENDIX D: LIST AND NUMBER OF INVENTORIED SPECIES

Acacia nilotica	**1**	*Carissa edulis*	**1**	*Faidherbia albida*	**1**	*Parinari curatellifolia*	**41**
Afzelia quanzensis	**1**	*Cassia abbreviata*	**1**	*Faurea rachetiana*	**1**	*Paullinia pinnata*	**1**
Albizia versicolor	**1**	*Catunaregam spinosa*	**8**	*Faurea saligna*	**1**	*Pavetta schumanniana*	**2**
Allophylus africana	**1**	*Combetum molle*	**1**	*Faurea salin*	**1**	*Pericopsis angolensis*	**74**
Annona senegalensis	**8**	*Combretum adeno*	**1**	*Ficus capensis*	**5**	*Pittosporum africanum*	**1**
Antidesma venosum	**4**	*Combretum adenogonium*	**6**	*Ficus ingens*	**1**	*Pittosporum viridiflorum*	**2**
Apodytes dimidiata	**2**	*Combretum molle*	**21**	*Ficus sycomorus*	**3**	*Pleurostylia africana*	**4**
Babgunia madagascariensis	**2**	*Combretum zeyheri*	**15**	*Flacourtia indica*	**5**	*Protea p*	**3**
Bauhinia petersiana	**5**	*Commiphora caerulea*	**1**	*Flarcourtia indica*	**3**	*Pseudolachnostylis*	**7**
Bauhinia thonningii	**12**	*Commiphora mossambi*	**1**	*Garcinia buchananii*	**1**	*Pseudolachnostylis maprouneifolia*	**57**
Bobgunia madagas	**1**	*Crossopteryx febrifuga*	**4**	*Gardenia jovis*	**1**	*Psorospemum febri*	**1**
Bobgunia madagasc	**2**	*Croton megalobotrys*	**1**	*Grewia bicolor*	**1**	*Psorospermum febrifugum*	**6**
Brachestegia utilis	**46**	*Cussonia arborea*	**8**	*Hippocratea parviflora*	**1**	*Pteleopsis myrtifolia*	**3**
Brachystegia boehmii	**68**	*Cussonia spicata*	**3**	*Holarrhena pubescens*	**8**	*Pterocarpus angolensis*	**41**
Brachystegia bussei	**265**	*Dalbergia boehmii*	**5**	*Juberlnadia panic*	**1**	*Rhus natalensis*	**1**
Brachystegia floribunda	**15**	*Dalbergia nitidula*	**27**	*Julbernardia globiflora*	**79**	*Rothmania engleriana*	**1**
Brachystegia glaucescens	**1**	*Dalbergia nyasae*	**21**	*Kirkia acuminata*	**1**	*Securidaca longepedunculata*	**1**
Brachystegia longifolia	**106**	*Dichrostachys cinerea*	**2**	*Lanchocarpus capassa*	**1**	*Sepium ellipticum*	**6**
Brachystegia manga	**110**	*Diospyros kirkii*	**7**	*Lannea discolor*	**55**	*Sterculia quinqueloba*	**1**
Brachystegia microphylla	**43**	*Diospyros mesipilifomis*	**1**	*Lonnea stuhl*	**1**	*Stereopsemum kunthium*	**1**
Brachystegia spiciformis	**44**	*Diospyros squarrosa*	**1**	*maprouneifolia*	**5**	*Stereospermum kunthianum*	**4**
Brachystegia utilis	**22**	*Diplorhynchus condylocarpon*	**72**	*Margaritaria discoidea*	**2**	*Strychnos innocua*	**6**
Bracken zangu	**2**	*Dombeya rotund*	**2**	*Maytenus heterophylla*	**1**	*Strychnos madagas*	**2**
Brackenridgea zanguebarica	**1**	*Drypetes mozambicensis*	**1**	*Monodora junadii*	**2**	*Strychnos spinosa*	**1**
Breonardia salicina	**3**	*Elephantorrhiza goetzei*	**6**	*Monotes africanus*	**14**	*Strychnos spinoza*	**2**
Bridelia cathartica	**17**	*Erythrina abyssinica*	**4**	*Mundulea sericea*	**2**	*Strynchos innocua*	**3**
Bridelia micrantha	**5**	*Erythrophleum sauveolens*	**2**	*Ochna puberula*	**1**	*Syzigium cordatum*	**2**
Briderlia cathartica	**7**	*Euclea crapes*	**2**	*Ochna schweinfurthiana*	**22**	*Tapiphyllum africana*	**1**
Burkea africana	**32**	*Euphorbia matabalensis*	**1**	*Olax dissitifolia*	**9**	*Terminalia steno*	**3**
Byrsocarpus orientalis	**2**			*Olax obtus*	**7**	*Terminalia stenostachya*	**3**
		Xeroderris stuhl	**1**	*Olax obtusifolia*	**15**	*Trema orientalis*	**14**
Vangueria infausta	**8**	*Ximenia amer*	**1**	*Oncoba spinosa*	**1**	*Turraea nilotica*	**2**
Vernonia myriantha	**4**	*Ximenia americana*	**11**	*Ormocarpum kirkii*	**3**	*Uapaca kirkiana*	**68**
Vitex doniana	**4**	*Ximenia caffra*	**5**	*Ozora insigns*	**2**	*Uapaca nitida*	**20**
Vitex payos	**10**	*Zanha africana*	**8**	*Ozoroa insigns*	**18**	*Uapaca sansibarica*	**2**

Figure 65: List and numbers of inventoried species

APPENDIX E: DEFORESTED AND DEGRADED AREAS IN MALAWI'S PROTECTED FORESTS (RESERVES)

Table 12 Deforested and degraded areas in Forest Reserves across Malawi.

	Area (ha)						
Protected Areas	2000-09 Deforested	2000-09 Degraded	2010-15 Deforested	2010-15 Degraded	2016-21 Deforested	2016-21 Degraded	Area of PA (ha)
Amalika Forest Reserve	0	1	17	0	0	0	545
Bangwe F. Reserve	28	89	70	310	478	954	4,487
Bunda Forest Reserve	1	6	1	4	1	15	471
Bunganya Forest Reserve	352	856	113	259	39	256	4,406
Chigumula Forest Reserve	1	1	1	4	0	1	619
Chimaliro Forest Reserve	110	1668	196	1211	133	345	16,302
Chiradzulu Forest Reserv	12	44	7	78	6	59	1,204
Chirobwe Forest Reserve	14	104	27	176	25	168	1,342
Chisasira Forest Reserve	63	247	63	352	28	79	2,569
Chongoni Forest Reserve	179	377	251	477	13	51	12,617
Dedza-Salima Escarpment	283	1261	491	5462	331	1273	26,818
Dedza Mountain F. Reserv	29	30	8	13	1	4	3,022
Dowa Hills F. Reserve	58	225	192	619	2	1	2,391
Dzalanyama Forest Reserv	517	820	2343	14320	1494	8225	97,695
Dzedza Forest Reserve	32	103	10	113	3	7	871
Dzonze	48	75	16	107	22	244	3,672
Kalulu Forest Reserve	1	17	145	1093	11	258	2,239
Kalwe Forest Reserve	30	10	7	1	0	1	116
Kaning'ina Forest Reserv	85	632	50	876	25	194	17,574
Kanjedza Forest Reserve	15	43	12	15	19	5	157
Kasungu National Park	678	1914	6820	11567	77	124	235,863
Kongwe Forest Reserve	35	156	29	73	14	99	1,871
Lake Malawi N. Park	6	10	116	1034	6	25	4,741
Lengwe National Park	268	282	3274	9176	4313	7197	92,819
Lichenya F. Reserve	3	11	21	60	3	15	228
Liwonde Forest Reserve	341	441	504	2500	3682	6303	27,565
Liwonde National Park	908	521	71	174	1568	2369	50,567
Mafinga Hills	12	378	5	22	47	144	4,417
Majete Game Reserve	25	33	1769	19182	1087	3381	64,632
Malabvi Forest Reserve	0	1	0	19	0	7	209
Mangochi	297	1168	287	2060	579	5414	43,755
Masambanjati F. Reserve	0	0	0	24	2	2	98
Masenjere F. Reserve	0	4	3	3	2	14	316
Matandwe F. Reserve	219	525	876	1348	1853	4108	28,596
Mchinji Forest Reserve	100	320	681	991	134	129	16,736
Michese Forest Reserve	90	268	149	1018	241	1127	8,889
Michiru Forest Reserve	23	86	3	117	27	53	2,900
Milare Forest Reserve	0	9	0	3	0	1	101
Msitolengwe F. Reserve	3	10	3	11	1	2	149
Mtangatanga	22	196	41	88	15	88	5,178
Mua-Livulezi F. Reserve	160	507	353	2331	348	1038	10,386
Mua-Tsanya F. Reserve	0	0	18	5	18	6	904

Table 12 (cont'd)

Mughesse	5	102	1	5	4	21	746
Mulanje Mountain Forest	133	485	255	1491	402	2636	47,299
Musisi	22	926	18	52	28	244	6,808
Mvai Forest Reserve	67	90	64	83	238	894	4,272
Mwabvi Game Reserve	232	239	208	160	2905	5196	34,435
Namizimu	779	2530	2578	7724	814	2718	79,731
Ndirande Forest Reserve	29	42	168	148	21	33	1,791
Ngara Forest Reserve	87	137	76	39	0	0	2,184
Nkhotakota Game Reserve	1230	2137	1048	5344	166	1344	178,439
Nkhwadzi Forest Reserve	122	41	60	161	0	9	1,722
North Senga Forest Reser	1	2	25	198	1	0	1,252
Ntchisi Forest Reserve	88	311	83	360	45	162	9,892
Nyika National Park	351	17520	4871	8581	221	1563	309,233
Perekezi Forest Reserve	161	520	305	593	120	278	17,688
Phirilongwe	3	9	5	86	40	161	8,969
Ruvuo Forest Reserve	106	456	8	206	13	95	4,295
Sambani Forest Reserve	0	6	16	23	1	1	120
Soche Forest Reserve	13	55	1	8	1	32	396
South Viphya F. Reserve	364	3002	518	2345	123	740	145,550
Thambani Forest Reserve	18	44	65	1011	1	66	5,153
Thuchila F. Reserve	0	5	165	350	17	38	2,056
Thuma Forest Reserve	200	703	689	3339	165	642	10,589
Thyolo Mountain F. Reser	2	20	85	867	9	72	1,320
Thyolomwani F. Reserve	1	47	22	593	11	122	1,332
Tsamba Forest Reserve	30	93	69	292	2	16	3,091
Uzumara Forest Reserve	0	3	0	0	0	1	615
Vinthukutu Forest Reserv	12	597	16	13	10	47	2,187
Vwaza Game Reserve	6505	18371	2553	3545	1169	819	98,067
Wilindi F. Reserve	5	105	1	4	2	28	946
Zomba -Malosa Forest	140	401	337	927	521	2264	18,984
SUM TOTAL	**15,753**	**62,450**	**33,352**	**115,848**	**23,694**	**64,031**	**1,799,201**

APPENDIX F: UPDATED ANNUAL RATES OF DEFORESTATION AND DEGRADATION IN MALAWI

Table 13: Updated annual deforestation and deforestation rates in Malawi

	Area (ha)		Rate (ha yr-1)	
2000–2009:	Deforested	Degraded	Deforested	Degraded
Intact forests, forest reserves and protected areas	39,661	248,576	4,407	27,620
Customary forests on agricultural and other land	162,028	138,072	18,003	15,341
TOTAL	201,689	386,648	22,410	42,961
2010–2015:				
Intact forests, forest reserves and protected areas	136,040	309,694	22,673	5,161
Customary forests on agricultural and other land	97,584	121,572	16,264	20,262
TOTAL	233,624	431,266	38,937	25,423
2016–2021:				
Intact forests, forest reserves and protected areas	57,175	157,851	9,529	26,309
Customary forests on agricultural and other land	78,662	102,874	13,110	17,146
TOTAL	135,837	260,725	22,640	43,454

APPENDIX G: LISTING OF ALL LANDSAT PATH/ROW COMBINATIONS, ACQUISITION DATE AND SCENE IDENTIFIER FOR IMAGERY USED IN THIS ANALYSIS

Table 14: Landsat acquisition dates and scenic identifier

Path/Row	Year 2000		Year 2010		Year 2015	
	Scene ID	Acq. Date	Scene ID	Acq. Date	Scene ID	Acq. Date
167/70	LE71670702002146SGS00	5/26/2002	LT51670702008155JSA01	5/26/2008	LC81670702015158LGN00 LC81670702014155LGN00* LC81670702015126LGN00*	6/7/2015 6/4/2014 5/6/2015
167/71	LE71670712002146SGS00	5/26/2002	LT51670712009157JSA02	6/6/2009	LC81670712015158LGN00 LC81670712014155LGN00* LC81670712015126LGN00*	6/7/2015 6/4/2014 5/6/2015
167/72	LE71670722002146SGS00	5/26/2002	LE71670722009149ASN00 LT51670722010128JSA00* LT51670722008123JSA00* LT51670722008139MLK00*	5/29/2009 5/8/2010 5/2/2008 5/18/2008	LC81670722015158LGN00 LC81670722014155LGN00* LC81670722015126LGN00*	6/7/2015 6/4/2014 5/6/2015
168/68	LT51680681998134JSA00 LE71680682002073SGS00*	5/14/1998 3/14/2002	LT51680682009148JSA02 LT51680682009164MLK00*	5/28/2009 6/13/2009	LC81680682015229LGN00	8/17/2015
168/69	LT51680691998134JSA00	5/14/1998	LT51680692009148JSA02 LT51680692009180JSA02* LT51680692009148JSA02*	5/28/2009 6/29/2009 5/28/2009	LC81680692015165LGN00 LC81680692015133LGN00*	6/14/2015 5/13/2015
168/70	LT51680701998134JSA00	5/14/1998	LT51680702009148JSA02 LT51680702009180JSA02* LT51680702009164MLK00*	5/28/2009 6/29/2009 6/13/2009	LC81680702015165LGN00 LC81680702015133LGN00*	6/14/2015 5/13/2015
168/71	LT51680711998134JSA00	5/14/1998	LT51680712009148JSA02 LT51680712008130JSA00*	5/28/2009 5/9/2008	LC81680712015165LGN00 LC81680712015133LGN00*	6/14/2015 5/13/2015
169/67	LE71690672002128SGS00 LT51690671998157JSA00* LE71690672002192SGS00* LT51690671999144JSA00*	5/8/2002 6/6/1998 7/11/2002 5/24/1999	LT51690672009155JSA02 LT51690672008185JSA00* LE71690672009259ASN00*	6/4/2009 7/3/2008 9/16/2009	LC81690672015156LGN00	6/5/2015
169/68	LE71690682002128SGS00	5/8/2002	LT51690682009155JSA02	6/4/2009	LC81690682015156LGN00	6/5/2015
169/69	LE71690692002128SGS00	5/8/2002	LT51690692009155JSA02	6/4/2009	LC81690692015156LGN00	6/5/2015
169/70	LE71690702002128SGS00 LE71690702001125SGS00*	5/8/2002 5/5/2001	LT51690702009155JSA02	6/4/2009	LC81690702015156LGN00	6/5/2015