ANALYSIS OF ANNUAL GROWTH PATTERNS OF *MILLETTIA STUHLMANNII*, IN MOZAMBIQUE

By

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Bachelor of Science-Honors, Universidade Eduardo Mondlane, Mozambique 2010
Forest Engineering

A Thesis
Submitted in Partial Fulfillment of the Requirements for the
Master of Science

Department of Geography and Environmental Resources
In the Graduate School
Southern Illinois University Carbondale
August 2013

THESIS APPROVAL

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Southern Illinois University Carbondale
MAY, 03rd 2013

AN ABSTRACT OF THE THESIS OF

IVAN ABDUL DULÁ REMANE, for the Master of Science degree in Geography and Environmental Resources, presented on May 03, 2013, at Southern Illinois University Carbondale.

TITLE: **Analysis of Annual Growth Patterns of *Millettia stuhlmannii*, in Mozambique**

MAJOR PROFESSOR: Dr. Matthew D. Therrell

The tropical hardwood forests of Mozambique are among its most important natural resources. Long-term sustainable management of these resources will require proper forest management, which depends on understanding the growth rates and the life history of important commercial species as well as the impacts of natural forces (e.g., climate variability) and human management. This study analyzes radial growth rate dynamics and climate-growth relationships of *Millettia stuhlmannii* and examines its dendrochronological potential. This tree locally known as Panga-panga or Jambirre is one of the most important timber species in Mozambique. Ranked as a *first class* commercial timber in Mozambique, it is frequently harvested in an unsustainable way and sustainable management of the species is urgently needed for the continued utilization of this resource.

Five different methods demonstrate that the semi-ring porous tree rings of *M. stuhlmannii* are annual: (1) Ring structure and anatomy; (2) Successful cross-dating within and between trees; (3) Ring counting in trees with known age (young trees collected from an experimental “plantation”) (4) Cambial wounding and (5) Correlation between ring width and climate data.

Through these methods, *M. stuhlmannii* trees showed distinct reaction to pinning, adding one annual ring after one year. Cross dating of annual ring width growth was successful within and among selected *M. stuhlmannii* trees, which indicates that this species forms annual rings and that growth responds to an external climate variability. *M. stuhlmannii* annual growth ring boundaries were characterized by alternating patterns of parenchyma and fibre vessels and marginal parenchyma. Precipitation during previous December ($r= 0.30$; $p<0.05$), current February ($r=0.30$; $p<0.05$) and the entire rainy season (NDJFM; $r=0.43$, $p<0.01$) over a long period (1900-1996) showed a significant influence on Panga-panga tree ring growth. Declining rainfall has caused a growth increment decrease since 1940. The results of this study show that the mean annual increment of *M. stuhlmannii* is 0.51 cm/year and it takes about 75 years for an average *M. stuhlmannii* tree to reach the minimum lawful cutting diameter of 40 cm DBH (diameter at breast height). Temporal differences in movement through increasing diameter classes are large among and within classes. The median time necessary for trees to grow into the next diameter class was not statistically significant (*Kruskal-Wallis* chi-squared = 9.568, $p>0.001$). The relationship between stem diameter and percentage of heartwood is significantly high ($R^2 = 0.9701$, $p < 0.0001$) and results suggest that from 33cm diameters on, the HW% remain stable. Partial correlation coefficients show that significant effects on growth to minimum cutting diameter occur while stems move through the 20-30 cm DBH class. This indicates the specific sizes at which silviculture treatments have to be started in order to maximize the productivity of this species. Correlation analyses revealed that heartwood width (HW) is positively correlated with total stem diameter (TSD), cambial Age (Ac), number of rings in heartwood (HWR), heartwood area (HWA), Total stem diameter area (TSDA) and Mean annual increment (MAI). This study suggests that further studies to improve diameter growth rate models as well as volume increment models need to be carried out. Strong correlation with precipitation during the rainy season suggests that this species is potentially useful for future climate reconstruction studies in Mozambique.

Key words**:** *Millettia stuhlmannii*, Annual Tree-rings, Climate, Miombo woodlands, Growth rates, Sustainable forest management, Dendrochronological potential

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ACKNOWLEDGEMENTS

I would first like to extend my gratitude to my advisor Professor Matthew Therrell for mentoring me and giving me insightful critiques during these two years and for giving me this unique opportunity to keep studying and gain more knowledge. Thanks Professor Therrell. I would also like to especially thank my committee members Professor Justin Schoof and Professor Guangxing Wang for all of their feedback and guidance throughout this long and challenging process. Second, I would like to thank Mr. James White (Catapú concession owner) for providing cross-sections free of cost that made it possible to accomplish this thesis. It is also important for me to acknowledge the field workers at Catapú who helped us during the collection of the samples and Professor Loren Intolubbe-Chmil for encouraging me all the time throughout my graduate school years.

Thanks also to Professor Judith Davie (Biochemistry), Professor Derek J. Fisher (Microbiology) and Bo Zhu (PhD candidate) for letting me use their department resources during my research.

Obrigado!!!

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CHAPTER 1

INTRODUCTION

Background

Past climate variability has had both direct and indirect effects on ecological processes and human economies. Mozambique is vulnerable to frequent climate disasters (floods and droughts), which significantly impact the population especially agriculture and economic growth. The economy in Mozambique and in other countries of southern Africa strongly depends on agriculture, which has and continues to be highly affected by global climate change. In many regions of the world, meteorological records are too sparse to investigate long-term climate patterns and the data acquired from these stations are limited to recent decades providing poor temporal and spatial coverage (Díaz et al., 2001).

Due to its geographical location, southern Africa is susceptible to extreme weather events and great inter-annual variability of the hydrological cycle (Fauchereau et al., 2003). Add to this the fast growing population and the resulting increased pressure on the natural and artificial water systems makes the region vulnerable to potential changes in the hydrological cycle due to global warming (IPCC, 2007). In Mozambique there are currently 32 synoptic weather stations distributed throughout the country. Most of climate records began in the 1960s and are often incomplete. Those weather stations present little information on the variability of the climate (Tadross, 2009).

Increases in atmospheric CO_2 due to anthropogenic emission are causing significant changes in climate (Cox et al., 2000). Extreme climate events have tremendous negative impacts on natural resources and economies of developing countries. Long term climate variability data is required to better understand the intensity, distribution and frequency of these extreme events.

Tree rings have been widely used as proxies for reconstructing long term climate events and forest growth dynamics. However in tropical regions, few dendrochronological studies are available (Rozendaal and Zuidema, 2011). Tropical forests are the largest terrestrial carbon sink and play an important role on carbon uptake and reduction of surface albedo (Betts, 2000; Cox et al., 2000). Less is known about tropical forest dynamics (Alvarez-Buylla, 1998; Worbes, 2002) and the degradation of these ecosystems around the world is increasing, resulting in significant releases of anthropogenic CO_2.

Records of growth increment (ring width) variability can provide important information for ecological and forest management. Increment estimation by ring-width can provide important information for sustainable management of forest resources (Worbes, 2002). Tree ring based research on radial growth increment dynamics, in southern Africa in general and in Miombo woodlands specifically is sparse (e.g., Stahle, 1999; Therrell et al., 2007). In the past some have argued that tropical trees do not form annual rings (Lieberman et al., 1985; Whitmore, 1990; Worbes, 2002) but several papers have documented annual rings in tropical tree species, such as *Brachystegia floribunda, Isoberlinia angolensis* and *Julbernadia paniculata.* (Syampungani et al., 2010), *Pterocarpus angolensis* (Stahle et al., 1999; Therrell et al., 2007), *Amburana cearensis, Cedrela odorata, Bertholletia excelsa, Cedrelinga catenaeformis, Peltogyne cf heterophylla* and *Tachigali vasquezii* (Brienen and Zuidema, 2005), *Brachystegia spiciformis* (Trout et al., 2009) and other tropical tree species (Rozendaal and Zuidema, 2011).

Mozambique's forest resources occupy around 50% of the land area of the country representing approximately 306.010 km^2 (Marzolli, 2007). In Mozambique, *Millettia stuhlmannii* forests appear as small islands within Miombo woodlands, which are primarily composed of species of genera *Brachystegia*, *Julbernadia*, and *Isoberlinia* (Millington et al., 1994; Campbell, 1996). In Mozambique *Millettia stuhlmannii* is classified as a *first class* timber and has a commercial volume stock/volume of about 4,200 x 10^3 m^3 (Marzolli, 2007), less than the other main species of Miombo wood lands, *Brachystegia boehmii* (14,372 x 10^3 m^3), *Brachystegia spiciformis* (23,214 x 10^3 m^3), *Julbernardia globiflora* (8,681 x 10^3 m^3) and *Pterocarpus angolensis* (5,620 x 10^3 m^3). A few species such as, *Pterocarpus angolensis, Millettia stuhlmannii* and *Afzelia quanzensis* are in high commercial demand for international marketing (around 78% of commercial wood comes from these three species) (Marzolli, 2007). This stock, along with intense pressure on a few *target* species coupled with illegal logging might endanger these species population dynamics. Studies in Mozambique regarding radial growth rates of *Millettia stuhlmannii* have been done by Sitoe (1997). However, these studies are based on short term data (three years).

Problem statement

Indirect methods (temporal plots) have been widely used to study tropical forest dynamics (Chidumayo, 1997). Sustainable management plans using indirect methods of studying radial growth rates of some tree species in Mozambique have been done. According to Sitoe (1997) *Millettia stuhlmannii* is the dominant species in the Miombo woodlands in the central part of Mozambique, representing 23% of the average 12 m^2/ha of overall basal area. The species is under pressure due to illegal logging, particularly from Chinese owned or affiliated operators (Mackenzie, 2006). Some of the species that belong to the genus *Millettia* are now classified as endangered (EN) by the IUCN (e.g. *Millettia laurentii* – A1cd. see IUCN list at http://www.iucnredlist.org./).

Studies have been done to determine the annual diameter increments based on the tree diameter at breast height (DBH), crown form and stem quality of this species, but these results are not very accurate because they are mostly based on two to six year periods; attempts to generate more accurate results have been carried out in order to support the development of sustainable management plans. Sitoe (1997) suggests that accurate results can be produced by using longer periods of measurement.

Mozambique's population depends on natural resources and about 70% of the population relies on agriculture to survive (World Bank, 2010). Precipitation plays an important role in agriculture since most of the households practice rain fed agriculture with few external inputs such as fertilizers (Arndt et al., 2010; World Bank, 2010). The agriculture sector accounts for 24 percent of the Gross Domestic Product (GDP) in this region of southern Africa (World Bank, 2010). Uaiene and Arndt (2007) demonstrated that the production of the four main cereals (maize, sorghum, millet and rice) between the 2001/02 and 2004/05 harvest season in Mozambique decreased, and that this may be associated with rainfall variability (drought). This supports the argument for the need to understand rainfall variability in Mozambique. However, studies have shown the weakness of weather records from this region, at capturing high and low frequency precipitation variability and tree rings might be one of the ways to address this issue. Increasing knowledge about tree growth dynamics and their relationship with climate factors can make it possible to predict impacts on forest resources, on agriculture, and can also provide long term climate variability data (through reconstruction) that would contribute to understanding anthropogenic and natural effects on recent climate shifts which have resulted in warming and water scarcity in some regions.

Purpose of the study

This study aims to use dendrochronology to analyze the growth rate dynamics of *Millettia stuhlmannii* in Miombo woodlands of Mozambique and test the potential growth response to climate. This paper describes one of the few research studies of tree rings in the southern Africa region and in Miombo woodlands. Other comparable studies have been done by Stahle et al. (1999), and Therrell et al. (2007). Specifically, the age and radial growth dynamics and the growth response to climate of *Millettia stuhlmannii* are presented. Monthly and seasonal responses to climate are analyzed to detect the influence of climate on growth. The median annual ring-width increment, growth rate dynamics according to size classes, and the effects of each size class on the minimum cutting diameter (MCD) class were also taken into consideration as part of this study. Heartwood (HW), due to its resistance to biological attacks, high density, high quality and darker color is the most desirable portion of the timber and represents the most important outcome of the logging process (Desch and Dinwoodie, 1996). In order to understand HW dynamics, special attention was given to its relationship with the total stem diameter (TSD).

Research questions

1. Does *Millettia stuhlmannii* form annual tree rings and is it possible to use these tree rings to accurately determine growth rates?
2. Is *Millettia Stuhlmannii* annual ring-width correlated with monthly and seasonal precipitation in the growth region (central Mozambique)?

Significance of the study

The results of this study will contribute to understanding natural and anthropogenic effects on tropical forests, and will make it possible for forest managers to effectively determine cutting rotations to implement sound management of tropical species in order to improve timber yields and to devise sustainable conservation plans. This study will also help to understand Miombo woodland species dynamics and ecology, including response to climate variability and change. There is no reference chronology in Mozambique and this study will build the first one representing and advancing the field of dendrochronology for this region. Climate plays an important role not only on tree growth but it also has an influence on forest dynamics (Rozendaal and Zuidema, 2011). The *Millettia stuhlmannii* climate-growth relationship will contribute to the knowledge about climate change impacts on ecology, and will contribute to the development of a chronology network throughout Southern Africa. This chronology will be useful to reconstruct pre-instrumental rainfall variability in Mozambique, a country that is strongly dependent on rainfall for economic development.

CHAPTER 2

LITERATURE REVIEW

2.1 Species Description

Millettia stuhlmannii is a member of the Fabaceae family, Papilionoideae Subfamily. It is also known as Panga-panga (Portuguese, English and French), Jambirre (Portuguese), Partridge wood (English), and Mpangapanga, Mpande (Swahili). The species is abundant in Mozambique, Tanzania, and Zimbabwe and in South Africa (small population). *M. stuhlmannii* is a medium size deciduous tree (growing up to 20m in height). Leaf drop occurs during the dry season, and leaf flush occurs immediately before flowering (September). This species is more common in low-latitude, high rainfall forest and riverine fringe forest (where it reaches greatest size). On rocky hillsides it only reaches 7-10 m in height (Palgrave, 2002). The leaves are large with 3-5 pairs of opposite leaflets, plus a terminal one. Flowers are large, lilac, pea-shaped and appear between November and January (Figure 1). The fruits are flat about 25cm long, with golden brown, velvety hairs and are dehiscent, typically coming in April – May (Palgrave, 2002).

Panga-panga wood has a density of 825 kg/m^3 at 12% moisture content. The timber is very strong and presents values of the modulus of rupture of 152 N/mm^2 and impact bending of 69 N/mm^2 (Ali et. al., 2008). The heartwood of the species is dark brown with tangential white tissue (parenchyma) and is resistant to microorganism attacks. This timber has high value and in Mozambique, Zimbabwe and Tanzania it has been overexploited. Panga-panga timber is widely used for furniture, flooring, veneer and decorative construction (Ali et. al., 2008). In South Africa, Panga-panga roots are widely used by traditional healers as medicine for treating stomach-aches and to protect houses (Tshisikhawe, 2011).

Figure 1: Panga-panga tree (left); flowers and Leaves (Middle); and fruits (right). Downloaded from: http://www.plantzafrica.com, on 9th December, 2011 at 11:27

2.2 Dendrochronological Potential In The Tropics

Dendrochronology is the science concerning spatial and temporal analysis of physical processes based on tree rings (Fritts, 1976). The terminology is derived from Greek, *dendro* standing for tree, *chronos* for time and *logy* for science or study of something.

Andrew Ellicott Douglass, known as the father of this science, recognized in the early 1920s that trees that were cut in Arizona for construction had synchronized ring width patterns allowing exact dating of the rings through matching of these relative similar ring widths (cross-dating) (Fritts, 1976).

Tree rings are layers added as the result of reproductive activity of the vascular cambium cells during the growing season (Figure 2). They are formed by earlywood that is produced at the beginning of the growing season and during rapid radial growth, and late wood that is produced at the end of the growing season when cambial activity slows down (Stokes and Smiley, 1968). Ring boundary formation is caused by photoperiodical conditions (see Trouet et al., 2012 for an overview) and extreme climate (temperature, precipitation and humidity) fluctuation (Schweingruber, 2007, Clark and Clark 1994). In tropical regions, the limiting climate factor for growth is precipitation and dry periods that last for at least two-to three months with precipitation of less than 60 mm per month induce stress on trees resulting in leaf drop and consequently cambial dormancy (ring formation) (Worbes, 1995).

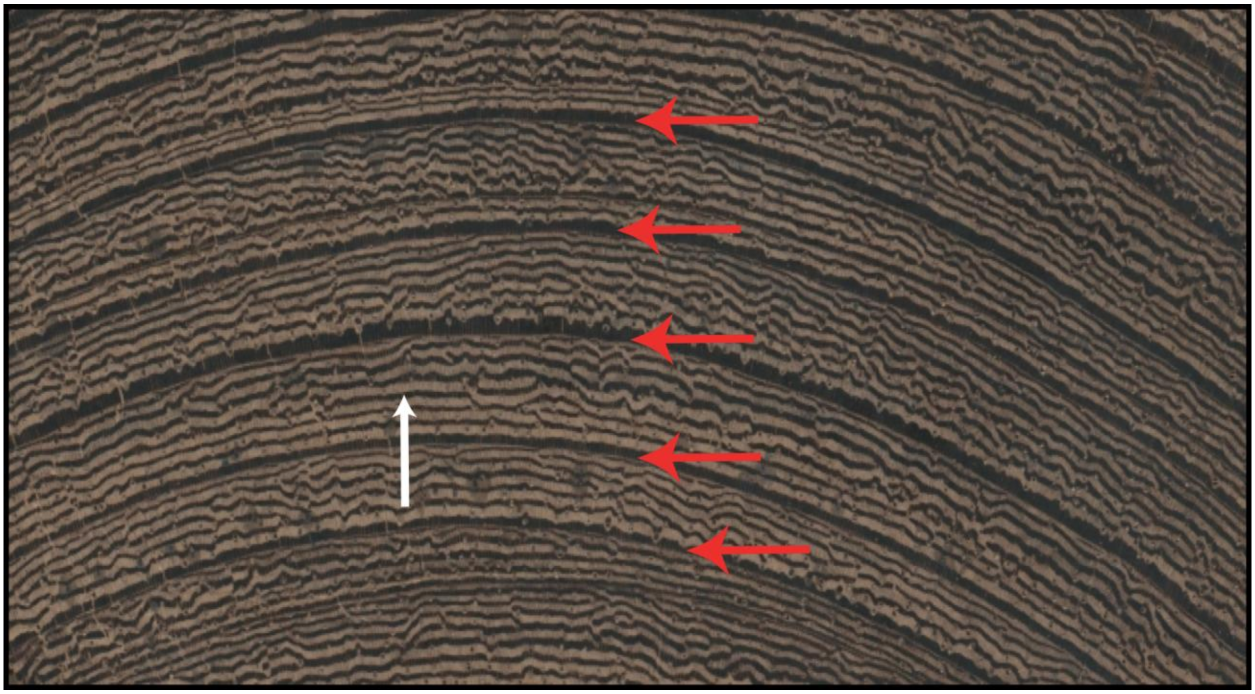

Figure 2: Photomicrograph of *M. stuhlmannii* tree rings in the darker heartwood portion of a cross-sectional sample. . Ring boundaries are marked with arrows (red) and growth direction is marked with a white arrow. It is possible to see fibers in each annual ring (dark zones) and the presence of paratracheal parenchyma surrounding the vessels (light zones). Vessels are distributed randomly in each annual ring

Tree ring width varies among and within species from year to year in response to climate fluctuation during the growing season. Some growth rings are easy to identify, while others are nearly invisible and the distinctiveness is determined by seasonal variation in cell-diameter and cell wall thickness and by the distribution of different kinds of cells within the wood (Hoadley, 1990). When there is a visible contrast between the earlywood and latewood portion of the growth ring the transition from one to another is abrupt and obvious, but there are some cases in which the transition is gradual and it is difficult to exactly determine the ring boundary. That is the case throughout most of the tropics, where there is a lack of clear seasonality so that growth may be consistent year-round and as a result some species may not exhibit apparent growth layers (Hoadley, 1990).

Tree ring boundaries in tropical tree species are characterized by flat fibers. There are species that when growing on good site conditions, tend to have only a few flat latewood tracheids while there are others species that under similar conditions have a wide latewood zone with thick-walled tracheids (Schweingruber, 2007). Tree rings are widely used in temperate regions to understand the ecological dynamics of temperate forests as well as to study climate dynamics. In the tropics, the field of dendrochronology is less developed due to the complex wood anatomy of many tropical species, (including the lack of distinctive ring boundaries, and unclear nature of annual ring formation; Worbes, 2002). Although annual ring formation in the tropics has now been demonstrated for many species (Rozendaal and Zuidema, 2011) there are still challenges to cross-date tropical tree rings due to problems of missing (Trouet et al., 2001; Worbes, 2002) and false rings (Priya and Bhat, 1998; Trout et al., 2001). During years when precipitation is very low, radial growth is minimal and tree rings may not be apparent along the entire circumference of the tree (wedging rings). False rings are due to climate fluctuation occurrences and are very difficult to identify (Stokes and Smiley, 1968). Trout et al. (2001; 2009) found that *Isoberlinia tomentosa* and *Brachystegia spiciformis* presents locally absent rings (wedging) and false rings (caused by dry periods during the wet/growing season) but this was corrected by successfully cross-dating the series.

Since annual ring formation in the tropics has now been supported by evidence, the challenge now resides in dating these and extracting useful information in an effort to better understand forest ecology, management and analyze climate patterns. Four requirements need to be met before performing an analysis on the data derived from tropical tree species (Stokes and Smiley (1968): "(1) evaluate first if the ring formation follows an annual pattern; (2) make sure that only one environmental factor is dominating growth; (3) determine that the limiting factor shows inter-annual variability and whether the resulting annual rings reflect such variation in their width and; (4) the growth limiting factor must be uniform over a large geographical area."

Ring width is not necessarily directly proportional to the growth-limiting factor but the rings must be narrow during times of observed drought and wider in rainy years (in the case of precipitation). This sequence of narrow and wide rings makes cross-dating possible and also allows for the reconstruction of events back in time (Figure 3) using trees of different ages and species (Stokes and Smiley, 1968). Under good conditions throughout the year, the tree ring pattern is complacent, meaning there is not enough variation in ring widths to produce the narrow and wide patterns so the sequence is uniformly wide or uniformly narrow depending on circumstances, making them useless for dating purposes.

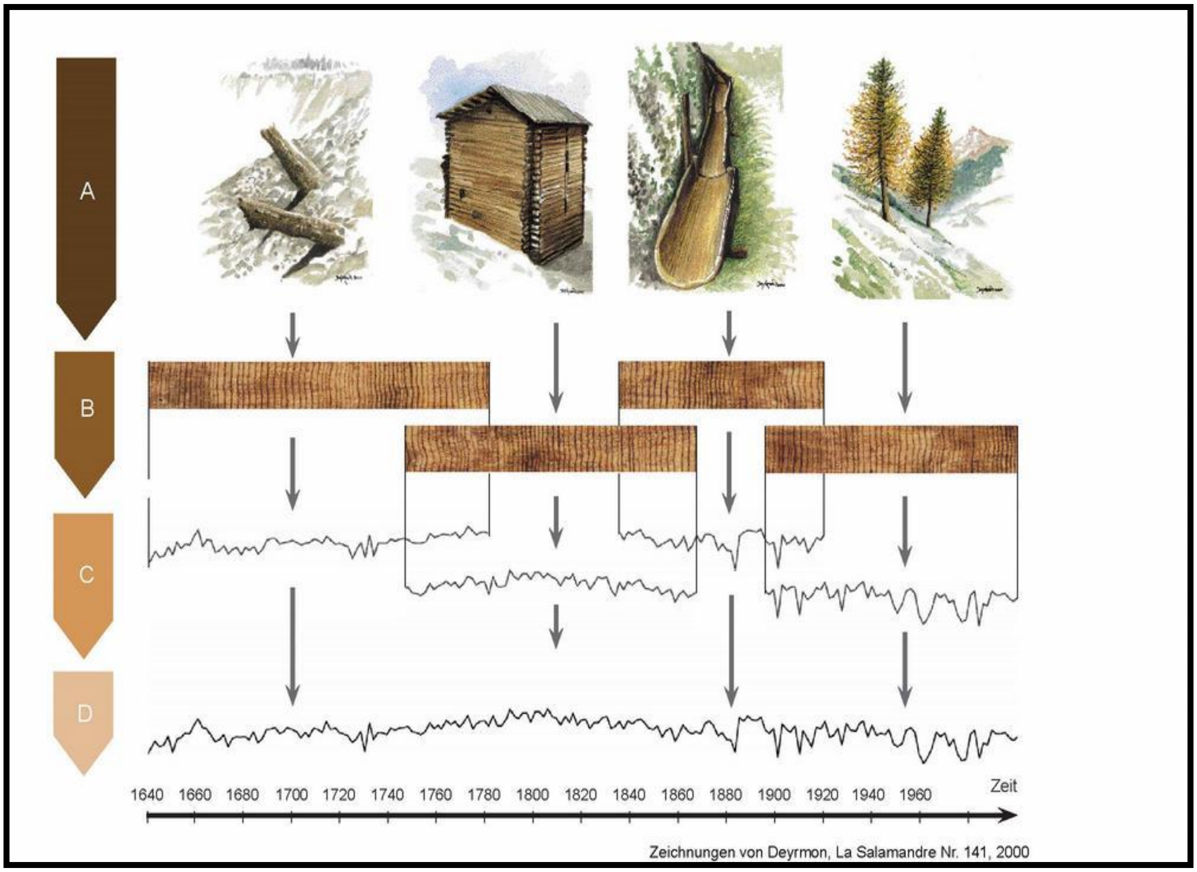

Figure 3: Process of cross dating using specimens with different ages and different sources. Image downloaded from: http://www.fe.ethz.ch/lab/Crossdating

Long chronology development is necessary to better understand tropical forest dynamics, climate variability and its impacts on forest resources as well as on society. Since the annual nature of tree rings is the pre-requisite for using them in dendrochronological studies, the first task before using the information derived from trees is to make sure that the rings are indeed annual. Although tree growth periodicity in the tropics is less well understood, efforts by many authors to prove the dendrochronological potential of the tropical species have been done before (Stahle et al., 1999; Trout et al., 2001; Fichtler et al. 2004) and is currently being conducted by different researchers in the tropics.

There are several approaches to confidently state the nature of the rings (Worbes, 1995). Worbes (1995) groups these methods in two major groups: non-destructive methods and destructive methods. Non-destructive methods consist of phenological analyses, dendrometer bands and cambial activity measuring using a Shigometer. Destructive methods as the name implies, consists of collecting samples from trees. There several destructive methods: wood anatomy analysis, ring counting in trees with known age, cambial wounding, fire scars or pointer years, radiocarbon dating, ring width series analysis, X-ray densitometry, stable isotopes and periodical shoot extension.

Among the different methods to prove the annual nature of tree rings in Africa, cross dating and climate-growth analyses are the most widely used, Dunwiddie and LaMarche Jr, (1980) in South Africa, Stahle et al. (1999) in Zimbabwe, (Fichtler et al., 2004) in Namibia and Trout et al. (2001) in Tanzania, Trout et al. (2006) in Zambia, Belingard et al. (1996) in Congo and Eshete and Stahl (1999) in Ethiopia. Wood anatomy analyses consists of identifying the ring boundaries between two rings. Tropical wood anatomy is complex and ring boundary visibility varies from species to species (see section 2.3 for more details). Despite this complexity, this technique has been applied in the African tropics in four different studies (Stahle et al., 1999; Fitchler et al., 2004; Schongart et al., 2006). Cambial wounding is another method for investigating the annual nature of the tropical tree rings. In this method, trees are deliberately mechanical injured using a nail at a known date (Mariaux, 1967). This method allows an exact ring count from the injured vascular cambium to the bark. Two different studies in Africa have employed this method, Verheyden et al. (2004) in a common mangrove species *Rhizophora mucronata* and Trouet et al. (2012) in a very common species of the Miombo woodlands *Brachystegia spiciformis.* Ring counting from trees with known age is the easiest method

(Worbes, 1995). However this technique relies on the knowledge of the exact date that trees were planted (e.g. plantations). In Africa (tropics), this technique has not been applied very frequently (e.g., Eshete and Stahl, 1999).

2.3 Wood Anatomy of Tropical Tree Species

Annual ring growth and formation are highly dependent on environmental changes (e.g., Stahle, 1999; Worbes, 2002; Therrell et al., 2007; Trouet et al. 2010). Precipitation is the main growth inducing climate factor in the tropics (Rohli and Vega, 2012) due to high inter-annual variability (Fauchereau, et al., 2003) and the almost constant temperature throughout the year (Rozendaal and Zuidema, 2011; Rohli and Vega, 2012). Ring boundaries for tropical species are less distinctive due to the complex anatomy (Worbes, 2002) and different anatomical characteristics of tree growth zones have been reported (Brienen and Zuidema, 2005).

Annual rings have been identified in several species in the tropics (Rozendaal and Zuidema, 2011) in spite of previous reports that they are not annual (Worbes, 2002). However, only a few long-term chronologies exist in the tropics (Therrell et al., 2006; Rozendaal and Zuidema, 2011) due to the occurrence of false and wedge rings in many tropical species (Priya and Bhat, 1998; Trout et. al., 2001 Dunish et al., 2002; Brienen and Zuidema, 2005).

The occurrence of anomalies on the growth rings is a big challenge for the field of dendrochronology (Stokes and Smiley, 1968) because it makes the process of cross-dating difficult between individual trees, leading to weak correlation with climate factors (February and Stock, 1998). Despite all of the issues with the tropical species, the field has developed (Rozendaal and Zuidema, 2011) and more chronologies with lengths of between 150~200 years are now available in western Africa (Schöngart et al., 2006), southern Africa (Therrell et al., 2006) and Ethiopia (Sass-Klaassen et al., 2008).

Maingi (2006) conducted research on 19 different tree species from the Tana riverine forest in Kenya. The author found different anatomical characteristics of the growth zone and he arranged these in three groups: 1) species with marginal parenchyma (*Acacia elatior, Acacia robusta, Albizia gummifera, Lepisanthes senegalensis, Newtonia hildebrandtii, Tamarindus indica, Terminalia brevipes and Trichilia emetica*), 2) species with distinct or abrupt anatomical changes at the growth ring boundary and 3) species with ring porous or semi-ring porous vessel arrangements.

Brienen and Zuidema (2005) studied the relationship between climate (rainfall) and the growth of six Bolivian species. Ring boundaries of each species varied in terms of distinctiveness because “the distinctiveness depends on ring width: wide rings were generally distinct, but distinctiveness decreased with decreasing ring width, e.g. towards the center of the tree or at very large diameters” (Brienen and Zuidema, 2005, p.5). The author used the classification adapted by Worbes (1995), which classifies ring structure in four groups: 1) Density variation (*Tachigali vasquezii* and *Cedrelinga catenaeformis*); 2) marginal parenchyma bands (*Cedrela odorata* and *Peltogyne cf. heterophylla*); 3) repeated patterns of alternating fibre and parenchyma bands (*Bertholletia excelsa*) and 4) variation in vessel distribution and/or vessel size (*Amburana caerensis* and *Peltogyne cf. heterophylla*).

Trouet et al. (2009) observed distinct growth rings on *Brachystegia spiciformis* and ring wedging occurred more frequently in older trees and close to the bark. Stahle et al. (1999) identified semi-ring porous structure of vessels on the growth bands and a line of initial parenchyma on *Pterocarpus angolensis*. This anatomical characteristic is typical of many species in the tropics and temperate forests that also form annual rings. The species also presents differences in vessel diameters and different colors between the beginning and the end of the growth zone (Stahle et al., 1999).

Sousa et al. (2012) found distinct rings on *Tectona grandis* (Teak), characterized by banded parenchyma. They observed a contrast between early-wood and latewood due to differences in vessel size (wide in early wood). The authors also found that wedging and missing rings occur in Teak.

2.4 Annual Tree Ring Based Forest Management In The Tropics

Tropical ecosystems have been experiencing extensive deforestation and overexploitation and relatively little is known about the growth dynamics of many tropical tree species. In order to preserve resources for future generations, sustainable management systems have to be implemented. Knowledge of growth rate, tree longevity and climate responses provides the opportunity not only to understand forest dynamics and productivity but also specific species' ecological requirements. Due to overexploitation and illegal logging, many tropical species are now listed in the IUCN red list (e.g. *Millettia laurentii* also known as Wenge is listed as endangered (EN). It occurs in central Africa and is very similar to *Millettia stuhlmannii*. Both species are used for the same purpose. See the IUCN (2009)). Age determination can be achieved through two methods (Worbes, 1999): 1) Direct method (ring count) and 2) Indirect methods (radiocarbon dating, diameter measurements over known periods (permanent plots) and mathematical equations based on the estimation of mortality. Although indirect methods such as diameter measurement in permanent plots can provide a great deal of information about tropical ecosystems ecology and management, there are still some pitfalls. For instance in the tropics, tree life span data from permanent plots does not extend longer than two decades (Fichtler et al., 2003) and most tropical species have a lifespan of more than one century (Rozendaal and Zuidema, 2011).

Dendrochronology has been widely used to determine age and growth rates of species that have annual rings (Worbes, 2002). Research using tree rings to study age and radial growth of tropical species has been conducted in numerous studies (e.g. Stahle et al., 1999; Brienen and Zuidema, 2005; Trouet et al., 2006; Therrell et al., 2007; and Syampungani et al., 2010). These studies were based on the full range of the tree lifespan, which increases the accuracy of the results.

The growth trajectory of tropical trees differs within and among species. As a result, growth rates within the same species are also different. This is associated with light availably in tropical ecosystems, which plays an important role when trees are juvenile or have not reached the canopy. However, in a study of a semi-deciduous natural forest in Cameroon, Worbes et al. (2003) found that light has an important influence on individual growth rates. They found that species growing under the canopy (understory – up to 15m tall) tend to have slow radial growth (ranging from 0.26 to 0.48 $cm.year^{-1}$) when compared with trees in the main canopy (15-30 m tall) and emergent trees (heights up to 55 m; ranging from 0.36 up to 0.82 $cm.year^{-1}$).

In a study of four threatened tropical tree species in Vietnam, Zuidema et al. (2010) also concluded that light plays an important role in achieving canopy status. They found that large canopy trees had faster growth rates from the juvenile stage.

Brienen and Zuidema (2006) also found different growth trajectories among and within six Bolivian species. The author have found that some species in the Bolivian tropical forest can live beyond 400 years (*Bertholletia excelsa*). Beyond offering the possibilities of looking to the entire lifespan of trees in order to provide accurate growth results and adaquate forest management practices, dendrochronology can also help to understand temporal variations in growth patterns as well as canopy accession patterns of tropical species (e.g., Worbes et al., 2003; Zuidema et al., 2010). Brienen and Zuidema (2006) performed analyses on the time species take to reach the canopy and found large differences. Some trees need many releases (strong growth changes) before reaching the canopy (Brienen and Zuidema, 2006) and fast growth when trees are juvenile plays an important role on the way to the canopy- the “juvenile selection effect” (Rozendaal et al., 2010).

Different authors have found that tropical species in general have slow diameter growth (Table 1). For example, Stahle et al. (1999) found that *P. angolensis* in Zimbabwe had relatively slow radial growth rates and Therrell et al. (2007) found that at even the best sites in southern Africa, it takes more than 80 years for *P. angolensis* trees to reach the MCD. Trouet et al. (2006) also found that *B. spiciformis*, one of the dominant species of Miombo woodlands is also slow growing (~ 0.33 cm/year). This has implications for forest management as the growth rate of certain species helps to identify not only the size of logging concessions but also the allowable cut per year for each species. Growth rate data are also key to promoting Sustainable Forest Management (SFM) in tropical ecosystems, especially because these ecosystems are under massive exploitation, which may result in the commercial extinction of some species.

Table 1: Mean annual diameter increment of some tropical species.

Species name	**Study area**	**Annual diameter increment (cm/yr)**	**Author**
Pterocarpus angolensis	Zimbabwe	0.33 – 0.4	Therrell et al. (2007)
Pterocarpus angolensis	Zimbabwe	0.26 – 0.4	Stahle et al. (1999)
Brachystegia spiciformis	Zambia	0.24 – 0.33	Trouet et al. (2006)
Burkea africana	Zimbabwe	0.17	Holdo (2006)
Millettia stuhlmannii* **	Mozambique	0.38	Sitoe (1999)
Brachystegia spiciformis	Zimbabwe	0.31	Holdo (2006)
Erythrophleum africanum	Zimbabwe	0.16	Holdo (2006)
Pterocarpus angolensis	Zimbabwe	0.03	Holdo (2006)
Terminalia sericea	Zimbabwe	0.22	Holdo (2006)
Acacia senegal	Ethiopia	0.22-0.29	Gebrekirstos et al. (2008)
Acacia seyal	Ethiopia	0.17-0.30	Gebrekirstos et al. (2008)
Acacia tortilis	Ethiopia	0.14-0.23	Gebrekirstos et al. (2008)
Balanites aegyptiaca	Ethiopia	0.16-0.22	Gebrekirstos et al. (2008)

** Based on permanent plots (3 years measurements)

Species specific diameter increments in tropical regions not only depend on light availability (Worbes, et al., 2003) but also depend on the amount of precipitation that falls at a specific place (Stahle et al., 1999). The author found two distinct growth increments for the same species (*Pterocarpus angolensis*) in Zimbabwe (see Stahle et al., 1999 for more details) and many other authors have demonstrated that growth rates in tropical region are influenced by precipitation regimes.

Tropical tree ages are still controversial (e.g., Rozendaal and Zuidema, 2011). Although the age of a tree is not useful for analyzing population dynamics (trees with same age may be different sizes due to environmental effects) (Martínez-Ramos and Alvarez-Buylla, 1998), age might be very useful for climate reconstruction purposes. Rozendaal and Zuidema (2011) in their latest review of tropical dendroecology summarized the ages for nineteen different tropical species (see article for more details). The maximum age reported was 241 years at 45 cm DBH for *Clarisia racemosa* growing in a moist Bolivian tropical forest. However Brienen and Zuidema (2006) have reported that some Bolivian species can live up to 400 years and Martínez-Ramos and Alvarez-Buylla (1998) have reported that trees in the tropical Amazon forest can live beyond 1000 years.

The passage time that trees take to move to the next size class can be an alternative method to analyze tree ages (Martínez-Ramos and Alvarez-Buylla, 1998). Nevertheless this method has been applied in the tropics to study temporal growth changes, class growth dynamics and influences on target diametric sizes (e.g. 40 cm for *M. stuhlmannii*; Brienen and Zuidema, 2006; Therrell, et al., 2007). Brienen and Zuidema (2006) found that all studies species had different growth dynamics. For all species the highest median passage was found in the smallest classes and the smallest diametric classes (0-20 cm) are crucial on the way to the target class. Therrell et al. (2007) performed temporal growth analyzes of *P. angolensis* in nine different places across southern Africa (see article for more details). The authors found that growth at smaller sizes was stable across the entire study area and larger classes (up to 40 cm) had less median time passage to the next class.

Most tropical trees have high commercial value. Heartwood (HW; see Figure 17) is the main product of the harvesting process. Attemps to analyze HW dynamics in the tropics have been done by Shackleton (2002) and Therrell et al. (2007) both for *P. angolensis*. Both authors reported high heartwood-stem diameter dependence.

2.5 Climate-Growth Relationship In The Tropics

Different factors can induce the formation of annual tree rings in the tropics: seasonal rainfall variation (Worbes, 1999), seasonal day length variation (Borchert and Rivera, 2001), temperature variations (Fichtler et al., 2004) and even annual flooding (Schongart et al., 2002) Many studies have shown that climate influences tree growth in various regions of the tropics (Rozendaal and Zuidema, 2011). *Pterocarpus angolensis* (Stahle et al., 1999; Shackleton, 2002; Fichtler et al, 2004; Therrell et al., 2006; Therrell et al., 2007), *Burkea africana* (Fichtler et al., 2004), *Tectona grandis* (Pumijumnong et al., 1995), *Swietenia macrophylla* and *Cedrela odorata* L. (Worbes, 1999; Dϋnisch et. al., 2003), *Acacia tortilis* Hayne, *Acacia seyal* Del, *Acacia Senegal* (L.) Wild. and *Balanites aegyptiaca* (L.) Del. (Gebrekirstos et al., 2008), *Juniper procera* (Sass-Klaassen et al., 2008), *Brachystegia spiciformis* Benth (Trouet et al., 2006; 2009), *Capparis indica* and *Genipa americana* (Enquist and Leffler, 2001), *Annamocarya sinensis, Calocedrus macrolepis, Dacrydium elatum* and *Pinus Kwangtungensis* (Zuidema et al., 2010), *Terminalia guianensis, Cordia apurensis* and *Sapium styllare* (Worbes, 1999), *Mimosa acantholoba* (Brienen et al., 2010), *Tachigali vasquezii*, *Cedrelinga catenaeformis*, *Cedrela odorata, Peltogyne cf. heterophylla* and *Bertholletia excelsa* (Brienen and Zuidema, 2005) and *Anogeissus leiocarpus, Daniellia oliveri, Afzelia africana, Isoberlinia doka, Pterocarpus erinaceus* and *Diospyros abyssinica* (Schöngart et al., 2006).

In Africa, dendrochronological studies concerned with climate-growth relationship started about three decades ago in Mediterranean zones (Dunwiddie and LaMarche, 1980; Till, 1987). Dunwiddie and LaMarche (1980) conducted a study in South Africa – Cape Province with the main goal of identifying the response of *Widdringtonia cedarbergensis* to climate. The authors found a positive response to spring (previous and current) and early summer total monthly precipitation and a negative response to monthly average daily maximum temperature during early summer of both the previous and current growing season. *Widdringtonia cedarbergensis* is the only South African conifer that has been dated so far, however it has not proven to be useful for climate reconstruction nor have the other *Widdringtoni* and *Podocarpus* species (February and Stock, 1998; February and Gagen, 2003). Moving to northern Africa, Till (1987) reported on the climate response of *Cedrus atlantica* in Morocco.

Stahle et al. (1999) demonstrated that *Pterocarpus angolensis* in western Zimbabwe (in Matabeleland, Mzola and Sikumi) formed annual growth rings, citing four lines of evidence indicating that *Pterocarpus angolensis* tree rings are annual (phenology, ring anatomy, cross-dating and correlation between climate and the tree rings).

Annual ring widths of *Burkea africana* and *P. angolensis* from a semiarid forest in Namibia were shown to have high positive correlations with different climate variables (Fichtler et al., 2004). For example, rainfall during the rainy season strongly influenced growth of both species, however the response of *B. africana* to climate was stronger than *P. angolensis*.

Therrell et al. (2006) also conducted research on *P. angolensis* in Botswana and Zimbabwe to reconstruct rainfall variability in Zimbabwe. The authors were able to build the first tree ring reconstruction of rainfall in this region using a 200-year regional chronology of *P. angolensis*. They found that the regional tree-ring chronology is correlated with monthly rainfall totals during the summer rainy season (November through February) and were able to reconstruct rainfall from 1796 to 1996.

Gebrekirstos et al. (2008) examined the climate effects on four different species' growth in an Ethiopian semi-arid savanna (*Acacia tortilis* Hayne, *Acacia seyal* Del, *Acacia senegal* (L.)

Wild. and *Balanites aegyptiaca* (L.) Del). All individual species and the Master chronology showed strong and positive response to both rainfall during the rainy season (June-September) and total annual precipitation.

On the high tropical mountains of eastern Africa (Ethiopia), Sass-Klaassen et al. (2008) evaluated *Juniperous procera* ring width variation response to changes in monthly total precipitation and monthly mean temperature from the end of the previous rainy season (June of previous year) to October of the current growing season. Temperature had no significant influence on *J. procera* ring width variation but instead, a strong signal between *J. procera* chronology and precipitation amounts during the rainy season was observed.

Trouet et al. (2009) undertook research in the dry Miombo woodlands in Zambia. This study presented five *Brachystegia Spiciformis* Benth. (BrSp) tree-ring chronologies and all samples showed distinct annual ring-width growth marked by terminal parenchyma bands. Cross-dating between radii was successful for all trees and five chronologies were developed. The study found significant influence of precipitation on tree ring growth which was strongest during the rainy season (DJF).

2.6 Recent Extreme Weather Events in Mozambique

> "The impact of climate change will fall disproportionately on the world's poorest countries, many of them here in Africa. Poor people already live on the front lines of pollution, disaster, and the degradation of resources and land. For them, adaptation is a matter of sheer survival" (taken from Hellmuth et al., 2007).
>
> UN Secretary General Kofi Annan, addressing the 12th Conference
> of the Parties to the United Nations Framework Convention on Climate Change,
> 15 November 2006, Nairobi, Kenya.

Mozambique is located in the tropics and subtropics and has high relief, which results in different climates types and regimes, as well as a high complexity of seasonal and spatial distribution of rainfall (Fauchereau, et al., 2003). The tropical zones of Mozambique experience high levels of rainfall variability (e.g. 0.21 to 0.48 on the Cheringoma plateau), which influences the frequency, amount and time of precipitation (Mason and Jury, 1997). Atmospheric circulation and moisture supply modification due to sea surface temperature (SST) forcing such as from ENSO (El Niño-Southern Oscillation), is also a major driving force of inter-annual climate variation in many African countries (Fauchereau, et al., 2003).

Climate is changing and extreme events are more likely to occur (IPCC, 2007). Africa is the poorest among all the continents and due to a high poverty index, dependence on rain fed agriculture and poor socio-economic infrastructures, the continent is expected to be significantly affected by climate change (IPCC, 2007). Additionally, Mozambique is one of the poorest countries in the world (ranked 184 out of 187 in the Human Development Index, 2012) with around 50% of the population living in extreme poverty (World Bank, 2010). This reality increases the likelihood that the country will be impacted by extreme climate event scenarios. Tropical regions are expected to get warmer and drier (MICOA, 2003). In Mozambique, mean air temperature projections indicate that by 2075 the country will experience an increase of 1.8 to 3.2 ^{o}C and a decrease of two-to-nine percent in mean rainfall amounts.

Droughts are the most frequent "natural" disaster in Mozambique and usually occur every three to four years causing a high number of deaths (Table 2). Extreme events such droughts and floods are frequently associated with ENSO. Between 1980 and 2000 Mozambique has experienced several extreme events such as floods, droughts and tropical cyclones resulting in massive infrastructure damage and human loss (Table 2; Hellmuth et al., 2007).

The economy of Mozambique relies heavily on agriculture, and is highly sensitive to water shortage. Accordingly, these extreme events coupled with climate change have resulted in increasing drought frequency and intensity in Mozambique bringing more poverty and diseases (MICOA, 2007).

Table 2: Recent extreme climate events in Mozambique. The country has experienced seven major droughts and seven major floods since 1980.

Year	Event	Number of people affected
2002-06	Drought	800,000 affected
2001	Floods	549,326 affected; 115 deaths
2000	Floods	More than 2 million people affected; 700 deaths
1999	Floods	70,000 people affected; 100 deaths
1997	Floods	300,000 people affected; 78 deaths
1996	Floods	200,000 people affected
1994-95	Drought	1.5 million people affected; cholera epidemic
1991-92	Drought	1.32 million people severely affected; major crop failure
1987	Drought	8000 people affected
1985	Floods	500,000 people affected
1983-84	Drought	Many deaths from droughts and war; cholera epidemic
1981-83	Drought	2.46 million people affected
1981	Floods	500,000 people affected
1980	Drought	6.000.000 people affected

Source: Hellmuth et al. (2007)

CHAPTER 3

SITE DESCRIPTION

3.1 Catapú Concession

Millettia stuhlmannii samples were collected at the Catapú concession, managed by TCT-Dalmann Furniture Lda. The concession is located in the district of Cheringoma at ± S18°00'05" and E35°08'13", and extends over an area of 24,821 ha (Figure 4). The concession is in the northern Sofala province, 30-40 km south of the Zambezi River. The Catapú concession has been operating in Mozambique since 1996, extracting about 2,300 m^3 of timber (primarily panga-panga) per year. In 2001 the concession was awarded a 25-year renewable lease, (*Alvará Nº. 007/sof/2001*). Three main species (*Afzelia quanzensis, Cordyla africana and M. stuhlmannii*) are currently being harvested at the concession. All trees at the concession are logged selectively in order to manage the resource in a sustainable way. Catapú concession is one of the few Forest Stewardship Council certified logging concessions in Africa (FSC certification number SGS-FM/COC-2421) and currently the only one in Mozambique, which means that all the activities within the concession are economically, environmentally and socially sustainable. The annual allowable cut (2,300 m^3) was set based on a pilot forest resources inventory undertaken in 1996. This inventory also established a 30-year cutting cycle, which means that if one block (~ 900 ha) is harvested in year *n*, it will only be harvested again in the year *n*+30.

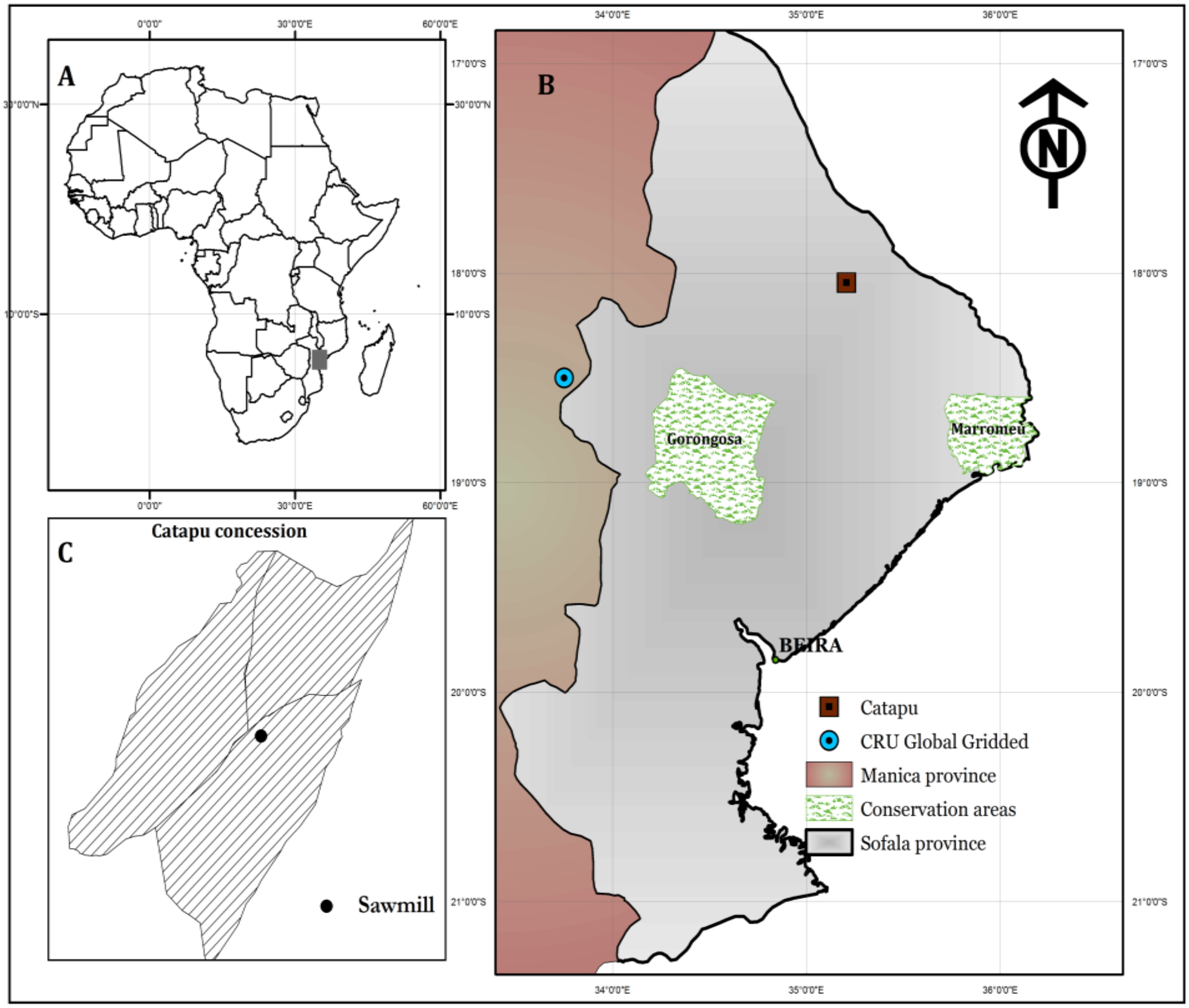

Figure 4: Map showing the general location of the study area (a), the location of Catapú concession within Sofala province (b) and concession area limits (c). Center of the grid is represented as a small blue circle and the concession falls within the grid box.

The concession follows all forestry harvesting requirements established by the FSC. Prior to felling activities, each block is well identified with tin plates nailed on trees close to the block boundary and georeferenced (Figure 5). Roads and paths for wood extraction are also identified in order to minimize damage caused by logging activities to the surrounding environment. The

Catapú concession also preserves traditional customs of the region. For example, within the concession there are areas where wood extraction is completely restricted. These areas are places in which the elders go to invoke rain in years of severe drought.

Figure 5: Tree with a thin plate showing the block boundary. This activity is done prior to the felling activity each year. Photo by: J. White.

All trees to be cut are first marked by well-trained individuals (*sinaleiros*) before the harvesting season. Only trees with DBH larger than the established MCD by RLFFB (2002) (e.g.

M. stuhlmannii – 40 cm, *P. angolensis* – 40 cm) are marked. However, this is not the only principle taken into account to mark the trees. The tree quality and possible negative impacts to the surrounding environment is also observed during the tree-marking phase. All trees are cut at heights lower than 0.25 m and higher than 0.10 m. This allows certain species such Panga-panga to coppice after some years (Figure 6).

Figure 6: Two young coppice stems of Panga-panga growing after selective block harvesting activity. Photo by: J. White.

The TCT Dalmann Catapú concession is one of the few companies in Mozambique that has had success in reforestation programs. About 10,000 seedlings of different species are planted every year at the beginning of the rainy season. Prior to seed distribution, all drag lines opened during the extraction phase are treated manually to allow the germination of the seeds during the rainy season (Figure 7). Other areas targeted for reforestation are mainly ones that were previously damaged by fire or cultivated by indigenous people.

Figure 7: Drag lines being prepared to allow better and fast germination of seeds during the rainy season. Photo by: J. White.

Since 2006 Local farmers have been also involved on the reforestation program as part of the FSC requisites. Although the work is voluntary, each member of community receives $0.50 USD for each tree planted. This improves local incomes and is contributing to reducing deforestation.

3.2 Geology and Soils

Very little research regarding Mozambique's geology is available. Most of the northern area of the country is covered by Precambrian rocks (about two thirds) and the southern part is covered by phanerozoic terrains (Venter, 2011). Catapú concession is located on the eastern side of the rift valley where elevation varies from 50 m to 200 m A.M.S.L. The region is characterized by occurrences of sandy soils with massive conglomeratic sandstones cemented by calcic-argillaceous rock (National Directorate of Geology, 2006). Termite hills occur very frequently in the region and affect the local geomorphology (Tinley, 1977).

3.3 Climate

The climate of the study site is tropical and is characterized by two distinct seasons, one warm and rainy with 80% of the annual total rainfall, and the other cold and dry. The rainy season lasts for about 4 to 5 months (November through March). The mean annual rainfall ranges from 700-1400 mm, although from 2003 through 2007 rainfall barely exceeded 500 mm during the rainy season (Figure 8). The maximum monthly rainfall normally occurs in January followed by February and December, with October being the driest month. The seasons have distinct differences in average temperature (~7^0C).

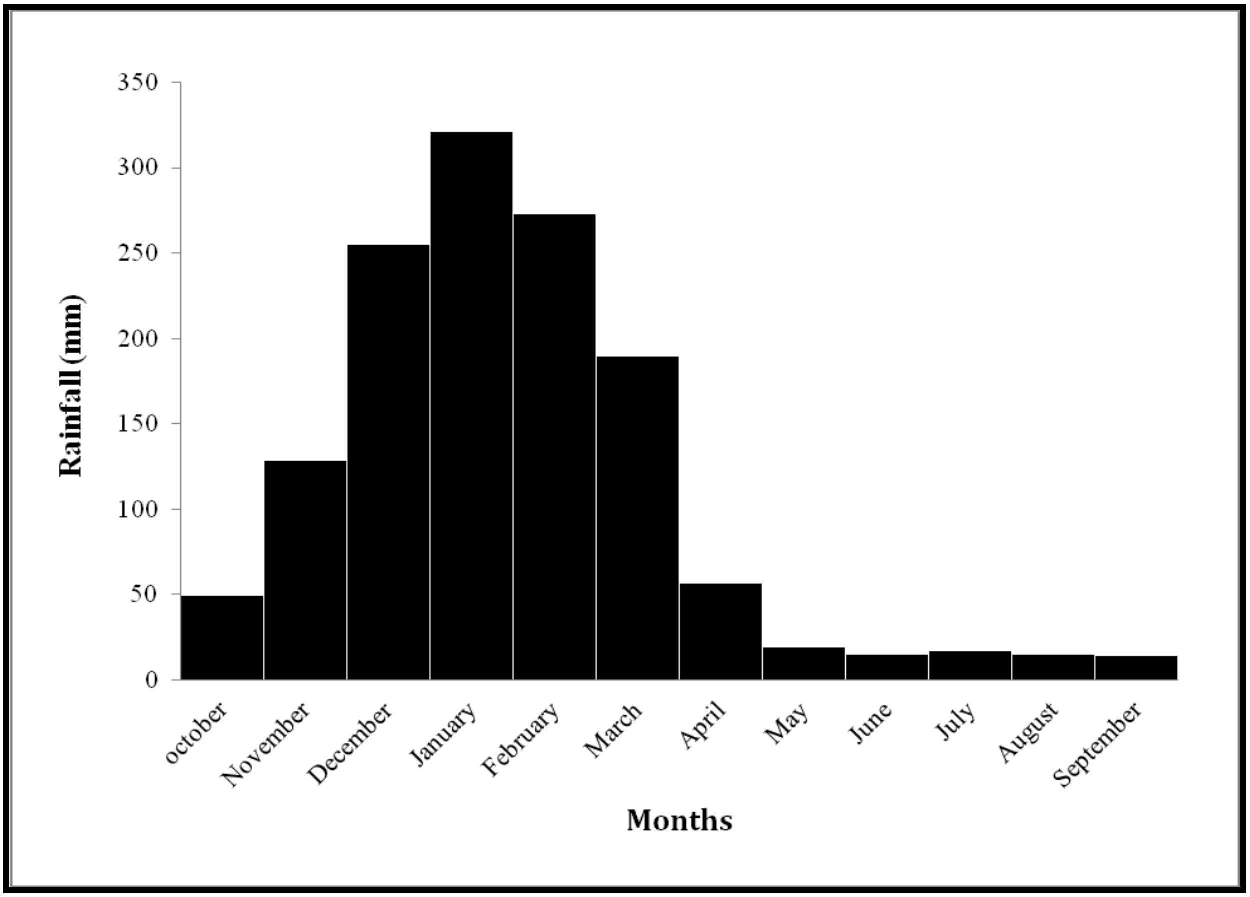

Figure 8: Monthly rainfall totals from October to September in central Mozambique obtained from grid point (S18°00'00" and E33°45'00") from 1901 to 1996. 80% of the rainfall is occurs in the rainy season (NDJFM; Hulme, 1992; 1994)

3.4 Vegetation

The concession falls within the Swahilian/Maputaland Regional Transition Zone and has in total 238 woody species distributed among 59 families and 167 genera. The Fabaceae is the largest family, with eight genera and eight species in Caesalpinioideae, seven genera and 20 species in Mimosoideae and 11 genera and 17 species in Papilionoideae, making a total of 26 genera and 45 species, followed by Rubiaceae with 12 genera and 14 species (Palgrave *et. al.,* 2007). The vegetation type of the concession is classified into three major classes, dry deciduous forest, dry deciduous thicket and woodland and the dominant species are *Afzelia quanzensis*, *Adansonia digitata*, *Balanites maughamii, Berchemia discolor, Bivinia jalbertii*, *Bombax rhodognaphalon*, *Celtis mildbraedii*, *Cordyla africana*, *Fernandoa magnifica, Milicia excelsa*, *Millettia stuhlmannii*, *Morus mesozygia, Sterculia appendiculata, Terminalia sambesiaca* and *Xylia torreana* (Palgrave *et. al.,* 2007).

CHAPTER 4

METHODOLOGY

4.1 Data Preparation

4.1.1 Sample Preparation

In this study, cross-sections rather than increment cores were used due to the complex anatomy of tropical species and frequent occurrence of wedging and false rings (e.g., Worbes, 1985; Stahle et al., 1999; Worbes, 2002; Therrell et al., 2007). Brienen and Zuidema (2005) also suggest the use of cross section instead of increment cores when dealing with new species, as with the case of *Millettia stuhlmannii*. Dendrochronological potential of this species was never estimated before and cross sections allow better understanding of the anatomical features of the species, easy detection of ring anomalies and accurate estimation of the age of the species.

Samples were collected from felled trees in June, during the logging season (dry season) in Mozambique between 2007 and 2010. The minimum diameter of all samples was 40 cm DBH as established by RLFFB (2002). Cross sections were obtained from about 0.25 to 0.5 m above the ground level using a chainsaw and all samples were then labeled and georeferenced to allow for FSC auditing (Figure 9). The justification for collecting samples from 0.25 to 0.5 m above the ground was to maximize the estimation of the tree age as the number of rings decrease with height and also so as not to affect the logging business, which must meet standard dimensions in order to be sold out. Additionally cross sections from a young pang-panga plantation were collected (Figure 10).

Figure 9: Sample Panga-panga cross section being labeled by SIU student. Strict labeling and chain of custody documentation is a requirement of the FSC. Each cross-section can be matched with the harvested log using the felling labels. Photo taken in 2009 by: M.D. Therrell.

Figure 10: Young Panga-panga tree from plantation felled to allow ring count and exact age determination of the trees. This process along with others was applied to prove the annual nature of the rings prior to chronology development.

All samples were submitted to agricultural sanitization in Mozambique, prior to transportation to the Southern Illinois University Carbondale Tree Ring Lab. The samples were dried naturally and prepared for analysis by sanding using a progressively finer paper (36 to 400grit) to increase visibility of the growth zones (e.g., Worbes, 1995). After sanding all the cross sections, each ring boundary was marked under the microscope and counted from the outermost to the innermost ring in order to determine the age of each tree. A single point was used to mark each decade, double points were used for marking 50 years and three points were used to mark each century on the cross section (Stokes and Smiley, 1968). In addition special marks were used to show missing rings and other anomalies. This entire process was very useful for measuring the tree ring widths and as well as for keeping records for future studies.

4.1.2 Visual Cross Dating

Samples were cross-dated by matching patterns of wide and narrow rings using the skeleton plot method (Stokes and Smiley, 1968). On the skeleton plot, one vertical line represents one ring and each ring based on the width previously marked is assigned a value on a scale of 1-10. Each ring was compared to the neighboring rings and the narrowest rings, which most of the times are indicative of water shortage (drought) were assigned high values close to 10. The rings with average width were not scored and the wider rings were marked with a "B" (Stokes and Smiley, 1968). After plotting the samples the patterns of narrow and wide rings should align in order to get the composite skeleton plot that allows dating the rings to the exactly year of formation (Stokes and smiley, 1968). As Cook and Kairiukstis (1990) explain, "there is no mechanical process, no rule of thumb, no formula and no correlation coefficient, to take the place of this personal comparison between different ring records. The operator does not dare to seek relief from his responsibility".

4.1.3 Xylem Anatomy Description

In order to examine the minute ring anatomy, samples of *M. stuhlmannii* were first cut in small pieces of 1 X 3 X 1 cm (transversal, radial and tangential). These small samples were boiled for around 10 hrs to allow water penetration and soften the wood. The boiled samples were then soaked for an additional 24 hrs. Microtomes were used to prepare micro-sections of the species. Micros-sections (~ 20 µm thick) were obtained from three directions- transversal, radial and longitudinal. A very small paintbrush and water were used simultaneously with microtome to keep the micro-sections hydrated and avoid micro section curling. After cutting a thin section, it was placed on a microscope slide and covered with a drop of glycerol to keep it hydrated while preparing others micro-sections. Pipettes were then used to drop the chemical mixtures used to prepare micro-sections. Micro-sections were stained to improve ring structure visibility. Micro-sections were stained using safranin and astrablue (at same proportion 1:1) and let to sit for five minutes. Alcohol (75% and 96%) was used to dehydrate the micro-sections and remove safranin and astrablue not absorbed by micro-sections (Figure 11). To test whether the micro-sections were completely dehydrated one drop of Xylol was placed on top of each micro-section. After dehydration, one drop of Canada balsam was placed on top of the micro-sections and covered with glass. Finally, the microscope slides were dried (at 60^{o}C) for 12 hrs.

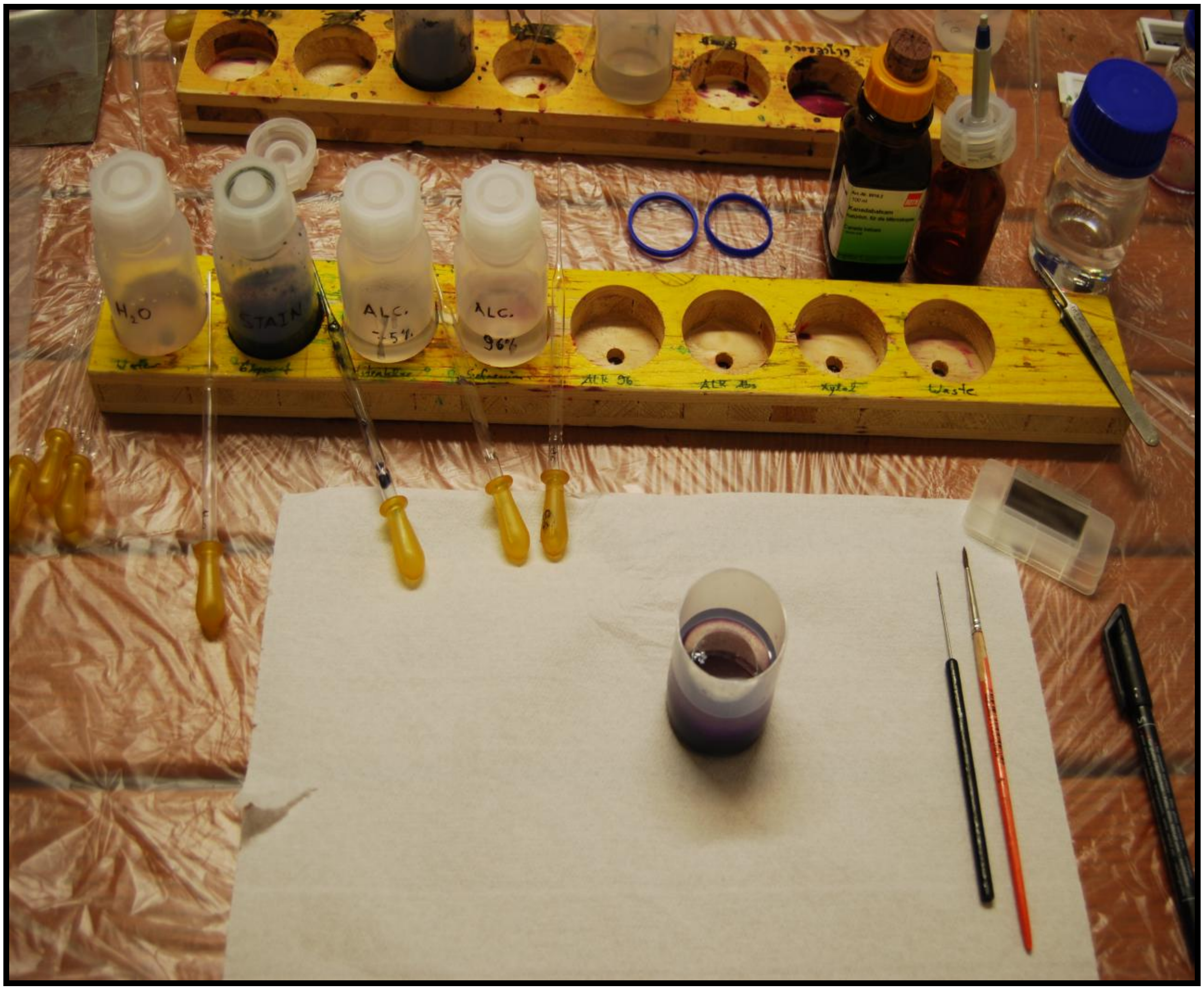

Figure 11: Chemical elements used to prepare the micro-section.

For micro-section analyses, inverse microscopy with different objective magnifications was used and analysis always started with lower magnification. Transversal sections were consistently the first ones to be analyzed right after checking micro-sections against natural light. Micro-section images were acquired using a digital camera hooked to the microscope (Figure 12).

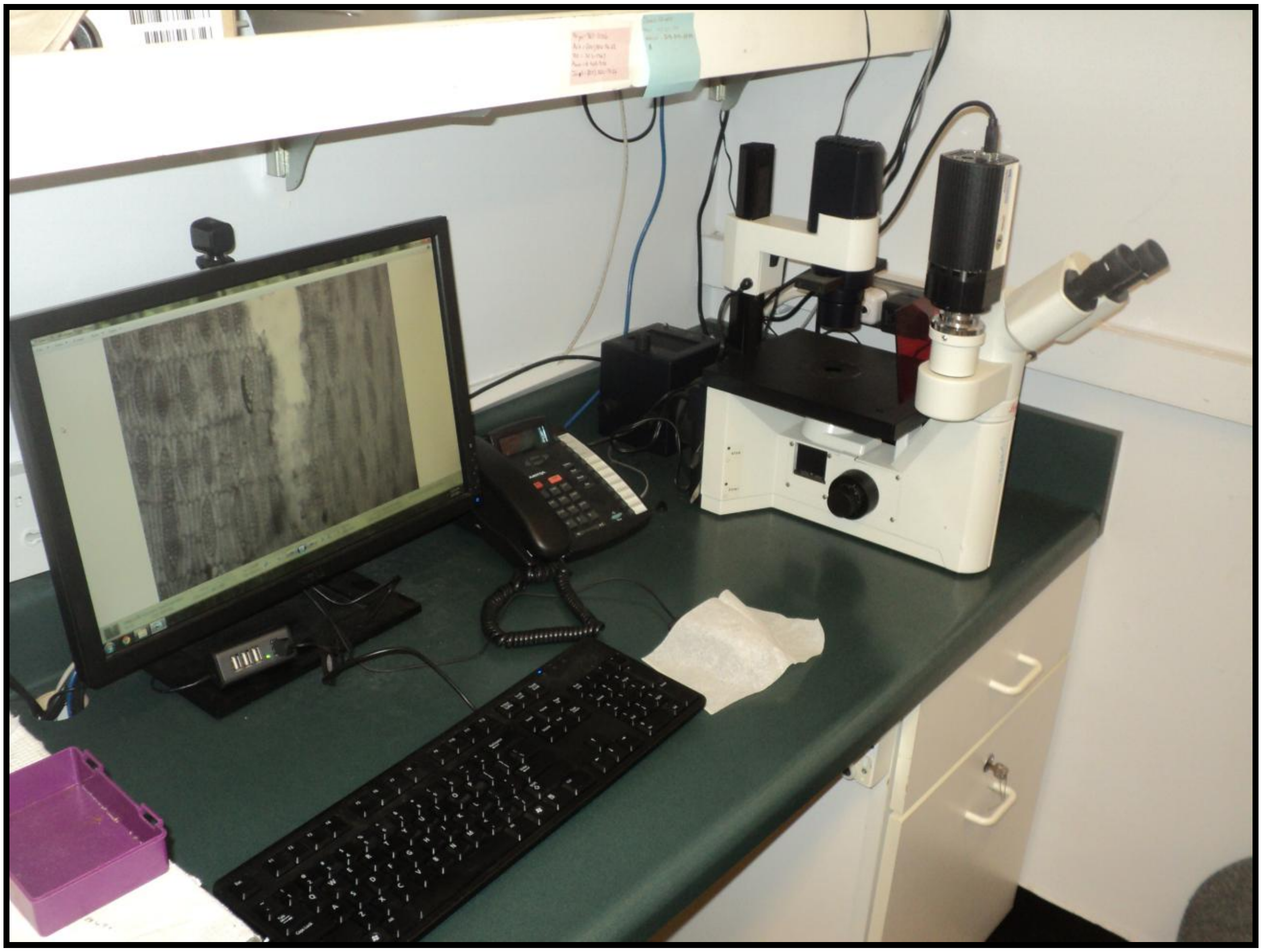

Figure 12: Inverse microscope with different objective magnifications used to analyze micro sections. Note digital camera on top of the microscope.

4.1.4 Ring Width Measurements

Rings were measured using a Velmex measuring system (precision of 0.001mm), which is linked to a computer to allow the sample to be moved during the measurements while using a binocular microscope (Figure 13). All measurements were made along two continuous radii. Samples were consistently adjusted to make sure that ring width was measured perpendicularly in order to avoid over or underestimation of ring width. All ring width data were stored in a computer in a RAW format and then exported to allow time series analysis.

Figure 13: Microscope used to analyze cross sections. A Velmex measuring system connected to a digital readout allows cross section mobility during measurement.

4.1.5 Cambial Wounding

The cambial wounding technique was first developed by Mariaux (1967) to study the cambial periodicity of broadleaved species in Africa. This method consists of deliberately injury the cambium by inserting a pin through the bark to the xylem and forcing a subsequent wound response in the tree that can be dated exactly (Mariaux, 1967; Seo et al., 2007). A cambial wounding experiment was done in 2008 during the dry season when the cambium was dormant by using a nail. A total of nine trees, scheduled to be felled the following year, were used in the experiment, and all of the trees were nailed once at 130 cm above the ground level. After one year (2009), all cambial wounding samples were collected (see Figure 14). Samples were dried naturally and small sub samples, 1cm thick, were cut and sanded in order to make the wound visible. Growth layers were counted from the wound tissue to the bark and each ring was measured using the Velmex measuring system to estimate the mean annul increment of trees after cambial disturbance.

Figure 14: Adult Panga-panga tree stem showing how the cambial wounding samples were collected from the tree prior to felling. A hole of not more than ~10 cm (radial, tangential and transversal) was opened in each tree to remove the samples. These holes were 1.3 m above the ground (standard height to perform diameter measurements). Photo taken by: M.D. Therrell

4.2 Data Analysis

4.2.1 Cross-Dating

The activity or process of determining the exact year of ring formation is referred as cross-dating (Stokes and Smiley, 1968; Schweingruber 1996). Successful cross-dating between tree series indicates an influence of external factor/s on tree growth rhythm (Worbes, 1995).

After visual cross-dating and measurement, ring width data were submitted to “R” software, which is a command line driven program and open source software licensed by the General Public License. This software was used to verify cross dating and helped to identify the problem segments before tree growth curves can be combined into a chronology. The dendrochronology program library in R (dpIR) was chosen rather than COFECHA (Grissino-Mayer, 2001) and ARSTAN (Cook and Holmes 1996).

This software identified locations of cross dating that might reflect errors by estimating the correlations between average tree series, which indicates the tree growth homogeneity (dating and measurement; Bunn, 2008; 2010). In this study, only mature trees were used, the young ones were not selected due to the different physiological responses to climate factors (Worbes, 2002) and to intra and inter-specific competition within the stand.

4.2.2 Ring Width Indexing

As trees age, they begin to show trends related to physiological processes. In order to compare growth curves from different tree series, these growth trends need to be removed by applying what is referred to as the standardization process. Standardization consists of dividing the observed (actual) tree ring width by the predicted values, which is derived from equations (Fritts, 1976). This process is also pre requisite before comparing the series with climate events

(Cook and Briffa, 1990). Standardization was performed using the R software package dplR for tree rings (Bunn, 2010). After removing the noise (series standardization), all series were averaged to build a regional chronology, which was subsequently used for climate response analysis.

4.2.3 Cumulative Growth Curves

Cumulative growth curves provide information about growth increment, stand age and growth patterns (Brienen and Zuidema, 2005). In order to construct growth curves, tree ring width data were accumulated from the innermost ring to the outermost ring right before the bark and were doubled to approximate the total stem diameter (TSD). First, all radii for the same tree were averaged using normal arithmetic average and the inner most ring was set as year "1" in order to determine the mean growth curve of Panga-panga in Mozambique. In this analysis, rings do not necessarily need to be dated to the exact year, but I am confident about the annual nature of these rings (Wood anatomy, ring count from plantation trees and cambial wounding) and the results reflect a very slight deviation from the true age.

4.2.4 Temporal Growth Patterns

To evaluate the median time the species takes to move to the next class, all the samples were grouped in seven classes of 10 cm. For example, starting at 0-10 cm, 10-20 cm, going up to 70 cm. This step was performed in order to test whether the speed of growth changes between different size classes. A Shapiro-Wilk test of normality was performed (.946, df = 20, p = .316) to evaluate the statistical distribution of the data. A non-parametric test, Kruskal-Wallis one-way ANOVA, was applied using R software to test for differences in diameter growth rates for the different classes. This was performed to evaluate the source of age variations among different trees and also to evaluate the growth rate changes with age. Kruskal-Wallis one-way Anova is very sensitive to differences in central tendencies, thus the justification for the selection of the test (Howell, 2007). The value of H is compared to the X^2 distribution with K-1 *df*.

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1) \quad (1)$$

Where:

K = the number of groups

n_i = the number of observations in $group_i$

R_i = the sum of ranks in $group_i$

N = $\sum n_i$ = total sample size

Partial correlation analysis (Howell, 2007) was applied between diameter classes to determine the exactly the age at which silvicultural treatments such weeding and thinning should be done. Each class contribution to the 40 cm diameter class age was evaluated and the one with larger coefficient and statistical significance indicates the age class that determines tree age at the MCD (Brienen and Zuidema, 2005).

4.2.5 Heartwood Dynamics Analysis

Panga-panga has very precious heartwood (see Figure 16), and sometimes the trees felled at the MCD do not have the desired heartwood dimensions, driving the loggers to abandon felled trees that have insufficient heartwood dimension (e.g., Therrell et al., 2007). Establishing a quantifiable relationship between total stem diameter (TSD) and heartwood diameter (HW) would provide loggers with an easy non-destructive method to establish the relative volume of heartwood. This attempt has been made for tropical species by Shackleton (2002) and Therrell et al. (2007) using *P. angolensis*, which belongs also to the FABACEAE family. TSD is the sum of sapwood width and HW and these variables are statistically dependent upon each other.

Heartwood diameter was measured along one radii of each stem section. The number of growth rings in heartwood (HRN) was counted and the number of sapwood rings (SWR) was obtained by subtracting the Cambial Age (Ac) by heartwood rings (HRN). The HW – SW limit was determined visually along each measured radius by identifying changes of the cell colors (from dark to light). In this study the last ring of the heartwood was counted as heartwood ring only if was totally free of sapwood. In this study the samples were considered to be circular and the heartwood area (HWA) was calculated using ($HWA = \pi * r^2$). Sapwood represents the "engine" of the trees. Forest water use as well as the growth rate of the trees depends in part on the sapwood area (Wullschleger and King, 1999). Heartwood percentage (HW %) was determined by dividing HW by TSD.

Correlation analyses between HW, SW, HW %, TSD, NR. HRN and HWA were performed. Piecewise regression model was fit between heartwood (HW %) and TSD using segmented package in R software (Muggeo, 2008). Attempts to determine the initial age in which Panga-panga starts to form the heartwood as well as the heartwood formation rate (HFR) were accomplished by fitting a model between the HWR and Ac and the initial age was obtained by equaling the HWR to zero on the model obtained (HWR= 0). The ratio of the HWR to the Ac was applied to determine the dynamics of heartwood formation (Nawrot et al., 2008).

4.2.6 Correlation Functions

In order to identify the specific months or periods of the year in which tree ring growth responds to rainfall, correlation function coefficients between the site chronology and monthly rainfall were obtained using R software, version 2.11.0 (R development code). Monthly precipitation data based on a 2.5 by 3.5 degree grid were obtained from the CRU global gridded dataset. The data set extends from 1900 to 1996 and it was constructed and supplied by University of East Anglia, Norwich, UK (Hulme, 1992; 1994). Correlation tests were performed between the Panga-panga chronology and monthly precipitation data from October (t-1) prior to the growth year to October (t) of the current year of growth. Previous year influence on growth was tested because ring width results from longer climate events over time instead of a single period of time (Fritts, 1976). The previous October was chosen as the first year in the response function because Panga-panga flushes around November and the rainy season in that particular region also begins around November, and lasts until March.

CHAPTER 5

RESULTS AND DISCUSSION

RESULTS

Results are organized in two sections. The first section reflects the nature of annual growth rings and the second section will be concerned with species dynamics and forest management. In the first section, special attention is also given to climate-growth relationships since it has been widely proven that trees grow in response to a certain limiting climate factors.

5.1 ANNUAL GROWTH RINGS OF MILLETTIA STUHLMANNII

Five different forms of evidence demonstrate that *M. stuhlmannii* produce annual rings: 1) Ring structure and anatomy; 2) Cambial wounding; 3) Ring counting in trees with known age (young trees collected from an experimental "plantation"); 4) Successful cross-dating within and between trees; and 5) Correlation between ring width and climate data.

5.1.1 Tree Ring Structure and Anatomy

M. stuhlmannii discs showed high eccentricity and irregular shapes. Annual growth ring boundaries in all samples were slightly distinct and characterized by alternating patterns of parenchyma and fiber vessels and by a thin line of marginal parenchyma. However, semi-ring porous boundary showed diminishing trends in distinctiveness, with a decrease in ring width and tree age. Rings closer to the pith were more distinguishable than rings closer to the bark, which means that the distinctiveness of the ring boundaries decreases toward the bark. Rings were characterized by slight vessel size changes throughout the ring. Ring boundaries were marked by thin light cells of marginal parenchyma and were identified accurately under the microscope due to the size of the parenchyma cells (see Figure 15 and Figure 16-A). *M. stuhlmannii* growth rings have a band of brown fibers without vessels at the beginning of each growth ring (Figure 15).

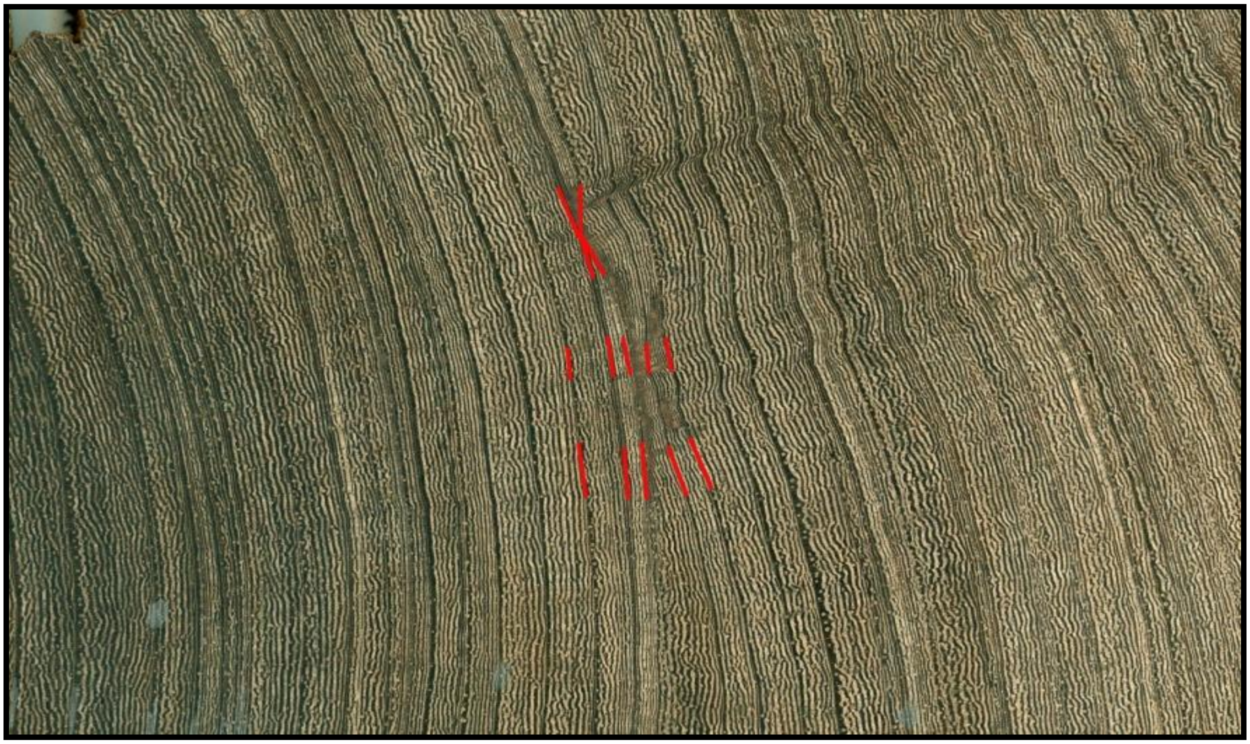

Figure 15: Panga-panga cross section (heartwood) with annual growth ring structure and boundary. Ring boundaries are marked red dashed lines. The occurrence of eccentric rings is common and sometimes results in wedging or locally absent rings (marked by two converging arrows).

Panga-panga vessels are mostly large and are randomly arranged throughout the ring with no discernable distribution pattern. Some vessels occur in groups of two to three but mostly they are solitary and in contact with rays. Vessels are normally surrounded by parenchyma cells. The perforation plates are simple and the inter-vessel pits are alternate, with relatively small ray-vessel pits. Paratracheal parenchyma varies from confluent (in tangential bands, surrounding many vessels) to aliform (surrounding one side of the vessels with a wing shape). The rings are formed by alternating longitudinal bands of fiber cells and parenchyma cells, with an absence of helical thickening (polarized light), and libriform fibers with simple to minutely bordered pits. Most vessels occurring throughout the ring are surrounded by these wavy bands of parenchyma and fibers have very thick walls. Panga-panga has wide ray spacing and most are multiseriate although a few are biseriate (two rows of parenchyma cells). Rays are composed of one type of cell, oriented in one direction (homocellular rays). Ray cells are procumbent, characterized by a horizontal rectangular shape.

Wedging and false rings were also found during the analysis, most frequently towards the bark and appearing mostly in the heartwood. The process of cross-dating between radii of the same tree was very helpful in identifying false rings and cross-dating between different trees was helpful to identify missing or wedging rings.

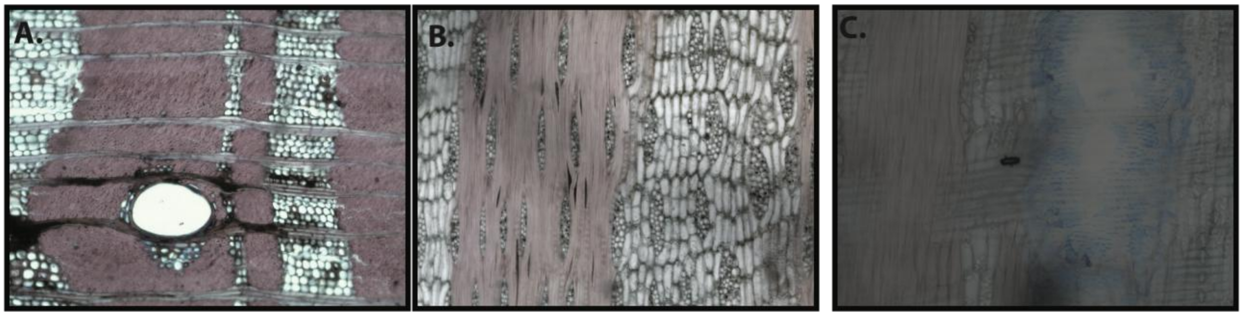

Figure 16: *M. stuhlmannii* minute anatomy. Staining makes unlignified cells appear in blue color and lignified cells in red color. (a) Annual growth rings boundary characterized by alternating patterns of parenchyma and fiber vessels and marginal parenchyma. Arrows illustrate narrow ring boundaries without vessels (typical for extreme dry years). Fibers appear in red and parenchyma cells surrounding vessels in blue. (b) Rays are homocellular, characterized by non-triangulate shape at the end of the rays (on type of cells orientation). Multiseriate and biseriate rays. (c) The perforation plates are simple and the inter vessel pits are alternate. Paratracheal parenchyma varies from confluent to aliform.

5.1.2 Cambial Wounding

Panga-panga trees showed distinct wood reaction to pinning. A total of nine trees out of nine were successfully marked and formed one complete ring after one year (Figure 17). As a response to pinning, sapwood parenchyma cells formed a black colored zone around the canal produced by the nail. This compartmentalization zone within the xylem contains high levels of extractives and is formed to protect the wound against pathogens and contain the volume of wood affected to avoid wood decay (Pearce, 1996).

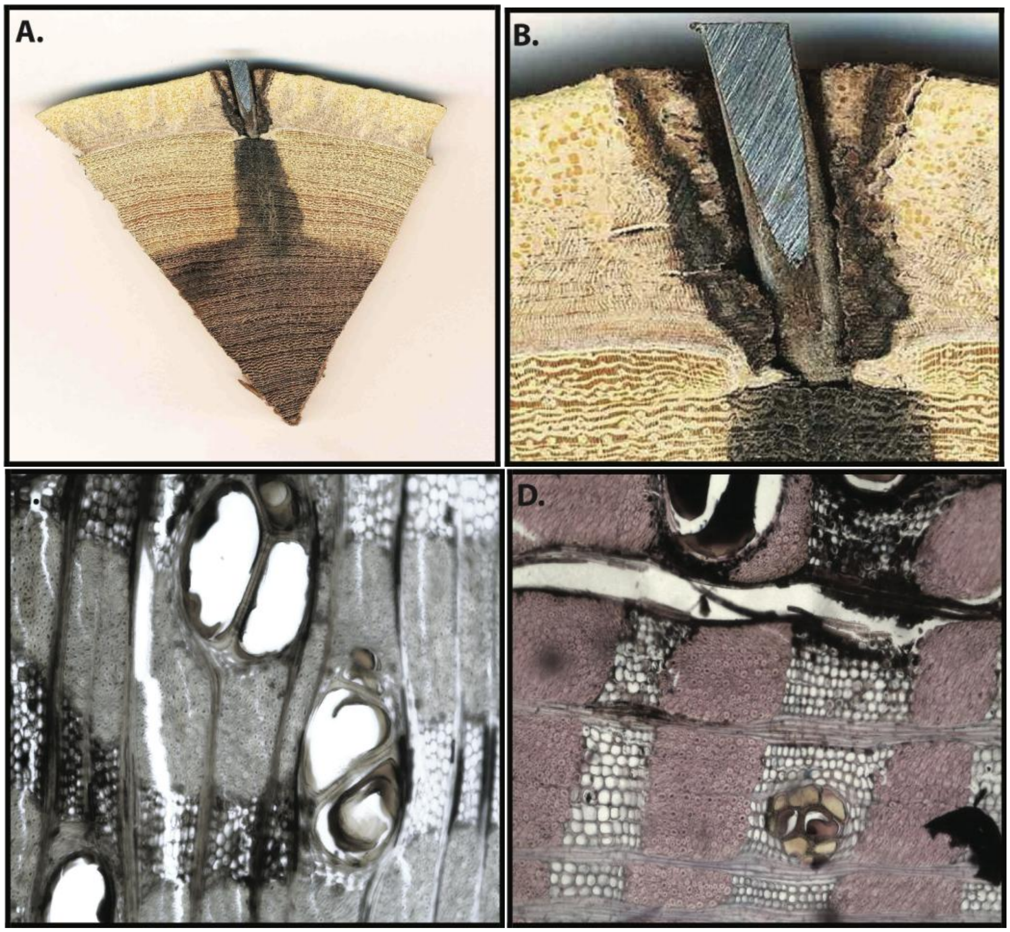

Figure 17: Wood reactions after pinning. (A) Wood sample showing the pinning canal. The black area around the pinning canal represents the sapwood parenchyma cells' response to the mechanical injury (compartmentalization zone). (B) New xylem (annual ring) added after one year is clearly visible. Ring formation by the time samples were collected (dry season-June) was already interrupted. This process was synchronized with Panga-panga phenology (leave shedding starts at the end of May). Magnified wound zone showing the compartmentalization zone and the new xylem formed by Panga-panga exactly after one year after pinning. Dead cambium cells resulted from the wounding process and callus tissue formed by wound reaction after pinning. Minute anatomy of the compartmentalization zone showing vessels filled by tyloses after pinning (C) not stained and (D) stained (Safranin + Astrablue)).

This compartmentalization zone was only restricted to the sapwood and the size varied according to the pinning or wood depth (Table 3). During the healing process, cambial cells on the pinning canal formed dark colored anomalous parenchyma cells immediately adjacent to the wound and the adjacent cambial cells produced new xylem during the growing season (annual ring) (Figure 17). During the growing season, along the edge of the wound callus tissue developed (Figure 17) resulting from the differentiation of parenchyma of xylem rays and phloem rays. Although callus tissue in most of the woody plants is produced by the vascular rays, Trouet et al. (2012) found that in *Brachystegia spiciformis* Benth. cambium cells are responsible for callus tissue production and this process continues even after the dormancy of the cambium.

5.1.3 Ring Counting In Plantation Trees of Known Age

Ring counting of trees with known age is one of the methods used to determine the annual nature of tropical tree rings (Worbes, 1995). In order to use this method, it is necessary to obtain the exact date in which the trees were planted in order to accurately determine age. In this study, young trees from plantations were used to prove the annual nature of Panga-panga rings but were excluded from the finally chronology. Mean ring width resulting from an arithmetic average of 12 trees also showed strong correlation coefficients with rainy season mean precipitation from 1998 to 2009 ($r=0.84$ $p < 0.001$) of the young trees ring width growth (Figure 18).

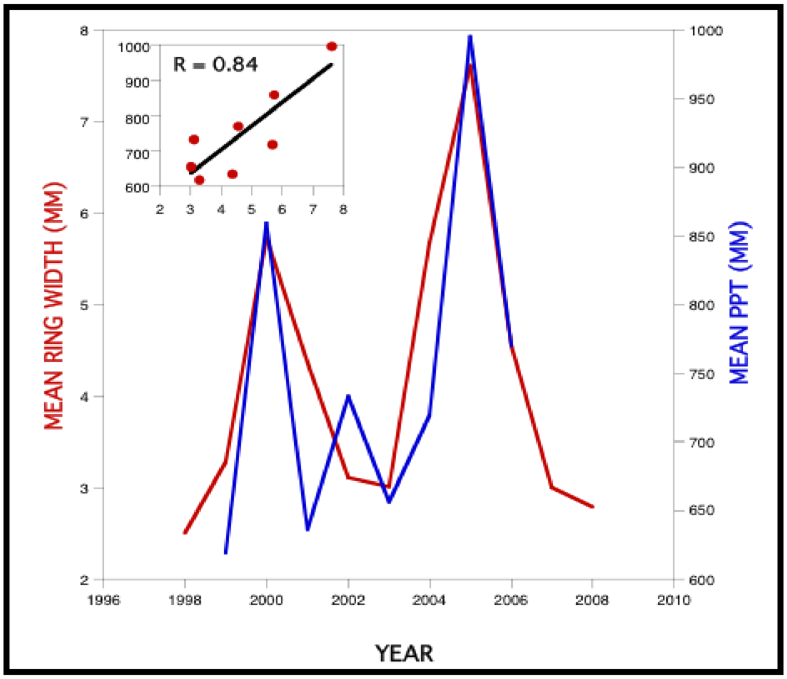

Figure 18: Correlation coefficients between Mean ring width of young trees and growing season mean precipitation from 1998 to 2009. Rainfall amounts during growing season explain around 71% ($p < 0.001$) of the young trees' ring width growth.

Throughout the course of growth, all trees formed distinct annual rings. The plantation was established in 1997 and trees were felled in 2009. Exactly 12 distinct annual rings were formed. Ring boundaries of the young Panga-panga were easy to identify macroscopically and microscopy was only used to facilitate ring width measurement. Most of the plantation trees showed highly concentric growth (Figure 19) but some of them have eccentric growth; additionally, some wedging rings are present especially in trees with irregular shape. Some missing rings were recorded especially during dry years (such as 2005). Significant correlation coefficients between average young tree ring width and rainfall during the core of the rainy season was statistically positively significant ($r=0.84$, $p<0.001$).

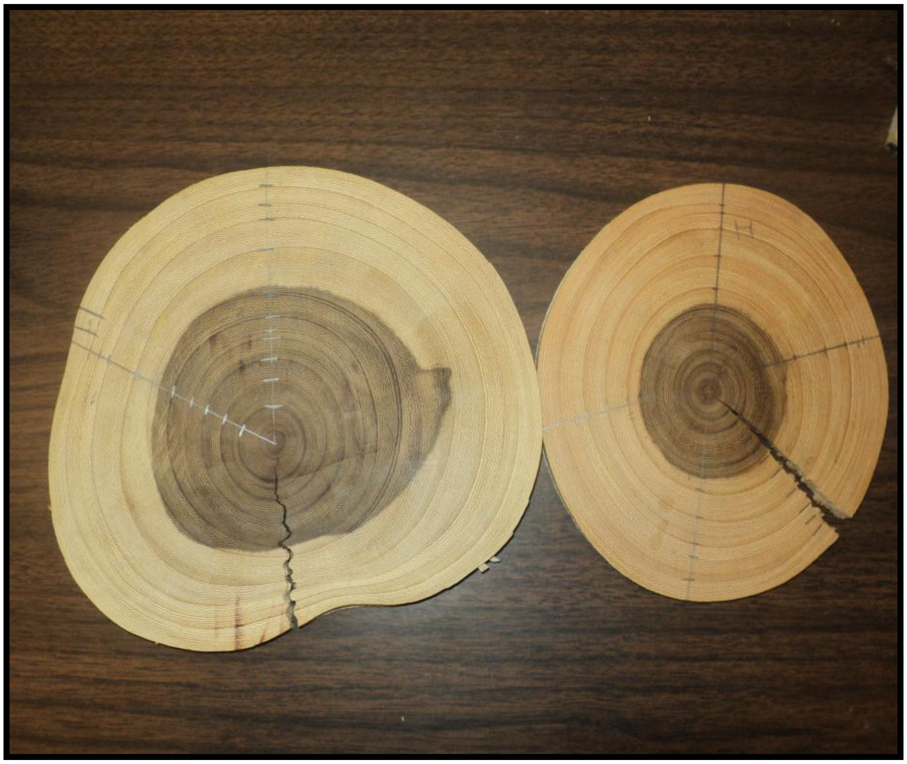

Figure 19: Young *M. stuhlmannii* cross sections. Left sample showing an eccentric growth and relatively fast growth rate compared to the right sample.

5.1.4 Visual and Statistical Cross Dating

Synchronization between tree-ring series for more than 50 years is one indication of seasonality of tree growth (Worbes, 1995, Stahle, 1999). In this work I first cross-dated each single tree visually using the skeleton plot technique (Stokes and Smiley, 1968; Figure 20). The cross dating process was useful to detect the occurrence of missing and false rings in each tree (2 radii). The reason two radii were used was to detect the occurrence of wedging rings. Series cross-dating was successful within and among selected Panga-panga trees. Although perfect synchronization between plantation trees was observed (see section 5.1.3), they were not included on the finally chronology due to phenological response difference to climate factors when compared with adult trees. Growth trends due to aging were not verified as part of this study; this may be an indicator that Panga-panga lives beyond the ages recorded here.

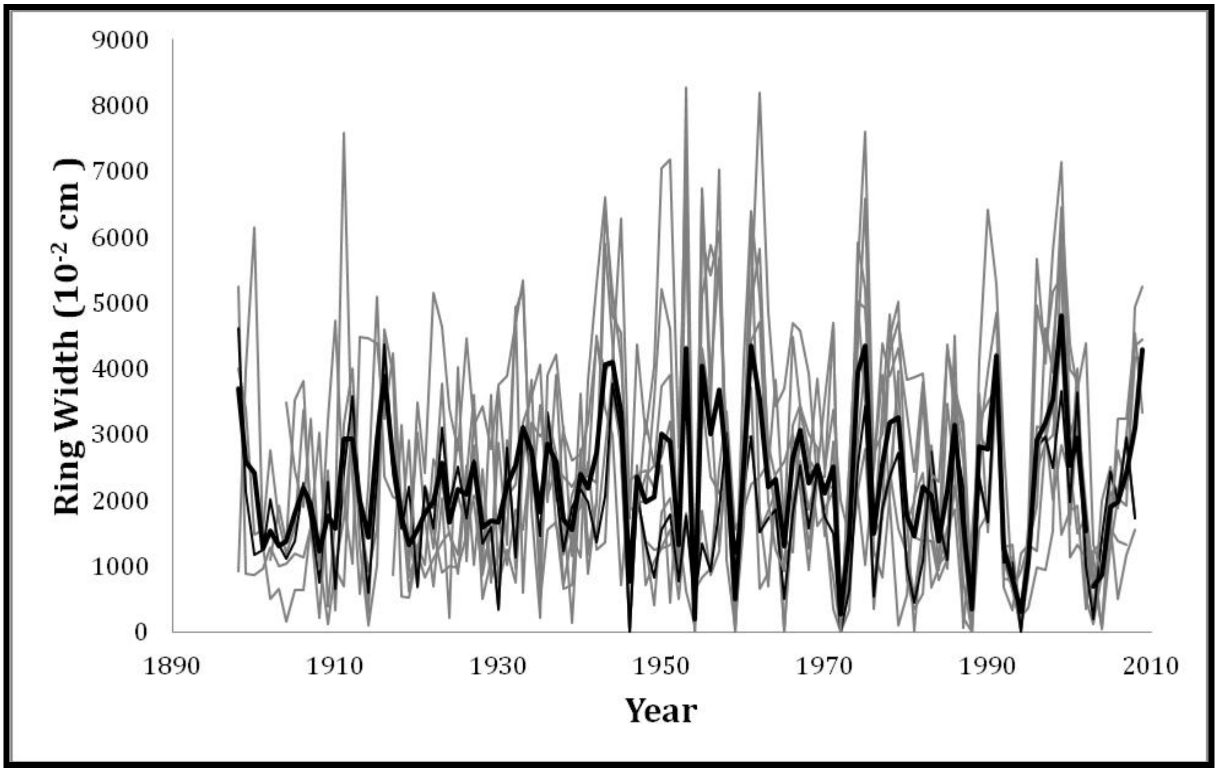

Figure 20: Raw ring width series of eight trees (grey) and mean ring width (black line). No apparent growth trend was observed on any of the series suggesting that the life span of Panga-panga exceeds the ages indentified in this work. Correlation coefficients between series ranged from 0.39-0.75.

Six out of eight trees were successfully cross-dated and the length of individual samples varied from 84 to 155 years. The chronology had a length of 111 years and it was developed based on six trees. The mean sensitivity value was 0.806 meaning that the trees growth is strongly limited by an environmental factor. Autocorrelation coefficients were relatively low for all series (0.008 to 0.424) hence the high mean sensitivity. Correlation between series was quite high for all trees (0.39 – 0.75). Analysis of chronology correlations in three 50 years segments with 25 years lag, 1900-1949, 1925-1974 and 1950-1999 was statistically significant ($r=0.472$, $p<0.0001$; $r=0.513$, $p<0.0001$ and $r=0.676$, $p<0.0001$ respectively) and the mean correlation was 0.50.

5.1.5 Correlation Function between Tree Rings Indices and Climate Data

Growth limiting factors can change depending on the region where the tree is growing. Temperature is the growth-limiting factor in temperate regions. But in tropical ecosystems cambial activity is normally triggered by precipitation (Worbes 1995, Stahle et al., 1999; Trouet et al., 2009; Rozendaal and Zuidema 2010). However a growth response to temperature by trees in the tropics has been found by Fichtler et al. (2004). In this study, the exact year of the tree ring was assigned to the end of the rainy season (e.g., ring formation that starts in 1991 and ends in 1992 is assigned to the year 1992) instead of assigned to the year in which growth began (Schulman, 1956). Precipitation during the previous December ($r= 0.30$; $p<0.05$) and current February ($r=0.30$; $p<0.05$) showed a strong influence on Panga-panga tree ring width (Figure 21). These are the two months with the highest amount of rainfall in that region. The wet season in Mozambique starts in November and lasts until May and the dry season extends from June through October. About 80% of the annual total rainfall falls during the rainy season.

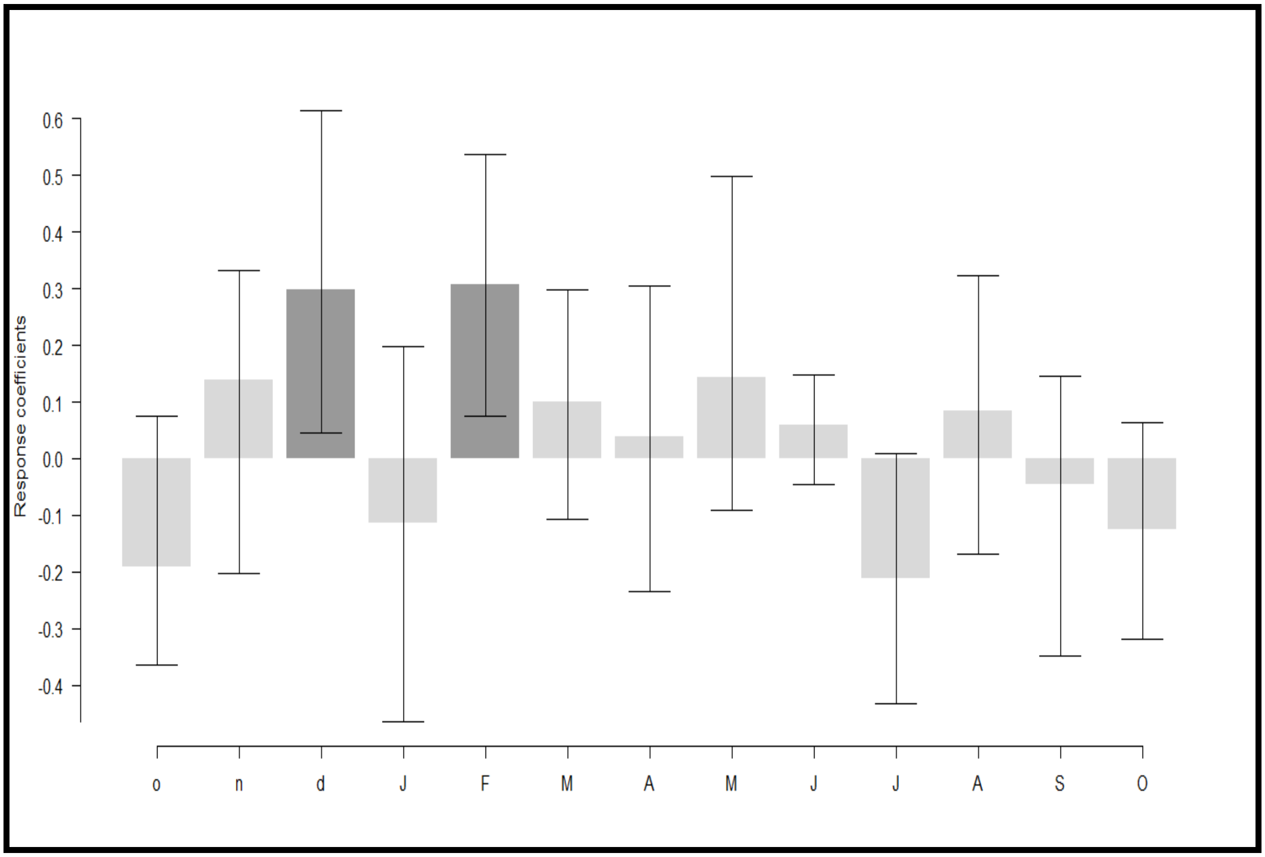

Figure 21: Correlation function between the Panga-panga tree ring chronology and monthly precipitation data from October of the previous year (lower case letters) to October of the current year (upper case letters). Significant climate-growth relationships are represented by dark gray bars (December of previous year and February of current year).

Ring formation by Panga-panga seems to start at the beginning of the rainy season (previous year) as shown by the strong correlation with December precipitation. The rainy season lasts until March and during the transition months, especially in May, even though the correlation coefficient is not statistically significant (r=0.19 , p>0.05), trees may still be using this rainfall to produce stored energy for the next growing season. This is synchronized with the phenology of the species. Panga-panga shed leaves after May (fructification occurs between April and May (see Palgrave, 2002) and still use the small amounts of rainfall during this period of transition between wet and dry season. Samples from pinning experiments collected at the end of June show complete annual rings, which suggests that cambial activity is interrupted before late June.

Rainfall during the rainy season (previous November through current March) explains around 43% of Panga-panga ring width variation (Figure 22). Monthly precipitation data with a resolution of 2.5 by 3.5 degree, obtained from the CRU global gridded dataset was used to test the correlations with Panga-panga chronology. Rainfall in Mozambique has great variability not only temporally but also spatially. The CRU gridded dataset represents a large area and this may have led to an underestimate of the coefficient of correlation between the chronology and rainfall during the rainy season. Correlations between the chronology and monthly rainfall during the dry season were negative, especially in July ($r = -0.20$; $p > 0.05$) and October ($r = -0.13$; $p > 0.05$). During the dry season, deciduous species such as *Brachystegia spiciformis* (Trouet et al., 2009), *Burkea Africana* (Fichtler et al., 2004) and *Pterocarpus angolensis* (Stahle et al., 1999), shed their leaves and cambial activity is interrupted resulting in ring formation, hence this negative response.

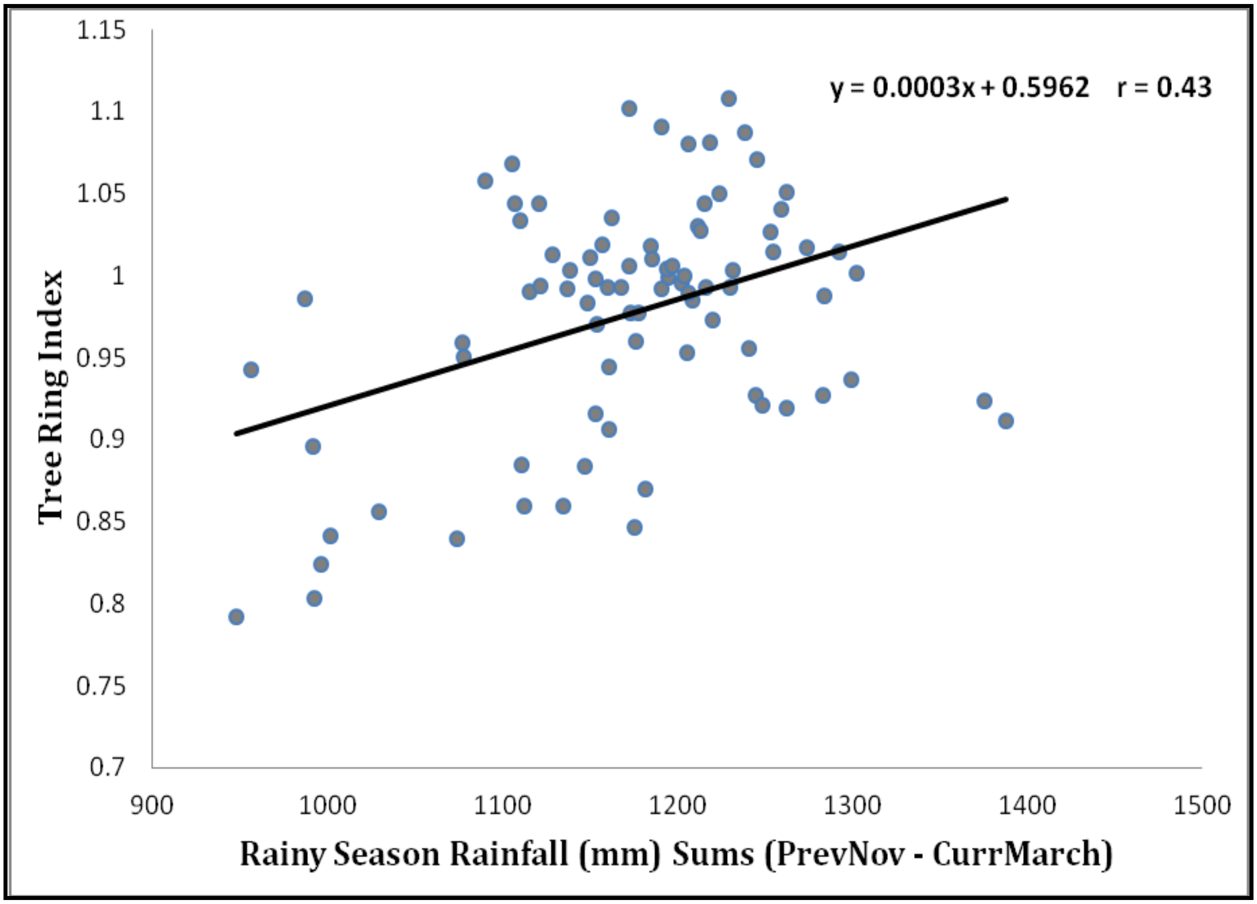

Figure 22: Rainy season (NDJFM) total rainfall plotted against the Panga-panga chronology from 1900 to 1996 ($r=0.43$, $p < 0.001$).

5.2 GROWTH DYNAMICS AND FOREST MANAGEMENT

5.2.1 Growth Increments

Diameter growth analysis can be useful to determine the volume of trees available at the harvestable size. To analyze diameter growth trends of *M. stuhlmannii*, ring width data from 36 tree cross-sections were accumulated from the first (innermost) ring (pith) through the last (outermost) ring and then plotted (Figure 23). Large differences in diameter growth trajectories were observed within and among trees. The black line represents the mean diameter growth of *M. stuhlmannii* in Mozambique (Sofala) and it is described by the following equation:

$$\text{Cumulative Stem diameter} = 0.4985\text{Age}+1.9737, \qquad R^2= 0.9993 \qquad (2)$$

The age of the trees ranged from 73 years to 155 years and the minimum and max diameter were 40.5 cm and 79.8 cm respectively. Growth rates to MCD were highly variable. It takes Panga-panga between 56 years (minimum time) to 118 years to achieve the MCD. These differences might be due to the genotypic of the tree and other environmental factors (Baltunis, et. al., 2010).

These results suggest that it takes about 75 years on average for *M. stuhlmannii* to reach the MCD. The median variation of ring width within trees was 0.25 and the minimum and maximum variations were 0.184 and 0.379, respectively. The coefficient of variance of the ring width among trees varied from 42% through 78%. Panga-panga mean annual increment is 0.51 cm/year (min=0.36 cm/year; max=0.79 cm/year; stdv= .103 – among individual trees). This value agrees with the Equation 2 presented previously in this paper, which suggests that it may take around 75 years for the species to reach the MCD. MAI increases with time until trees reach ~50 years of age (~23cm) and starts to decline in advanced age. Mean annual increment increases with stem diameter and reaches the maximum increment in the 20-30 cm diameter class. After emerging from this class, ringwidth increments start to decrease as stem size increases (see appendix B).

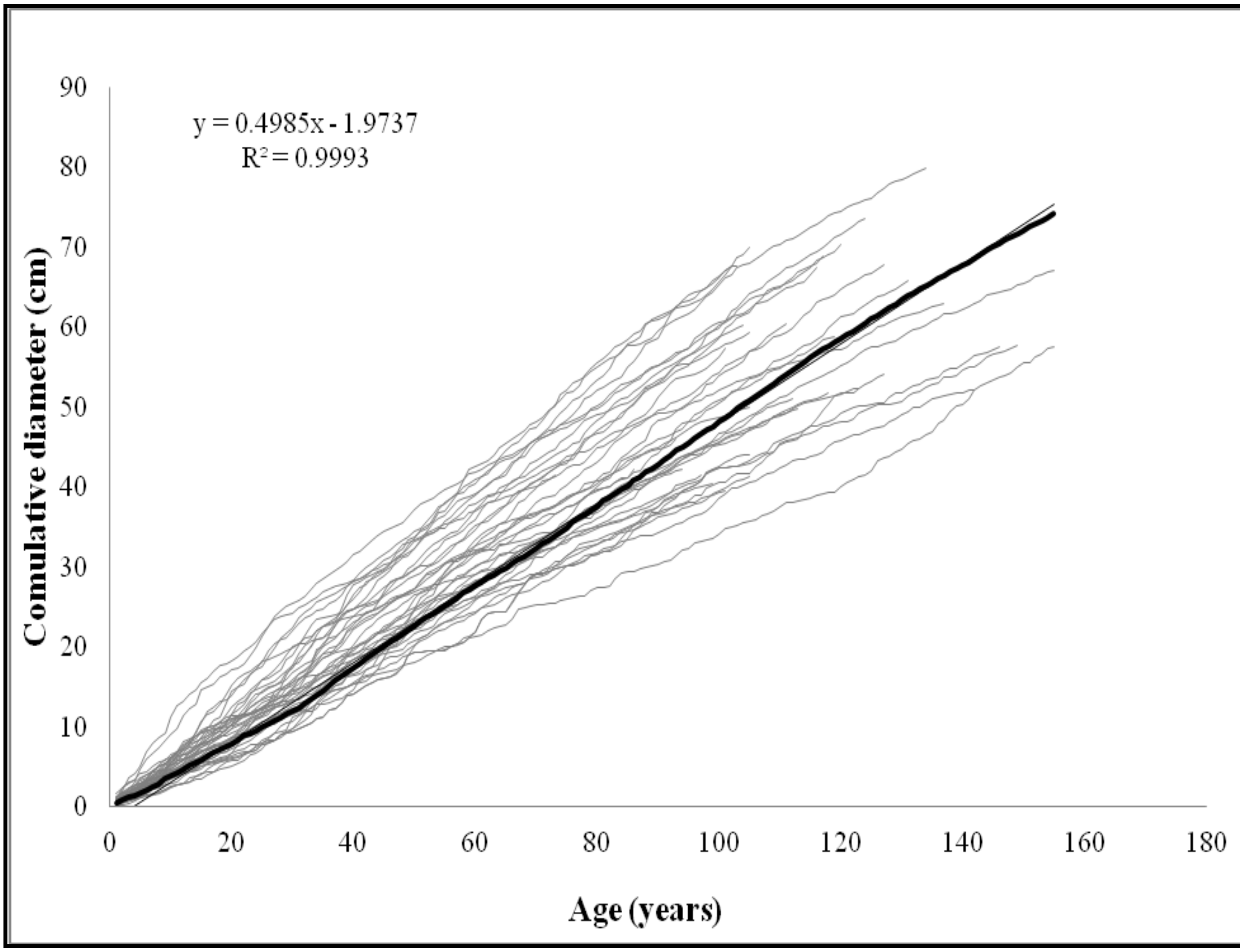

Figure 23: Cumulative annual growth for 36 trees (gray lines) and average growth (black line). Each line represents an individual tree. Ring width data from a single radius were doubled to approximate the total stem diameter (TSD).

Mean annual growth rate of *M. stuhlmannii* varied largely within class and among classes. The non-parametric Kruskal-Wallis test ($p<0.001$) shows that there is a significant difference among the median increment of different classes. The differences of MAI among years begin to show less variability after age 20. Sitoe (1999) found that *M. stuhlmannii* median ringwidth growth of 0.38 cm/year and suggeseted that it may take about 105 years to grow from

10 to 50 cm. But Sitoe (1999, p. 29) also states that “the period considered for the study is relatively short to produce precise and definite information”.

The reduction of tree ring width variability among trees with trees aging in this study might be an indicator of similar responses to the environmental conditions as the trees get larger with age. Large variabilities were observed only until the MAI reaches the maximum values (40-50 years). The age in which Panga-panga reaches the maximum MAI might be taken as an important finding because it may be an indicator of the at which time silviculture treatments should be undertaken in order to maximize the commercial value of panga-panga timber.

Climate is changing and a good understanding of the relationship between forest growth dynamics and climate variables (e.g., precipitation) might help in predicting future climate impacts on tropical ecosystems ecology. Rainfall has proven to have a large influence on Panga-panga growth. Both rainfall and growth increments has shown a negative trend since 1940 (Figure 24). Growth increment reductions have large impacts on the harvest cycle, as the year in which trees reach the MCD of 40 cm gets delayed.

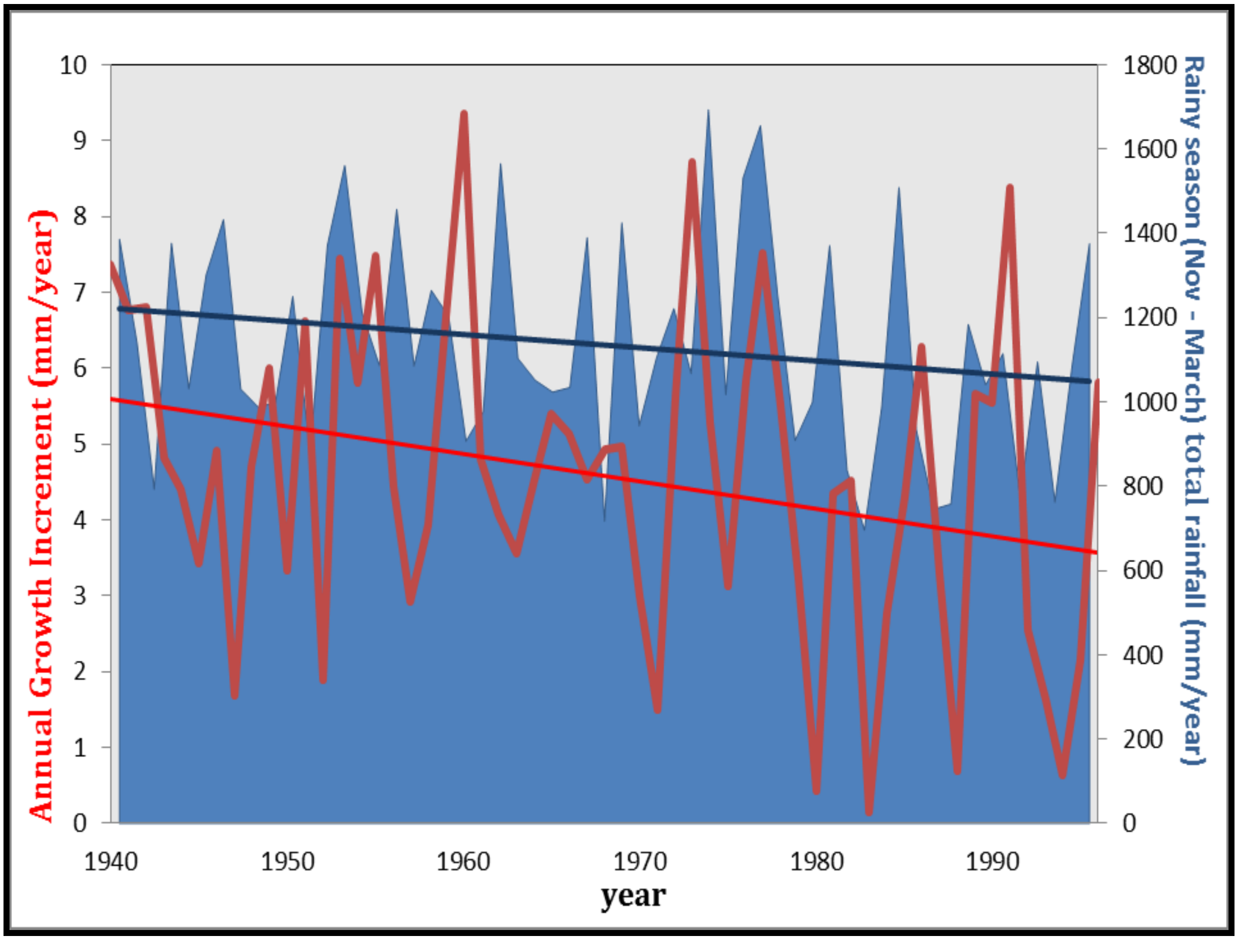

Figure 24: Annual growth increment declining with rainfall reductions over a long period (1940-1996). Correlation between Annual growth increment and rainfall during the rainy season (November – March, $r = 0.27$, $p<0.01$).

Growth increments between trees were different. Some trees take only a few years to reach 40 cm in diameter and some take more than 100 years and this will be aggravated with growth declines in response to climate change in the tropics. Although different factors influence tree ring width growth (climate, genotype, nutrients, type of soil) fast growing trees at the study site areas might be coppices that grew from stumps left from colonial-era (~1960s) logging. The area was harvested by Portuguese colonialists and some stumps that did not coppice remain in the field. Potential colonial coppices, when compared separately with other trees, showed high MAI. Analysis of variance (ANOVA) between plantation trees, potential colonial coppices (hereafter referred as coppice) and normal trees (hereafter referred as non-coppice) showed significant differences among the three types of growth (Table 3).

Table 3: Analysis of variance between plantation trees, coppice and non-coppice trees (treatment). Results show significance difference between treatments at almost 100 % of confidence level

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Treatment	4.325486	2	2.16274	334.751	1.22E-22***	3.2849177
Error	0.213205	33	0.006461			
Total	4.538691	35				

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 ' ' 0.1 ' '

Tukey's *honestly significant difference* test was applied to test the differences among all the three different treatments. Results show that all the treatments are different from each other Table 4). Forest trees showed less MAI when compared with the other treatments and plantation showed the highest MAI increment. Although all treatments showed differences in terms of growth rates, unmanaged coppices showed considerably higher increments (plot not shown).

Table 4: Tukey's honestly significant difference test

	Difference	Lower limit	Upper limit	P adjusted
Non coppice[a] -Coppice[b]	-.2847266	-.3652467	-.2042065	0
Plantation[c]-Coppice[b]	.5503732	.4698531	.6308933	0
Plantation[c]- Non coppice[a]	.8350998	.7545797	.9156198	0

Different letters (a, b and c) and same signal between upper and lower limit indicates significant difference between mean annual increment of treatments.

These results suggest that coppice management not only contributes to SFM but also can result in shorter cut cycles due to fast growth.

5.2.2 Temporal Growth Patterns

It is evident from the box plot below that the median time Panga-panga takes to pass from 0-10 cm and from 30-40 cm classes are the largest, 21.5 years. The growth from 0-10 cm classes starts to decrease slightly and the classes 10-20 and 20-30 cm have a median of 18.5 years. The growth when Panga-panga trees are young is fast (Figure 25). Some trees take only 10 years to move from the first class (0-10cm) to the second class (10-20 cm). Differences in time to move to the other class are large among and within classes when the trees are young, but as they get old the variability is reduced. This variability explains the high variability among trees to reach the MCD. The variability among trees to move to the next class is reduced with increasing stem size and class 60-70 cm shows very low variability while the class from 0-40 cm shows high variability with some outliers.

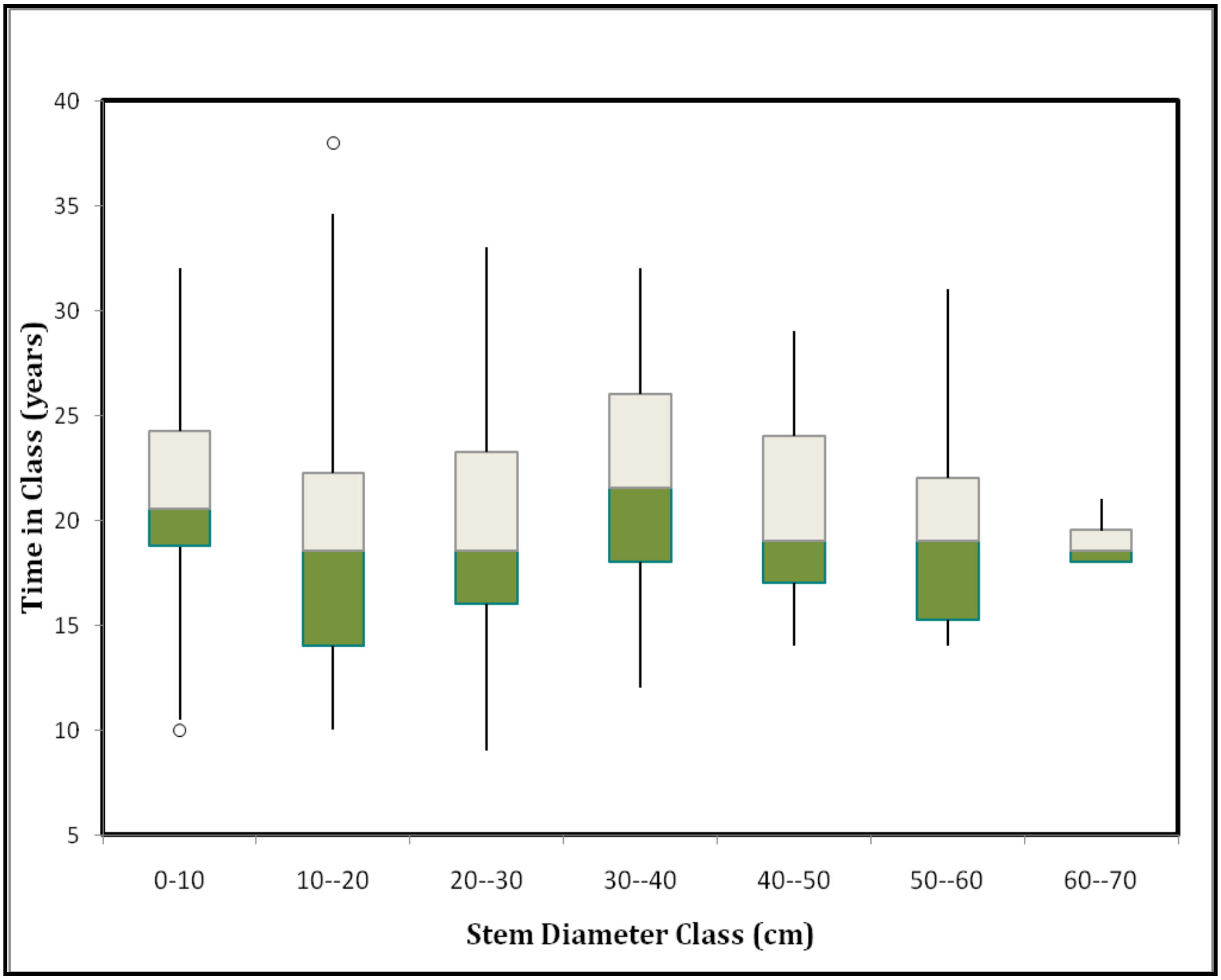

Figure 25: Time in years *M. stuhlmannii* needs to pass from one class to another. The plot clearly shows decreasing variability among trees in each class as diameter increases. Passage time did not differ between trees in each class (Kruskal-Wallis chi-squared = 9.568, p>0.001).

When *M. stuhlmannii* reaches 40 cm DBH the time needed to move to the next class is normally distributed (Gaussian). The remaining class distribution is positively skewed (many trees take a short time to move to the next class). Unlike other classes, class 0-10 cm showed negative skewness (many trees take a long time to move to the next class). The largest difference in time necessary to move from one class to another was found in the first two classes.

Based on the Kruskal-Wallis test, there isn't enough evidence to suggest that there is a difference in the median time trees need to move to the next diametric class ($p > 0.001$, Kruskal-Wallis chi-squared = 9.568, Kruskal-Wallis test). Partial correlation coefficients (Table 5) shows that the first and second diameter classes do not have significant effects on the growth through the MCD while class 20-30 cm shows high significance ($r = 0.7138$, $p= 0.000$). This suggests that once Panga-panga trees reach 20 cm DBH, silvicultural treatments to accelerate growth should be performed.

Table 5: Partial correlation analysis showing the effect of each class size on the passage time through Minimum cut diameter (MCD = 40 cm) for M. stuhlmannii.

	Parameter	**0-10 cm**	**10-20 cm**	**20-30 cm**
30-40 cm	Pearson Correlation	-.0786	.1263	.7138**
	Sig. (2-tailed)	.659	.477	.000

** Correlation is significant at the 0.01 level.

As shown previously, MAI reaches the maximum value when trees are about 40 to 50 years old, corresponding to approximately to 23 cm DBH. The analyses above show that this is the class that has the most significant effects on the rate of growth to the MCD. However, these results do not necessarily suggest that silvicultural treatments should not be carried out prior to reaching the 20–30 cm DBH class. The results do suggest that in order to maximize efficiency, foresters might give priority to performing treatments on trees in this class.

5.2.3 Heartwood and Total Stem Diameter relationship

Due to its esthetic characteristics (Desch and Dinwoodie, 1996) and resistance to insects and deterioration by other microorganisms (Taylor et al., 2002), heartwood (HW) is more highly desired than sapwood in the forestry industry. Quantifying the amount and percentage of heartwood (HW%) and its relationship to different variables such as TSD and Ac offers additional opportunities for the sustainable management of tropical forests. Previous studies on Miombo woodland species, such as *P. angolensis* (e.g., Therrell et al., 2007) suggest that 49% of the variance in Heartwood volume is explained by TSD. Shackleton (2002) in South Africa also analyzed the heartwood-TSD relationship and reported very high correlations (r = 0.90). In this study, a piecewise regression model was fitted between the HW% and TSD (Figure 26) and the relationship is described in the following equation:

$$HW\% = -20.5232 + 3.4656\ TSD \text{ IF: } TSD \leq 33 \quad \text{Multiple adjusted } R^2 = 0.9701 \qquad (3)$$

$$HW\% = 93.650916 + 0.0281 TSD \text{ IF: } TSD > 33 \qquad (4)$$

Where:

Dummy variable (0, if $x_{i1} \leq 33$ and 1, if $x_{i1} > 33$)

TSD explains about 97% of the HW% variation. HW% shows a rapid increase along with TSD before the trees reach 33 cm in diameter (equation 3). The maximum percentage of heartwood that *M. stuhlmannii* can apparently reach is 96.6%. However, when trees are larger than 33 cm in diameter, the HW% do not show increases. These results suggest that from 33 cm on, the HW portion in the tree is maximed and the actual MCD of 40 cm set by the RLFFB (2002) is appropriate for this species. Therrell et al. (2007) also suggest that *P. angolensis* harvesting, should be delayed until stems reach 50 cm in order to maximize the yield of heartwood volume.

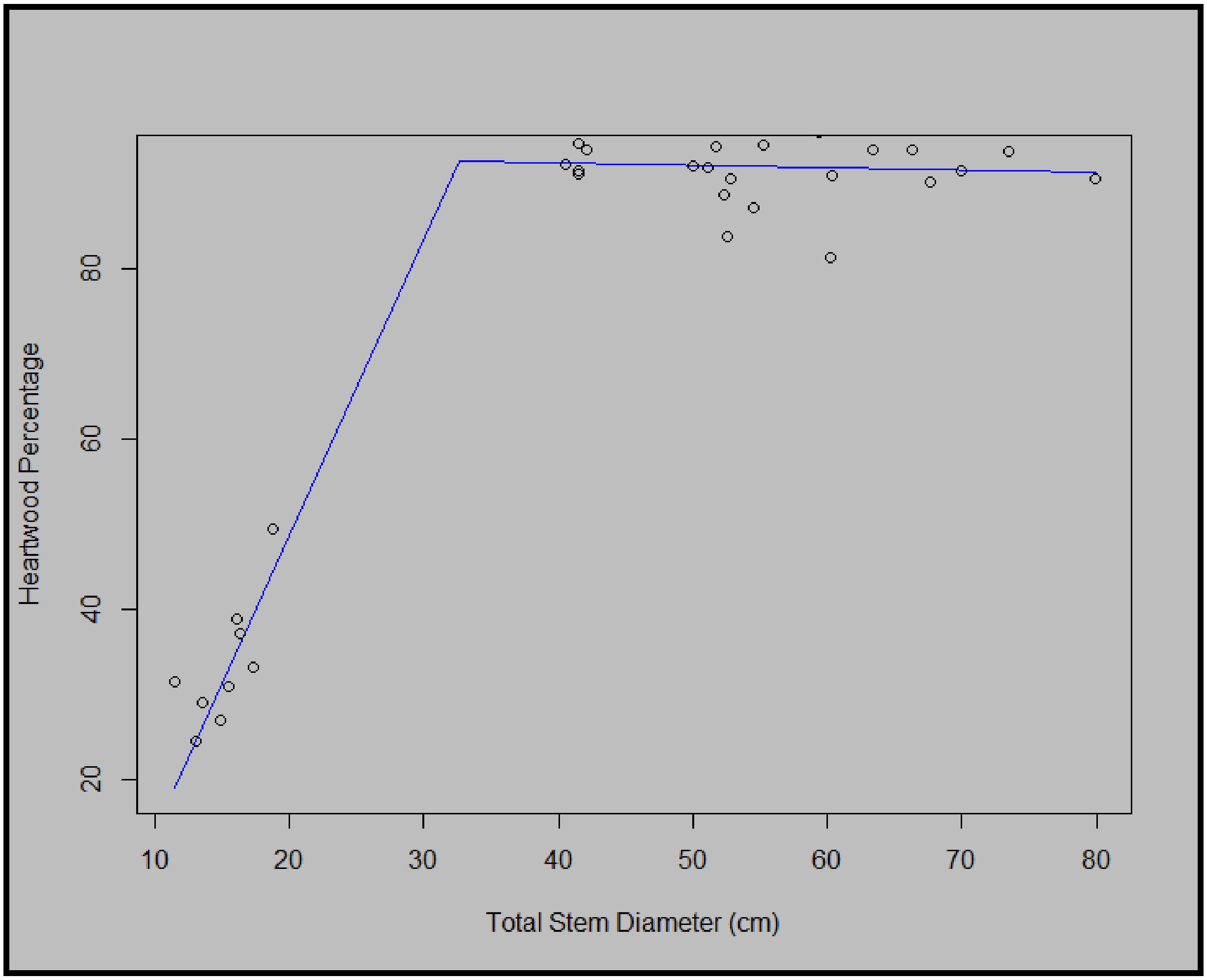

Figure 26: Heartwood percentage compared with the total stem diameter based on 36 samples. The Piecewise regression model better explains the variable fitting. This function also takes into account break-lines relationships (R^2 = 0.9701, $p < 0.0001$).

A linear model between HWR and Ac was fit based on the coefficient of determination (Highest R^2). Ac explains about 98% of the variability on the HWR (HWR = 0.9593Ac - 7.5562, R^2 = 0.9869). For the samples in this study, heartwood formation (HW (0)= 0.9593Ac - 7.5562) probably started when trees were about 7.88 years old (Figure 27). Compared with other species, for example, *Pinus pinaster* (Pinto et al., 2003), Panga – panga starts to form heartwood rings earlier. Heartwood rate of formation is variable both within and among groups (young and adult trees). The median heartwood rate formation for the adult trees was 0.91 rings/year and for the younger trees was 0.33 rings/year. Heartwood rate of formation increases with the expansion of total stem diameter as well as with the increasing Ac for this particular species.

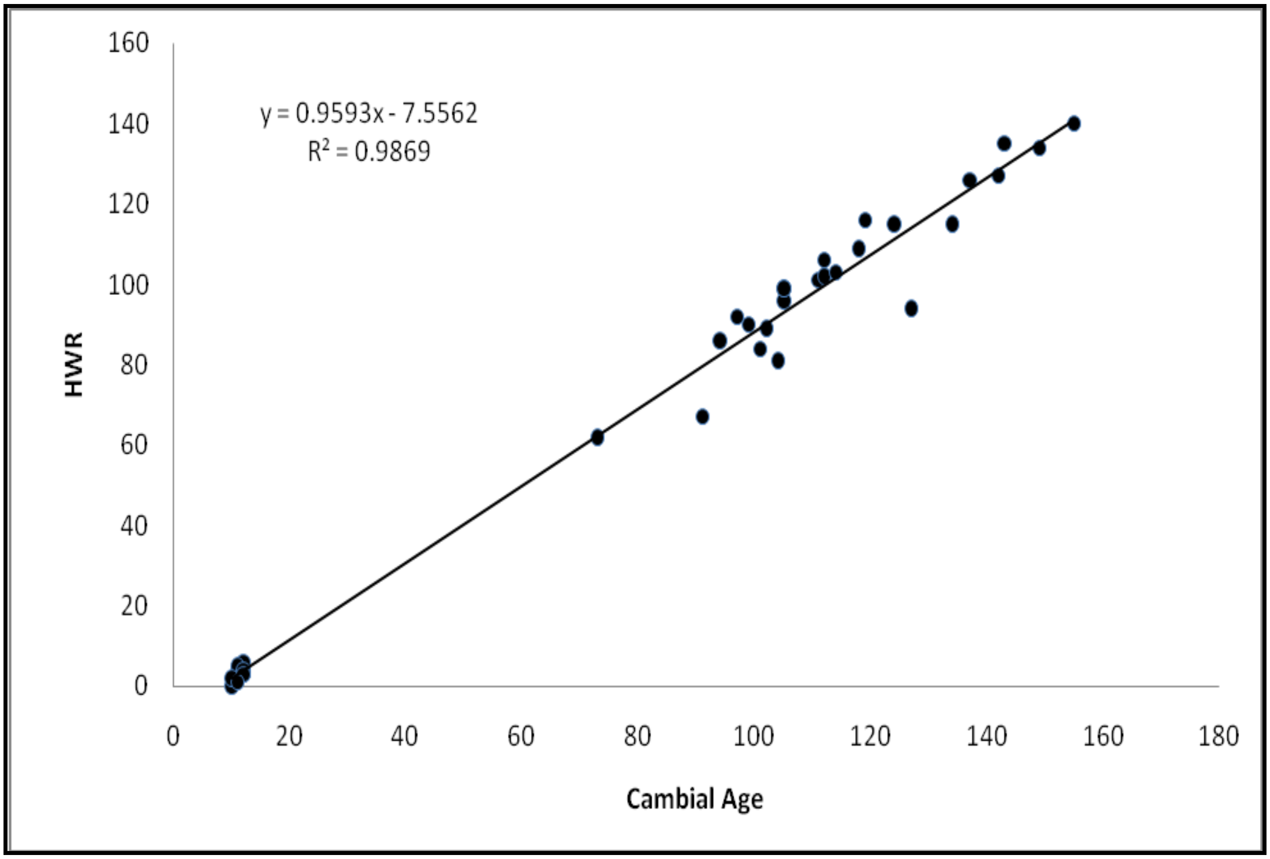

Figure 27: Linear relationship between Heartwood rings and Cambial Age (total stem rings) and fitted model (HWR = 0.9593Ac - 7.5562, $R^2 = 0.9869$, $p<0.001$

Analysis of the Heartwood rings and cambial age relationship has been done previously by Pinto, et al. (2003), Bjorklund (1999). By fitting both a second degree polynomial model (R^2=0.89, p<0.001) and a linear model (R^2=0.88, p<0.001), Pinto, et al. (2003) determined that *Pinus pinaster Ait*. heartwood initiation age was 13 years and 18 years respectively. They also suggests that the rate of heartwood formation for the same species depends on age. For ages below 55, years they report a rate of 0.5 rings/year and 0.7 rings/year for ages above 55 years. Björklund (1999) found that rate of heartwood formation in *Pinus sylvestris* also differs with age, older trees showing a fast rate of formation. *Pinus sylvestris* forms 0.5 heartwood rings/year (Ac= 45 years), 0.7 rings/ year (Ac~90years), and 0.8 rings/ year (Ac ~ 115 years).

Correlation analyses revealed that HW is positively correlated with TSD, cambial age, HWR, HWA, TSDA and MAI (Table 6). As a tree gets older, the number of annual heartwood rings is consistently expected to increase. A positive and significant relationship was expected between HW and HWR (r=.933) because HW increases as sapwood rings turn into HWR. The number of HWR increases with tree age (r=0.942, p<0.001). These results agree with those reported previously by Yang and Hazemberg (1991). HW was better correlated with TSD (r = .993) compared to HWA, HWR and Ac (r = .902; .977; .931). Heartwood is the result of the dying of sapwood cells, hence the negative correlated between HW and SW (r=-.682) which means that as the HW portion increases in terms of diameter, the SW decreases.

Table 6: Correlation coefficients among the variables; heartwood width (HW), Sapwood width (SW), Total stem diameter (TSD), Cambial age (Ac), number of rings in heartwood (HWR), heartwood area (HWA), Total stem diameter area (TSDA) and Mean annual increment (MAI). Values in parentheses indicate the probability of no correlation between the variables.

	HW (cm)	**SW (cm)**	**TSD (cm)**	**Ac**	**HWR**	**HWA**	**TSDA**	**MAI**
HW (cm)	1	-.682** (.000)	.993** (.000)	.931** (.000)	.933** (.000)	.966** (.000)	.954** (.000)	-.809** (.000)
SW (cm)		1	-.591** (.000)	-.752** (.000)	-.793** (.000)	-.562** (.000)	-.470** (.004)	.746** (.000)
TSD (cm)			1	.906** (.000)	.902** (.000)	.975** (.000)	.977** (.000)	-.773** (.000)
Ac				1	.993** (.000)	.848** (.000)	.826** (.000)	-.893** (.000)
HWR					1	.853** g(.000)	.821** (.000)	-.885** (.000)
HWA						1	.991** (.000)	-.692** (.000)
TSDA							1	-.669** (.000)
MAI								1

** Pearson Correlation is significant at the 0.01 level (2-tailed).

* Pearson Correlation is significant at the 0.05 level (2-tailed).

MAI was strongly negatively correlated with most of the variables except with SW, with which it is strongly positive correlated (r = 0.746). Sapwood is physiologically active and the main function is to transport nutrients from the roots to the canopy, hence the strong relationship with the MAI. As shown previously (Figure 4), heartwood formation is the result of increasing cambial age (r = 0.993) and this has strong influences changes on the growth increment (r = -0.885).

DISCUSSION

5.3 Millettia stuhlmannii Annual Rings

No dendroclimatological or dendroecological studies such as this one have been done in Mozambique. However, many researchers have conducted studies in countries nearby Mozambique, where the climate sometimes demonstrates patterns of variability similar to those in Mozambique. Studies on species in the *Fabaceae* family have previously shown that tropical trees indeed form annual rings, such as *Pterocarpus angolensis* in Zimbabwe (Stahle et al., 1999; Therrell et al. 2007), *Brachystegia spiciformis* (Trouet et al., 2009), and *Burkea africana* (Fichtler et al., 2004). In this study, the annual nature of *Millettia stuhlmannii* rings was shown by five different methods: (1) Cambial wounding; (2) Successful cross-dating within and between trees; (3) Ring structure and anatomy (4) Ring counting in trees with known age (young trees collected from an experiment "plantation") and (5) Correlation between ring width and climate data.

The pinning process was successful in Panga-panga trees and as result the trees showed distinct wood reaction and subsequently one entire ring was formed during the growing season. This technique was first introduced by Mariaux (1967) to study the cambial periodicity and since then has been applied to prove the annual nature of several tropical tree species. However based on this experiment, it was only possible to conclude that Panga-panga forms annual rings. Further studies to determine the onset and growth length using this technique should be undertaken. Trouet, et al., (2012) have done a growth periodicity evaluation on *Brachystegia spiciformis* in Southern Africa. They applied the pinning method on a bi-weekly period from October 27, 2001 through October 17, 2002 and concluded that one month after the rainy season starts (December), all trees started their cambial activity which then lasted approximately four months (all trees by March 16 had completed the ring formation process).

Rainfall seasonality in Tropical rainforest is responsible for phenology patterns and cambial activity. Although most of the tropics lack clear seasonality (Hoadley, 1990), which sometimes may result in unclear indistinct ring boundaries, dendroecologic and dendroclimatic methods have been widely applied to tropical species and evidence indicates that ring boundaries can be identified. Wood anatomy descriptions of some tropical species have also been done. *M. stuhlmannii* is classified as semi-ring porous (vessel size decreases gradually towards the latewood) and ring boundary in all samples were slightly distinct. Ring boundaries were characterized by alternating patterns of parenchyma and fibre vessels and a thin line of marginal parenchyma. Stahle et al. (1999) found distinct ring boundaries for *P. angolensis* in Zimbabwe forests. *P. angolensis* is a member of Fabaceae family, the same as *M. stuhlmannii* and ring boundaries were characterized by initial parenchyma and by altering sizes of the vessels between EW and LW (semi ring porous).

Brienen and Zuidema (2005) found that six different Bolivian tree species also form annual rings that varied in terms of distinctiveness. Distinctiveness ranged from rather clear to very clear. Ring boundaries were characterized by marginal parenchyma (*Cedrela odorata*), vessel distribution and alternating pattern of parenchyma and fibre bands (*Amburana cearensis*), repeated pattern of alternating fibre and parenchyma bands (*Bertholletia excels*), density variation (*Cedrelinga catenaeformis*), marginal parenchyma bands and vessel distribution (*Peltogyne cf. heterophylla*) and density variation (*Tachigali vasquezii*). When comparing the distinctiveness of ring boundaries between the six species they found that species in which ring boundaries were characterized by marginal parenchyma had clear ring boundaries hence the distinctiveness when compared with other forms of ring boundary characterization. Fichtler et al. (2004) found that *Burkea africana*, another species that belongs to the Fabaceae family, forms annual rings characterized by marginal parenchyma bands. The anatomical results presented here do not diverge from those studies done previously for different tropical tree species, especially those occurring in southern African tropical ecosystems. The minute anatomy of *M. stuhlmannii* revealed that ring boundary distinctiveness is clear and can be identified.

Despite tree ring anomalies (wedging rings, false rings and missing rings), cross dating between six series was successful and a pilot ring width chronology was developed. Panga-panga tree ring width showed a strong response to inter-annual precipitation variability. Significant correlation between monthly precipitation and the chronology was found for the previous December and current February. Despite the fact that January typically has high amounts of rainfall, precipitation during this month was not significantly correlated with ring width, this might be due to convective precipitation, which is characterized by cluster rainfalls associated with intensely rapid increases. Heavy rains during this month resulting in high runoff values and less usage by plants might be a potential reason for this negative correlation. Strong correlations with rainfall at the end of the rainy season might imply that Panga-panga cambial activity extends longer than expected. During the dry season, negative correlations were observed between climate monthly rainfall and the chronology. This is an indicator of cambial dormancy.

A similar response to climate during the core of the rainy season was reported for *P. angolensis* in Zimbabwe by Stahle et al. (1999). The author found that seasonal (DJF) rainfall influenced tree ring width by 10 to 30%. Trouet et al. (2009) reported a strong influence of rainfall on *Brachystegia spiciformis* during the rainy season (December through February) and negative correlations were found at the end of the dry season and beginning of the rainy season

(October and November). The findings from this study show that during October, when rainfall amounts remain below 60 mm, per month, *M. stuhlmannii* vascular cambium remains dormant and at the beginning of the rainy season (November) a positive correlation was found between radial growth and rainfall, which indicates that during this month, secondary growth begins.

In Namibia Fichtler et al., (2004) found positive correlations with rainy season precipitation for two Fabaceae family species, *P. angolensis and Burkea africana*. *P. angolensis* showed less correlation with rainfall variability when compared with *Burkea africana*. However, both species' growth showed a strong response to April rainfall (highest amounts of rainfall in the area sampled occur in April, see Fichtler et al. (2004) for further details). The Catapú concession receives the high amounts of rainfall during December and February (MAI, 2005). These months also have the most significant correlation coefficients with the chronology. Different species have different water usages strategies, hence the difference in growth response to climate by different species. For instance, Fichtler et al. (2004) also reported strong positive correlation between a *B. africana* chronology and precipitation during the dry season (August, September and November). In this study, radial growth increments were associated with rainfall at the beginning of the rainy season. Nevertheless, rainfall during the end of the rainy season (May) also influences radial growth, suggesting that Panga-panga delays cambial activity secession when compared with *P. angolensis* (Stahle et al., 1999).

Rainfall patterns in southern Africa are strongly influenced by ENSO resulting in high rainfall variability from year to year. Besides, meteorological data are sparse and discontinuous (see Figure 28 for correlation between DJF of three closest stations from the area samples were collected) making the reconstruction process a big challenge. Mozambique lacks research in the field of dendrochronology. This study is the first successful attempt to build a chronology for the country. Replications of the chronology spatially as well as temporally would enable a long term reconstruction of climate events allowing for a better understanding of regional and global warming drivers as well as related impacts on tropical forest ecology and human society.

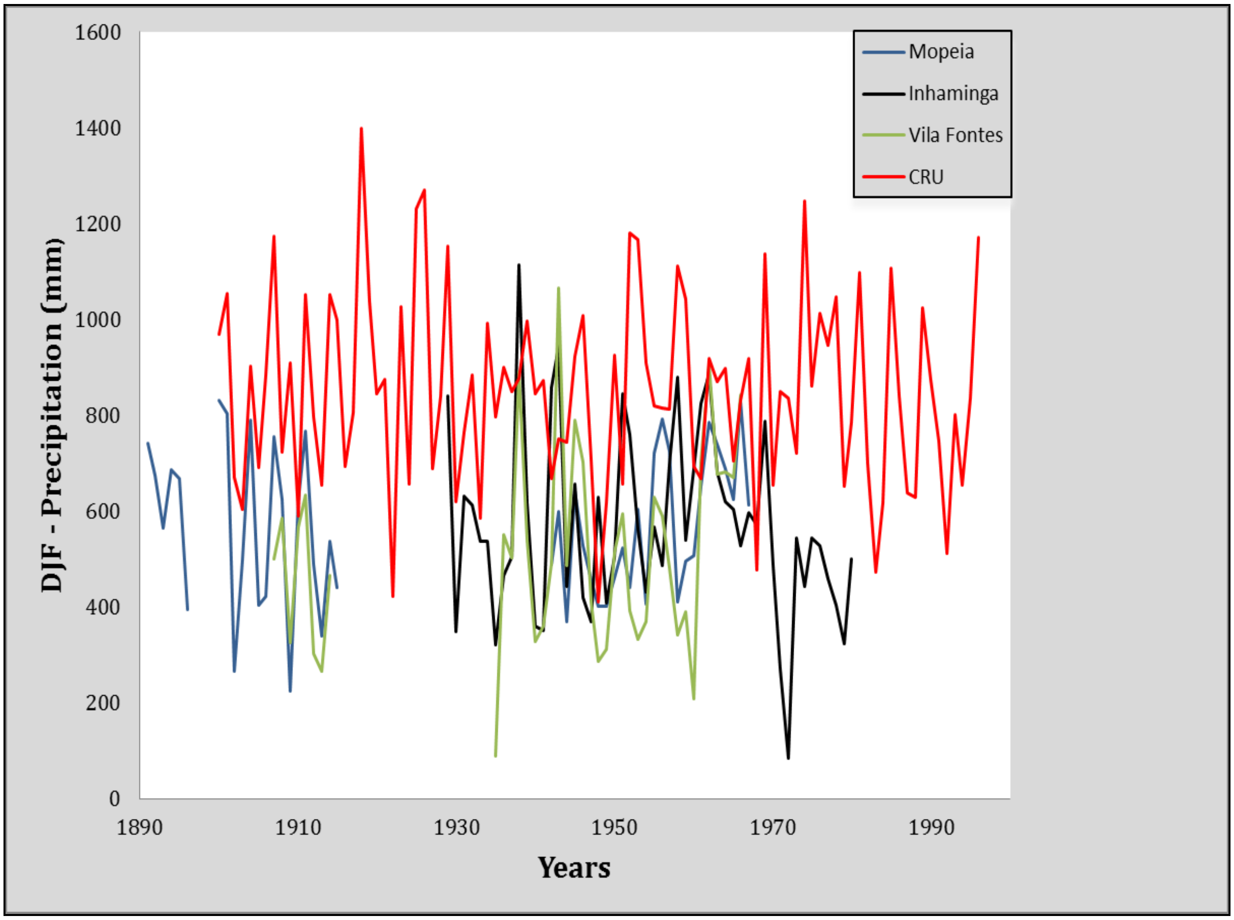

Figure 28: December through February (DJF) total precipitation from three weather stations near the Catapú concession and CRU grided data from one grid. Correlation coeficients between CRU grided data and the three meteorological station are 0.27, 0.099 and 0.05 for Mopeia, Inhaminga and Vila fontes station respectively.

5.4 Forest Management Implications

As part of this study, growth rate dynamics of *M. stuhlmannii* were analyzed in Mozambique. The growth rings have shown good potential to be used to estimate stand age and growth rates. The species presents relatively slow growth rates (0.51 cm/year). Cumulative growth of individual trees shows great variability over time both within and among trees. The results show that it takes between 56 and 118 years (average of 75) to reach the MCD. The mean annual increment is comparable with those reported from other tropical regions, such as; *B. spiciformis* (Trout et. al., 2006), *P. angolensis* (Stahle, et. al., 1999; Therrell, et al. 2007) and *M. sthulmannii* (Sitoe ,1999). Therrell, et al. (2007) reported annual diameter increment of 0.4 cm/years for *P. angolensis* and the species takes 85 to 100 years to reach MCD. Stahle et al. (1999) reported that it takes 88 to 137 years for *P. angolensis* to reach the MCD. Trout et al. (2006), in western Zambia, reported values that range from 2.44 to 3.25mm/year.

The mean annual increment obtained in this study is signifincatly larger than the value found by Sitoe (1999) of 0.38cm/year ranging from -3.47 to 1.54 cm/year in the Miombo woodland. Compared to Sitoe (1999), which was based on only two years of measurements, this current study provides more precise results because it is based on tree ring (lifetime data) analysis. The results here presented are comparable with those presented in the tropical region by different authors (see table 1 in section 2.4).

M. stuhlmannii shows great variability in diameter growth both within and among trees. The median variation of ring width within tree was 0.25 cm and the minimum and maximum variations were 0.184 cm and 0.379 cm, respectively. The coefficient of variance of the ring width among trees varied from 42% through 78.3%.

The median time the species takes to pass from one class to the next is similar to the pattern shown by Brienen and Zuidema (2006), and Therrell, et al. (2007). When trees are small, they are highly affected by environmental conditions (soil nutrient, solar radiation, etc). Trees in the understory generally are affected by the sun exposure (Chazdon et. al, 1996). This situation might explain the variability seen on the smaller classes. When trees reach 40 cm in diameter, the growth pattern show less variability which may be because tress already reached the canopy.

The highest median time passage was found at the first and third classes (0-10 cm and 30-40 cm). A study on Bolivian rainforest trees by Brienen and Zuidema (2006) found that the smallest class (0-10cm) has the highest median passage for some of the species but for two Fabaceae family species (*Amburana* c*aerensis* and *Peltogyne* cf. *heterophylla*), the second and third classes showed the highest median passage.

Based on the Kruskal-Wallis test, there isn't enough evidence to suggest that there is a difference among the median time panga-panga takes to move to the next diameter class ($p>0.001$, Kruskal-Wallis chi-squared = 9.568, Kruskal-Wallis test). Partial correlation coefficients show that the first and second diameter classes do not have significant effects on growth through the MCD and class 20-30 cm showed high significance ($r = 0.7138$, $p < 0.01$). This might be an indicator of the time in which silvicultural treatments should be performed in order to accelerate growth.

Heartwood due to it anatomical characteristics (Desch and Dinwoodie, 1996) is more desired than sapwood in the forestry industry. Correlation analyses revealed that HW is positively correlated with TSD, Ac, HWR, HWA, TSD and negative correlated with MAI and SW. Heartwood in this study was better correlated to the TSD ($r = .993$) than HWA, HWR and Ac ($r = .902$; .977; .931). Regression analysis between Heartwood width and TSD ($R^2 = .986$, p<0.01) shows that for Panga-panga diameter is the primary factor that dictates heartwood formation. Similar studies have been reported for *Tectona grandis* in Costa Rica, by Cordero and Kanninen (2003), *Eucalyptus globules,* (Gominho and Perreira, 2000) and *Pinus sylvestris* (Björklund, 1999).

TSD explains about 97% of the HW% variation. HW% shows a rapid increase along with TSD before the trees reach 33 cm in diameter and when trees are larger than 33 cm in diameter, the HW% does not show significant changes in proportion. Panga-panga heartwood formation started when trees were about 7.88 years old. When compared with other species Panga – panga starts to form heartwood rings earlier. The median heartwood rate formation for the adult trees was 0.91 rings/year and for the younger trees was 0.33 rings/year. This is might be due to the role sapwood plays in the integral functions of transporting water and providing storage for metabolites, which are vital to tree growth. Compared to other species Panga-panga has shown higher rates of sapwood- heartwood transformation. This might be due to the quality of soils in tropical regions specifically on Miombo woodlands (Dewees et. al., 2011). The other reason might be due to sunlight competition (Chazdon, 1996) in the tropical ecosystems compared to the temperate regions.

A study in Zambia by Syampungani et al. (2010) also revealed that the key Miombo species (*Brachystegia floribunda, Isoberlinia angolensis* and *Julbernardia paniculata)* within growing charcoal and slash and burn regrowth stands produce distinct growth rings and all three species showed strong correlation between the number of growth rings and the DBH of trees, in both slash and burn ($r = 0.8806$; $P < 0.01$) and charcoal ($r = 0.9068$; $P < 0.01$) regrowth stands.

Growth rate reductions (e.g. 0.0036 cm/year for *M. stuhlmannii*) over time might be an indicator of global warming affects on tropical ecosytems dynamic. However this study was only restricted to rainfall and further analysis and future projection of potential growth declines with global warming should be done including different climate variables (temperature). The knowladge of growth rate changes with climate will contribute to a sustainable management of tropical ecosystems and to better understand land use-climate feedbacks. Stable isotope analyzes should be carried out also to help understanding *M. stuhlmannii* water use efficiency and carbon concentration variations overtime.

CHAPTER 5

CONCLUSION

This study presents, for the first time in Mozambique, precise dendroclimatic and dendroecology analysis. This is the first study using tree rings from a hardwood species in Mozambique to determine growth dyanamics and sustainable management actions. *M. sthulmanni*, also known as Panga-panga, presents rings that showed good dendrochronological potential, for both climate analysis and for forest management implications. Meteorological data in Mozambique is sparse and discontinuous and Panga-panga has potential for climate reconstruction.

The purpose of the study was to analyze the influence of climate on tree growth and to perform growth dynamics analysis based on tree rings, in an attempt to answer the two questions that were posed at the beginning of this paper. The first was: Do *M. Stuhlmannii* trees form annual tree rings and is it possible to use these tree rings to accurately determine growth rates? The findings from this study indicate that this species does form annual tree rings and that these rings are useful in determining growth rates. Five methods used for the study, support the hypothesis that the rings of Panga-panga are annual (wood anatomy, inter-series cross-dating, ring counting on trees of known age, cambial wounding and growth response to climate). The second question was: Is *M. Stuhlmannii* annual ring-width growth correlated with monthly and seasonal precipitation in central Mozambique? The findings from this study also demonstrate a positive correlation between precipitation and annual ring-width growth during the rainy season. Rainfall during December and February explains about 43% of the chronology variation. Hence there is good potential for climate recontruction using Panga-panga.

These results are relevant for conservation and management of the species in Mozambique, as well as for the maintanance of sustainable harvesting. The analysis of tree rings can provide insightful information about tropical forest dynamics. Further research, such as growth modeling, should be done in tropical forests to better understand the complexity of these ecosystems. Regarding climate growth relationship, promising results were found and further studies such as climate reconstruction should be done. Droughts are some of the most serious threats for African countries and tree ring proxies have proven to be valuable for such event reconstruction. Furthermore, tree ring proxies and satellite proxies should be used simultaneously to determine the onset and duration of extreme climate events in Mozambique. Such information would be helpful for drought monitoring and for drawing new strategies for adaptation since Mozambique relies on the rainfall (more that 3 quarter of the population) for subsistence.

This study indicates that the current cutting cycle that has been used by most of the concessions is too short (30 years). This means that commercial species have been harvested in non-sustainable ways, which may result in population declines. Based on these findings, the cutting cycle should be increased to at least 75 years, the average time *M. stuhlmannii* takes to reach the MCD. Heartwood analysis revealed that the actual MCD set by law is appropriate for keeping sustainable forest practices. However, in further heartwood analysis “middle age” trees should be taken into account to help defining accurately the MCD for this precious species. Short rotation cycles coupled with massive illegal logging, leads me to believe that in the not-to-distant future high rates of tropical forest deforestation will result in the degradation of tropical ecosystems.

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APPENDICES

APPENDIX A

Tree-ring Widths Measurements (cumulative)

Age	CAT01	CAT14A	CAT14B	CAT03	CAT05B	CAT06	CAT007	CAT08A	CAT09C
1	0.882	0.3438	0.3396	0.2488	0.2398	0.7148	1.0082	1.0298	0.5934
2	1.3512	1.0056	1.1138	0.512	0.5128	1.5514	1.9866	1.8296	1.1286
3	1.7138	1.756	1.7164	0.813	0.7394	1.8546	3.6058	2.4106	1.3718
4	2.1666	2.1084	1.9618	1.1658	1.1878	2.3854	4.214	2.6386	1.7966
5	2.8602	2.2662	2.4426	2.3384	1.692	2.7746	5.0694	3.4474	2.1558
6	3.2868	2.8152	3.1972	3.4948	2.4024	3.1174	6.8654	3.9544	2.6606
7	3.7096	2.998	3.5366	4.3172	2.8338	3.3692	7.888	4.455	2.988
8	4.083	3.5226	4.4544	5.0582	3.1006	3.8074	8.7214	4.9882	4.1156
9	4.3104	4.0902	5.1618	5.4154	3.7782	4.042	9.1196	5.4126	4.6272
10	5.1424	4.2086	5.4048	5.7948	4.215	4.1936	11.236	5.9006	5.4128
11	5.7214	4.3164	6.1184	6.3928	4.5076	4.7742	12.6128	6.5478	6.282
12	6.0076	4.796	6.7618	7.0268	4.7238	5.0052	13.2036	7.0816	6.5684
13	6.2316	5.501	7.5652	7.3924	5.0172	5.1736	14.0888	7.7152	6.7656
14	6.6228	6.2536	8.1798	7.665	5.2402	5.9518	14.6558	9.3468	7.2104
15	6.9596	6.9122	8.5032	7.728	5.7318	6.2958	15.4486	10.505	7.7114
16	7.2706	7.2212	9.2794	8.123	6.2776	6.9912	16.0482	11.8528	7.982
17	7.5112	7.7698	9.493	8.429	6.6226	7.3602	16.8724	12.5184	8.443
18	7.6368	8.0156	9.7048	8.7584	7.2194	7.716	17.6428	13.0954	9.0624
19	7.8558	8.3138	9.961	8.9354	7.864	7.9034	17.9404	13.4258	9.5824
20	8.3466	8.579	10.1858	9.2962	8.4244	8.0818	18.2082	13.9306	10.3298
21	8.84	8.6272	10.2808	9.5676	8.9696	8.4974	18.6882	14.9188	10.9202
22	9.395	8.7418	10.722	10.2576	9.2158	8.6816	19.4862	15.825	11.4498
23	9.7476	8.9128	11.1096	10.655	9.6204	9.0102	20.0874	16.5112	11.7852
24	10.0508	9.4618	11.7094	11.1802	9.855	9.677	20.6298	17.1878	12.0954
25	10.6478	10.1684	12.501	11.7858	10.1416	9.856	21.6842	17.5444	12.3526
26	10.908	10.8658	12.9848	12.1256	10.5336	10.5768	22.5792	18.6964	12.993
27	11.387	11.1582	13.3594	12.4128	10.748	11.3366	23.3748	19.9362	13.5924
28	11.65	11.5112	13.6594	12.6804	11.075	12.1224	23.7342	21.0646	14.6108
29	12.1092	11.7566	13.9496	12.9124	11.4662	12.81	24.0152	21.5986	15.0846
30	12.2768	11.8882	14.161	13.51	11.635	13.1354	24.248	22.4144	15.967
31	12.7052	12.462	14.8266	14.039	11.9566	13.6352	24.9178	23.6076	16.6186
32	13.1138	13.2606	15.0262	14.788	12.4448	14.3712	25.2644	24.3294	17.1382
33	13.5522	13.472	15.5058	15.3998	13.2212	15.2156	25.7536	24.8972	17.8296
34	14.4086	13.8794	16.0756	15.755	13.9574	16.3346	26.2032	25.6814	19.6588
35	14.9332	14.1704	16.9718	16.275	14.7006	16.865	26.8256	25.991	19.998

36	15.8698	14.8696	17.2856	16.6694	15.173	17.8924	27.2686	26.3562	21.4828
37	16.1346	15.6146	18.1666	17.2602	16.1734	18.4642	27.5698	26.7124	22.6546
38	16.3098	16.2192	18.9638	17.924	17.1544	18.7456	27.7802	27.2176	24.0424
39	16.405	16.5584	19.2798	18.7216	17.936	18.9154	27.974	27.565	24.5544
40	16.6174	17.2028	20.1762	19.8318	18.3656	19.0932	28.2504	28.3502	24.674
41	16.9194	17.8926	21.3676	20.2732	18.7134	19.3714	28.5518	29.2276	25.0048
42	17.8182	18.6794	22.2186	20.6054	19.1662	20.3128	28.888	29.9284	25.2088
43	18.3528	19.1508	22.8156	21.0346	19.6146	21.1936	29.6694	30.4216	25.6248
44	18.8034	19.502	23.5054	21.6522	19.7346	21.6732	30.1882	31.0748	25.8496
45	19.5088	19.6782	24.0172	22.2056	20.4568	22.5844	30.7712	31.6006	26.5458
46	19.8744	19.8816	24.394	22.8198	20.5926	22.8534	31.1918	32.098	27.3394
47	20.1376	20.036	24.679	23.273	20.9012	23.623	31.953	32.9034	28.3558
48	20.8622	20.495	25.3746	23.5926	21.1328	24.0324	32.761	33.303	28.8318
49	21.8158	20.918	25.842	24.0194	21.9608	24.7244	33.0664	33.7352	29.7552
50	22.5556	21.599	26.5582	24.4982	22.2182	25.8944	33.3348	34.409	30.3492
51	22.7972	21.9452	26.7792	24.811	22.3388	26.8916	33.783	34.882	31.1696
52	23.0674	22.1124	27.08	25.4236	23.0652	27.301	34.2132	35.6414	32.1416
53	23.5296	22.5968	27.2892	26.0086	24.0968	27.6514	34.6198	36.5918	32.883
54	24.1646	23.4138	27.7944	26.6018	24.7774	28.3514	34.9454	37.5914	33.2314
55	24.4808	24.2284	28.8318	27.2834	25.251	28.6916	35.3002	37.872	33.803
56	24.7824	24.5366	29.6666	27.9698	25.6068	29.4186	35.4806	38.5516	34.2156
57	25.1932	24.7028	29.8782	28.7742	26.1354	30.0804	35.8862	39.3958	34.3954
58	25.7748	25.1006	30.2764	28.9794	26.6388	30.6672	36.0624	41.0054	35.3542
59	26.0014	25.491	30.9326	29.602	27.3894	31.2978	36.7138	42.1718	36.082
60	26.2234	26.0034	31.628	29.9686	27.9282	31.8954	37.0374	42.6048	37.09
61	26.4572	26.2908	31.918	30.4294	28.5122	32.2078	37.4262	42.8544	37.886
62	26.934	26.5208	32.1412	30.808	28.988	32.7732	38.0328	43.2216	38.7696
63	27.454	26.8616	32.6156	31.764	29.408	33.207	38.2522	43.9942	39.0308
64	28.3858	27.119	33.2208	32.5854	29.6526	33.7992	38.4632	44.8704	39.8328
65	29.0082	27.4724	33.5196	32.8784	30.747	34.3338	38.7132	45.4836	40.1416
66	29.4078	27.6874	33.9888	33.41	31.4556	35.337	38.9304	45.9274	40.6554
67	30.2984	27.8554	34.2802	34.1836	31.9504	36.0942	39.3974	46.4752	41.1408
68	30.7178	27.9858	34.8704	34.5826	32.3756	36.376	39.6916	47.077	41.9528
69	31.108	28.5364	35.2392	34.8822	32.7432	37.079	39.8546	47.7428	42.8554
70	31.656	28.9884	35.5454	35.1274	33.26	38.0178	40.0982	48.1756	43.2636
71	32.017	29.0836	36.2936	35.3826	33.5426	38.5348	40.3756	48.691	43.8812
72	32.207	29.7354	36.617	35.8376	33.924	38.7412	40.9804	49.6422	44.3238
73	32.4638	30.1426	36.6964	36.5468	34.6716	39.0308	41.5036	50.0698	44.7634
74	32.9612	30.3812	37.009	36.9582	34.9384	39.6054		51.4946	45.6458
75	33.726	30.9986	37.4718	37.56	35.195	40.2482		52.1906	46.103

76	34.3774	31.3194	37.6846	37.7786	35.4798	40.992		53.0322	46.6542
77	34.9468	31.72	38.0208	38.1886	35.9168	41.4576		53.3562	47.6056
78	35.4136	32.0512	38.6844	38.6714	36.249	42.1146		53.661	48.259
79	35.6006	32.4986	39.3266	39.3836	36.795	42.5676		54.3736	48.703
80	36.0368	32.8438	39.619	40.1232	37.8022	43.1354		55.034	49.0188
81	36.3524	33.1258	39.7864	40.7046	38.5756	43.9036		55.542	49.2634
82	37.118	33.6084	40.0226	41.103	39.2154	44.8276		56.0192	49.5698
83	37.5416	34.029	40.5172	42.105	39.5904	45.631		56.25	49.875
84	37.7098	34.2492	40.876	43.266	40.2604	46.1992		56.8148	50.29
85	38.171	34.441	41.1438	43.6816	40.6102	46.681		57.9658	50.5664
86	38.6238	34.6376	41.9228	44.0086	41.0112	47.3572		58.2954	51.0306
87	39.8054	35.0762	42.0704	44.5256	41.2588	47.7602		58.8504	51.8072
88	40.293	35.3522	42.988	45.0554	41.7334	48.3086		60.2338	52.4652
89	40.6872	35.7084	43.7806	45.426	41.9318	48.9136		61.0046	52.802
90	41.4172	36.1736	44.2444	45.9412	42.1566	49.53		61.3296	53.303
91	41.7828	36.4766	45.003	46.2456	42.5046	49.8566		61.7058	53.6924
92	42.1902	36.6902	45.7836	46.5242	43.0064	50.447		62.0108	54.6654
93	42.8246	36.8528	47.2752	46.9196	43.4472	50.719		62.3956	55.139
94	43.4324	37.2782	47.9284	47.2848	43.865	50.9758		62.615	55.2772
95	43.8994	37.5872	48.2066	48.1222	44.0638	51.4088		62.8192	55.4156
96	44.3888	37.9042	48.3428	49.1212	44.4868	51.9136		63.1168	55.8056
97	44.6998	38.015	48.897	49.3526	44.8996	52.6226		63.4132	56.1232
98	44.959	38.4074	49.5332	49.9	45.289	53.1896		63.9916	56.4336
99	45.211	39.2154	49.995	50.4896	45.5558	53.8678		64.653	56.9542
100	45.6456	39.5492	50.4448	50.8804	46.0006	54.3376		65.6996	57.419
101	46.1006	39.914	51.124	51.13	46.769	55.1506		66.5814	57.8156
102	46.5564	40.4054	51.9904	51.7314	46.9782	55.5082		67.6612	58.0922
103	46.74	40.8174	52.1762	52.0448	47.3256	55.8376			58.3644
104	47.0328	41.003	52.8916	52.377	47.6662	56.2082			58.7532
105	47.3652	41.2404	53.5246	52.742	48.3792	56.9032			59.3554
106	47.6926		53.7742	53.195	48.9996	57.3054			
107	47.9686		54.0934	53.5158	49.4998	58.1218			
108	48.285		54.8242	54.313	49.9738	58.7756			
109	48.7538		55.7862	54.6406	50.2178	59.3276			
110	49.2526		55.9684	54.9066	50.484	59.8222			
111	49.5264		56.1894	55.3194	50.7414	60.4012			
112	50.0046		56.7116	55.9502	51.1036				
113	50.3832		57.2476	56.4358					
114	50.7162		57.6378	56.7138					
115	50.9234		57.9766	57.1176					

116	51.1038	58.4458	57.6616
117	51.4852	59	58.3548
118	51.7714	59.9316	58.6228
119		60.5744	58.8252
120		61.2662	
121		61.5232	
122		61.7282	
123		62.132	
124		62.6954	
125		63.3086	
126		63.7568	
127		63.9668	
128		64.401	
129		64.7028	
130		65.2198	
131		65.7908	

Age	**CAT10**	**CAT11**	**CAT13**	**CAT14A**	**CAT14B**	**CAT15A**	**CAT15B**	**CAT16**	**CAT117**
1	0.6212	0.5272	0.8634	0.9232	1.1858	1.1604	0.7586	1.6396	0.937
2	1.0428	0.927	2.3184	1.708	1.7356	1.546	1.3018	2.377	1.5126
3	1.439	1.299	2.8208	2.0928	2.012	1.7992	1.8254	3.0094	1.7566
4	1.9078	1.6246	3.4232	2.7106	2.4836	2.0022	2.2334	3.3384	2.188
5	2.2842	2.0698	4.216	2.9666	3.19	2.4272	2.6142	4.7084	2.5804
6	2.6676	2.6042	4.4022	3.4406	3.5538	3.239	3.0772	5.8994	3.194
7	3.2394	3.1162	5.0398	4.0546	4.4694	3.4916	3.386	6.7634	3.6204
8	3.675	3.4598	5.5982	4.7452	5.147	3.8848	3.7828	7.4204	4.4348
9	3.9708	4.7292	5.7922	5.4532	5.417	4.3234	4.1756	8.293	4.5928
10	4.384	5.5362	6.4254	6.1708	6.1464	4.9182	4.7238	8.9816	5.2264
11	4.5748	6.037	6.9212	6.8622	6.7528	5.553	5.315	9.7228	5.7602
12	4.748	6.4142	7.7128	7.1624	7.5754	6.4586	5.9744	11.3254	6.001
13	5.1904	6.7364	8.3492	7.8732	8.1854	7.1278	6.8806	12.2312	6.3184
14	5.6022	7.2584	8.8112	8.1992	8.5288	7.5668	7.4772	12.8868	6.7838
15	5.8442	8.194	9.629	8.5194	9.3	7.9452	7.8992	14.6628	7.4596
16	6.031	8.9344	9.9488	8.7988	9.497	8.4354	8.2142	14.9768	8.0002
17	6.2244	9.444	10.1588	9.3892	9.7284	8.9568	8.5744	15.4218	8.8498
18	6.602	9.892	10.6564	10.0488	9.9902	9.5834	9.1086	16.1782	9.4858
19	6.8372	10.074	11.1386	10.7482	10.308	10.6604	9.795	16.5978	10.4088
20	7.2006	10.721	11.291	11.0834	10.754	11.5056	10.3684	17.1202	11.522
21	7.526	10.9464	11.4338	11.388	11.1422	12.7426	11.4222	17.3458	12.1632

22	7.9296	11.253	11.5432	11.5958	11.745	13.24	12.347	17.8034	12.8088
23	8.255	11.5248	11.6396	11.748	12.511	14.2884	13.411	18.9532	14.035
24	8.8102	11.9688	11.852	12.296	12.9634	14.6852	14.0648	19.7666	14.7594
25	9.441	12.3924	12.144	13.0792	13.3644	15.0102	14.3188	21.2806	15.7956
26	10.0996	12.8004	12.5004	13.3164	13.6662	15.3718	14.7192	22.508	16.1204
27	10.5866	13.281	12.7324	13.717	13.95	15.6378	15.1406	23.7738	16.5642
28	11.4814	13.7004	13.0678	13.9862	14.6144	16.5018	15.7534	24.4624	17.1736
29	12.119	13.9804	13.3722	14.7194	14.758	17.0108	16.7686	25.1216	18.446
30	12.5656	14.3592	14.0282	15.497	15.2218	17.7072	17.4088	25.4356	18.863
31	12.93	14.6398	14.2658	16.0176	15.79	18.111	18.517	25.8108	20.2046
32	13.135	15.3178	14.8674	16.3902	16.5906	19.1222	19.1704	26.4264	21.5032
33	13.5156	15.7546	15.1972	17.0282	16.962	20.1774	20.0802	27.1746	22.765
34	13.894	16.4532	15.9204	17.7368	17.8518	20.874	21.4632	27.8818	23.5028
35	14.2992	16.8374	16.3926	18.534	18.6508	21.1212	22.6158	28.4872	23.7202
36	14.6608	17.4496	16.5164	18.9822	18.9758	21.737	22.9012	29.0356	23.8394
37	15.1468	17.7092	16.865	19.3218	19.8702	22.7364	23.3436	29.5792	24.0806
38	15.552	18.3862	17.2642	19.5098	21.0178	23.5564	24.919	30.0448	24.3462
39	16.3604	18.8362	17.6618	19.7186	21.811	24.3152	26.4398	30.7414	25.2614
40	17.301	19.012	18.3496	19.8778	22.411	24.6808	27.731	31.5178	26.4648
41	17.9178	19.408	18.7274	20.3808	23.033	25.1254	28.1626	31.9524	27.4264
42	18.5554	19.8482	19.1274	20.7324	23.5606	25.4832	28.654	32.6636	27.6978
43	19.0468	20.3972	19.8594	21.4846	23.9402	26.1942	28.981	33.3932	28.6232
44	19.413	20.7092	20.6086	21.7838	24.2148	26.7642	29.3222	33.9724	29.159
45	20.3228	20.9884	21.2256	22.0378	24.9274	27.3658	29.7362	34.537	29.606
46	20.9212	21.1868	21.5242	22.4694	25.372	27.9006	30.4942	34.856	30.2954
47	21.3564	21.3704	21.72	23.2358	26.0478	28.4694	31.6668	35.223	31.1676
48	22.0242	21.72	22.1728	24.043	26.3972	28.719	32.3442	35.5574	31.7272
49	22.6838	22.6954	22.3374	24.5288	26.6504	28.974	33.324	36.22	32.2926
50	22.9788	23.2928	23.3788	24.9124	27.254	29.7114	33.7624	37.083	33.151
51	23.1054	23.6422	24.3554	25.3102	28.3998	30.0658	34.438	37.807	33.6234
52	23.8548	24.5702	25.0942	25.6998	29.2256	30.1954	34.8428	38.272	33.9562
53	24.2754	24.9288	25.6114	25.9556	29.6238	30.4214	36.0164	38.5612	34.3062
54	25.1472	25.5728	25.921	26.2712	29.9954	31.2452	37.1438	39.2112	34.6838
55	25.462	26.2384	26.1696	26.6008	30.4702	31.8806	38.01	39.697	35.7296
56	26.0778	26.5182	26.5758	26.7648	31.067	32.7094	38.5212	40.0766	36.1812
57	26.568	26.7134	27.4084	26.9556	31.4518	33.0892	39.1544	40.4576	37.122
58	27.295	27.5642	27.9482	27.0948	31.702	33.5398	39.339	40.9464	37.8446
59	27.516	27.7536	28.5556	27.6344	32.019	34.4398	40.004	41.6272	38.445
60	28.0632	28.4006	28.9738	28.0886	32.6284	35.2336	40.412	41.852	38.8926
61	28.4388	28.5874	29.5232	28.4856	32.9854	35.4772	41.364	42.2834	39.6438

62	29.1358	28.8188	29.7854	28.7612	33.4016	36.1876	42.0562	42.7652	40.2468
63	29.428	29.0344	30.636	29.1342	33.6588	36.761	42.5682	43.0608	40.969
64	30.08	29.3632	31.404	29.4738	34.2256	37.3666	43.0414	43.4428	41.1946
65	30.4156	29.8054	31.5914	29.7012	34.6586	37.7158	43.5484	43.8224	41.4852
66	31.1988	30.247	32.1716	29.9272	35.0174	38.7044	43.726	44.0566	42.6848
67	31.8858	30.6842	32.6844	30.2564	35.8288	39.437	44.2598	44.5478	43.6582
68	32.3936	31.0396	32.8046	30.794	35.9892	39.7276	44.9088	44.9266	43.903
69	32.665	31.2038	33.0056	30.9936	36.1628	40.3226	45.3886	45.4624	44.7016
70	33.0926	31.5966	33.357	31.1484	36.4118	40.7582	45.9002	45.9256	45.6392
71	33.3566	31.9756	33.6572	31.2624	36.8948	41.3748	46.5612	46.2414	46.1252
72	33.9784	32.2216	34.039	31.8506	37.121	41.842	46.9938	46.5312	46.5924
73	34.531	32.4122	34.3924	32.5452	37.426	42.3528	47.2956	46.9362	47.2578
74	35.0114	33.0054	34.628	32.8994	38.0044	42.6804	47.7068	47.1786	47.8378
75	35.4986	33.4088	34.9062	33.0718	38.8394	43.0088	48.037	47.371	48.3622
76	35.9322	33.703	35.477	33.6944	39.1804	43.942	48.3584	47.9392	49.0152
77	36.55	33.942	35.7706	34.1196	39.3828	44.843	48.6158	48.2508	50.0358
78	36.8052	34.1176	36.0122	34.459	39.5876	46.0064	49.0688	48.7648	51.0776
79	37.0632	34.513	36.1516	34.8068	40.1178	46.3358	49.5106	49.7108	51.411
80	37.4052	34.792	37.1544	35.1644	40.881	47.1426	49.7896	50.1432	52.082
81	37.8682	35.2394	37.619	35.5142	41.5746	47.6726	50.287	50.6162	52.4082
82	38.2296	35.5254	37.7878	35.951	41.7798	48.1148	50.9988	51.5492	52.9914
83	38.9328	35.7314	38.5686	36.4026	42.764	48.36	51.7126	52.1086	53.3888
84	39.1534	35.938	39.253	36.7188	43.6258	49.1852	52.1678	52.7952	53.7116
85	39.4158	36.1288	39.9486	37.0524	44.137	49.6906	52.5876	53.1048	54.9612
86	39.8848	36.4054	40.191	37.3118	44.9716	50.4874	53.264	53.3686	55.7662
87	40.153	36.686	40.5018	37.5866	45.3978	51.4006	53.5078	53.8598	56.8126
88	40.3286	36.913	40.795	37.9068	45.8668	51.9248	54.5424	54.2766	57.8394
89	40.7848	37.15	41.2102	38.2864	47.6178	52.4058	54.9416	54.7464	58.2284
90	41.0652	37.5338	41.6992	38.5892	48.3222	53.1028	55.1294	55.1684	58.657
91	41.4652	38.4136	42.204	39.0076	48.5212	53.6104	55.5652	55.7822	60.0138
92	41.6984	38.7014	42.7864	39.2536	48.8236	54.3788	55.8912	56.3152	60.5748
93	41.9366	39.067	43.2546	39.7632	49.3462	55.2432	56.4704	56.8028	60.8762
94	42.1536	39.2602	43.849	40.1008	49.9934	55.8612	57.0322	57.0674	61.252
95		39.464	44.1294	40.4644	50.568	56.4338	57.4376	57.3832	61.6244
96		39.8404	44.3368	40.629	51.1404	57.0538	58.1478	58.5662	62.2434
97		40.0562	44.655	40.9428	51.8232	57.7136	58.6818	59.1242	63.1598
98		40.257	45.0342	41.6448	52.7922	58.9846	59.0788	59.6484	63.882
99		40.4898	45.321	42.1876	53.0682	59.45	59.4912	60.3174	64.4666
100			45.524	42.6192	53.8328	60.2078	59.8154	60.6046	65.3686
101			45.9518	43.0278	54.4406	60.633	60.6962	60.8306	66.2034

102			46.319	43.5036	54.746	61.0546	61.2378	62.0574	66.5736
103			46.515	43.7458	55.1546	61.9744	61.5194	62.3878	67.362
104			46.7376	43.9196	55.8038	62.699	61.707	63.3786	67.7222
105			47.1234	44.0476	57.0146	63.5388	62.2562	64.175	67.9106
106			47.4004		57.2258	63.7542	62.9278	64.61	68.5116
107			47.5558		57.4632	63.983	63.1438	64.909	69.1108
108			48.0468		57.9968	64.224	63.3846	65.5742	69.684
109			48.8674		58.7146	64.7382	63.8684	66.2446	70.0686
110			49.1058		59.0428	65.0028	64.4258	66.7184	70.3998
111			49.2552		59.3918	65.5752	64.9384	67.3622	70.8544
112			49.7502		59.8654	66.2522	65.1558	67.704	71.1306
113			50.1964		60.6402	66.8504	65.3872	67.9278	71.3976
114			50.4518		61.4438	67.3052	65.6912	68.5228	71.9476
115			50.6258		62.0692	67.6494	66.464	69.0062	72.4346
116			50.838		63.1188	68.0078	67.3882	69.3484	72.8826
117			51.0596		63.4366	68.8932		69.931	73.4844
118			51.1606		63.7386			70.561	73.9384
119			51.3894		64.0866			71.1428	74.2746
120			51.6328		64.6568			71.5436	74.5018
121			51.9136		65.2198			72.128	75.0832
122			52.2684		65.7238			72.612	75.3628
123			52.2684		66.0494			73.1514	75.625
124					66.4708			73.5044	75.861
125					66.7262				76.1318
126					67.2632				76.7344
127					67.8588				77.3542
128									77.9202
129									78.2846
130									78.4326
131									78.8418
132									79.2412
133									79.531
134									79.8832

Age	CAT18	CAT020	CAT21	1631TSD	1850TSD	120B	Cat04A	2137	Cat12
1	0.6514	0.6984	0.7064	0.3294	0.475	0.3478	1.0198	0.4718	0.7526
2	1.0394	1.3526	1.186	0.6664	0.8006	0.5432	1.5082	0.8234	1.1102
3	1.7926	2.0892	1.461	1.4948	1.118	0.7264	1.8554	1.3012	1.7784
4	2.6866	3.101	1.867	2.1046	1.438	0.9814	2.2824	1.7472	2.316

5	2.9196	3.614	2.4324	2.431	1.6692	1.1658	2.6242	2.0172	2.8694
6	3.4174	4.0236	2.8202	3.1786	1.9936	1.3834	3.0062	2.5222	3.098
7	4.3824	4.2888	3.0792	3.708	2.5558	1.5104	3.3694	2.9046	3.3726
8	5.323	4.5722	3.758	4.0048	2.8668	1.6672	3.7232	3.2214	3.8032
9	5.8752	4.9156	4.2728	4.8938	3.1786	1.9314	3.9924	3.3792	4.4624
10	6.1614	5.1926	4.5362	5.9588	3.6562	2.3812	4.4356	3.6884	4.7206
11	6.8068	5.4294	4.7226	6.6342	3.8792	2.656	4.8134	4.126	5.1972
12	8.142	5.72	5.4612	7.492	4.1468	2.8334	5.2468	4.4918	5.7356
13	8.5284	6.1366	5.936	8.2334	4.4088	3.11	5.7662	4.6786	6.7738
14	8.9284	6.5626	6.417	9.2226	4.7306	3.3526	5.9898	4.8718	7.7044
15	9.1578	6.909	6.6912	10.7184	5.3516	3.5068	6.4084	5.0414	8.6044
16	9.8632	7.246	7.48	11.5286	5.564	4.0348	6.9566	5.3192	9.6772
17	10.1528	7.61	8.2874	11.9948	5.6916	4.4246	7.3526	5.4962	10.7462
18	10.436	7.772	8.7056	12.7964	5.9244	4.6538	7.696	5.6288	11.1312
19	10.7134	8.231	9.2774	14.0948	6.1446	4.877	8.1036	5.778	13.0488
20	10.95	8.6364	9.8076	15.1058	6.341	5.073	8.4682	5.925	14.425
21	11.256	9.3312	10.1662	16.0922	6.6204	5.4162	9.2296	6.1254	14.9288
22	11.4934	10.0734	10.5374	16.6682	6.8174	5.7726	9.8248	6.5234	15.2658
23	12.367	10.358	10.992	17.0218	6.9358	6.4476	10.9976	6.8386	16.554
24	12.8934	10.769	11.356	17.4482	7.0348	6.7244	11.3538	7.5092	17.186
25	13.609	11.1944	11.679	18.1152	7.7142	7.3126	11.8848	8.2884	18.2698
26	14.1648	11.637	12.1614	19.4764	7.912	8.1916	13.0638	8.6014	18.4654
27	14.5166	12.3704	12.65	20.465	8.2724	8.388	14.3998	9.2552	18.7064
28	14.7576	12.5926	13.1106	20.85	8.9942	8.741	15.0102	9.3442	19.0678
29	15.094	12.888	14.0148	21.1538	9.1404	9.298	16.406	9.6284	19.4158
30	15.5398	13.2104	14.7824	22.0214	9.4238	9.7254	17.6798	11.1532	19.8184
31	16.5406	13.6172	15.8604	22.8444	9.7244	10.3582	19.1512	11.5662	20.3532
32	17.0398	14.1136	16.3788	23.5956	10.1414	10.903	20.1336	12.1482	21.1044
33	17.7194	14.7356	17.6054	23.9744	10.4606	11.5926	20.663	13.1548	21.3362
34	18.3264	14.9528	18.865	24.489	11.0278	12.908	20.9098	13.6622	21.954
35	19.0408	15.3752	20.1128	24.7658	11.1888	13.9138	21.1538	14.0132	22.6136
36	19.8158	15.877	20.5362	25.4388	12.1688	14.3304	22.0252	14.4316	22.7752
37	20.0046	16.4782	21.1582	25.818	12.2978	14.6956	23.0254	14.609	23.0216
38	20.5472	17.0092	21.9982	26.4686	13.0622	14.8212	24.0196	14.8444	23.3818
39	22.0026	17.2238	22.3208	27.6128	13.9252	14.9886	24.2998	15.0426	23.626
40	22.704	17.37	23.0518	28.0858	14.0812	15.2936	24.7438	15.4982	23.8884
41	23.564	17.6596	23.5366	28.579	14.622	15.5248	25.4842	15.9898	23.9858
42	24.1204	18.0764	24.2884	29.125	15.2186	15.7324	26.222	16.345	24.1728
43	24.5058	18.5442	24.5946	29.5128	15.585	16.3722	27.2658	16.516	24.5254
44	24.6926	18.8644	25.4602	29.7678	15.8092	17.2142	28.3322	17.0742	24.8644
45	25.3446	19.0944	26.8014	30.277	16.0238	18.627	28.9458	17.3104	25.1918
46	25.9776	19.3518	28.0964	30.5292	16.2932	19.9378	29.5258	17.8342	25.64

47	26.3724	19.5538	28.4976	31.0122	16.7258	20.409	30.7876	17.9658	26.1322
48	26.5032	19.706	28.7362	31.3738	17.5116	21.9628	31.733	18.684	26.342
49	26.8068	20.3574	29.137	31.729	18.9686	23.324	32.6754	19.0202	26.5838
50	27.1804	20.8188	29.523	32.2968	19.3096	24.4448	33.556	20.0342	26.8638
51	27.8274	21.1622	30.3716	33.1084	19.3676	25.3922	34.5866	21.0918	27.204
52	28.4918	21.5474	31.125	34.0034	19.409	26.0818	35.1492	21.4648	27.4882
53	28.975	22.1712	31.8688	34.2572	19.4558	26.563	35.796	22.161	27.7314
54	29.5064	22.7618	32.313	34.8336	19.5052	27.894	36.748	22.5356	27.8588
55	30.4188	23.157	33.356	34.8658	19.5254	29.39	36.9772	23.107	28.07
56	30.6068	23.3542	33.7108	35.7424	19.9824	30.3652	37.9904	23.5196	28.3418
57	30.7124	23.632	34.177	36.2914	20.472	31.0274	39.0486	23.9872	28.512
58	31.274	23.8152	34.5532	36.9106	21.1262	31.5864	39.9824	24.4544	28.7204
59	31.6028	24.1672	35.2952	37.707	21.3196	32.5124	40.454	24.893	28.8946
60	32.6334	24.3698	35.9312	37.9648	21.7458	33.3524	40.8592	25.7768	29.1158
61	33.4828	24.9638	37.135	38.4996	23.444	34.1198	41.3416	26.438	29.349
62	34.1132	25.4628	38.048	38.923	24.2132	34.5808	41.6724	27.0068	29.605
63	34.674	26.1192	38.2876	39.1234	24.3656	34.9998	42.6754	27.2854	29.7398
64	35.3266	26.4684	39.0298	39.2328	24.3956	35.3202	43.7304	27.7204	30.0266
65	35.5882	26.702	39.8064	39.4724	24.4334	35.7124	44.5736	28.1904	30.3134
66	35.8874	27.3638	40.6744	39.9372	25.556	36.7654	45.1878	28.6984	30.5294
67	36.147	27.795	41.1246	40.3248	26.794	38.1154	45.6838	29.1784	30.7114
68	36.315	28.0036	41.3908	40.7262	27.788	38.3902	46.548	29.6642	30.9344
69	36.6178	28.435	41.7796	41.1424	28.7468	39.1296	47.2832	30.1528	31.3616
70	36.7772	28.744	42.4112	41.5696	29.15	39.8916	47.4814	31.6118	31.799
71	37.1022	28.9446	42.8638	42.02	29.2066	40.8126	48.2892	32.4542	32.4108
72	37.363	29.286	43.4816	42.4536	29.4112	41.0292	49.4836	33.0996	32.8794
73	37.6314	30.1916	44.0942	42.6918	29.7322	41.3446	50.3634	33.9444	33.3038
74	37.917	30.5894	44.4174	43.1398	29.9908	41.7388	50.7974	34.5746	33.6258
75	38.4784	31.3834	44.7932	43.9008	30.096	42.3466	51.7862	35.2774	33.9958
76	38.882	31.8484	45.4542	44.0956	30.4998	42.6778	51.9912	35.528	34.2216
77	39.3402	32.7386	45.6924	44.3886	30.8854	42.772	52.6108	35.9762	34.3664
78	39.5984	32.9544	46.7282	44.4192	31.4016	43.0546	53.95	36.2042	34.5692
79	39.9038	33.1286	47.5768	44.8112	31.5064	44.076	54.7874	36.5442	34.733
80	40.4094	33.3724	48.3854	45.3624	31.8126	44.9894	55.5974	36.8498	34.9788
81	41.0682	33.801	48.9412	45.9434	32.2744	45.141	56.1162	37.387	35.15
82	41.3926	34.087	49.7942	46.5712	32.3848	45.6604	56.7816	38.0022	35.2998
83	41.7856	34.3272	50.5532	46.8556	32.6572	45.9664	57.5266	38.254	35.473
84	42.2484	34.716	51.0304	47.0636	33.6226	46.6672	57.8564	38.6612	35.7348
85	42.688	35.0806	51.2788	47.5202	34.525	47.7114	58.5188	39.1566	36.2932
86	43.507	35.3622	51.9012	47.8492	35.1016	48.2508	59.2076	39.6258	36.6148
87	43.8646	35.7734	52.4466	48.0918	35.8682	48.6548	59.4826	39.7568	37.153
88	44.3786	36.0698	53.0586	48.479	36.7782	48.9674	60.4078	40.3062	37.4176

89	44.677	36.4918	53.7286	48.935	36.8982	49.9956	60.8226	41.0678	37.7372
90	44.9026	36.6786	54.349	49.1684	37.6044	51.192	60.9952	41.491	38.1742
91	45.3978	36.8624	54.867	49.3126	38.2112	52.2022	61.282	41.6536	38.78
92	45.8434	37.2476	55.1692	49.4918	38.6544	53.0658	61.8336	42.0798	39.3022
93	46.2426	37.4764	55.4592	49.6628	38.752	53.5596	62.6668	42.6058	40.1794
94	46.7774	37.696	56.0648	49.7648	39.492	53.797	63.0394	42.9216	40.4394
95	47.166	37.9926	56.4386	50.3832	39.9332	53.8736	63.3156	43.2148	40.6746
96	47.8186	38.1368	56.8706	50.6612	40.2022	54.0372	63.6034	43.6518	40.8896
97	48.1116	38.549	57.3742	50.9384	40.7084	54.4186	64.4838	43.9606	41.4988
98	48.3232	38.8426	57.6638	51.3406	41.7662	54.8758	64.8662	44.3508	
99	48.4274	39.0014	58.1904	51.5468	42.1454	55.4666	65.7662	45.0584	
100	48.6824	39.231	58.7114	52.118	42.3654	56.322	66.3818	45.2618	
101	48.9498	39.5114	59.0818	52.489	42.418	57.2772	67.0582	45.5256	
102	49.3296		59.4838	52.8212	42.543		67.6974	45.7558	
103	49.5658		59.8728	53.1208	42.631		68.624	45.987	
104	49.7522		60.1666	53.3228	42.7046		69.0074	46.5618	
105	49.873			53.6926	42.9444		70.0342	47.3008	
106				53.9552	43.3662			47.6548	
107				54.261	43.8112			48.0808	
108				54.6658	44.2676			48.3962	
109				54.91	44.355			48.6308	
110				55.0778	45.4902			48.921	
111				55.3288	45.8956			49.2548	
112				55.5176	45.9828			49.5454	
113				55.6826	46.087			49.7884	
114				55.8958	46.5878				
115				56.1468	46.6872				
116				56.431	47.0716				
117				56.7304	47.5654				
118				56.9012	47.6816				
119				57.1316	48.024				
120				57.1954	48.0998				
121				57.4606	48.1566				
122				58.174	48.534				
123				58.429	49.205				
124				58.9134	49.5676				
125				59.37	50.0216				
126				60.0162	50.2444				
127				60.3064	50.2634				
128				60.6188	50.3294				
129				61.0256	50.5732				
130				61.2592	50.6072				

131				61.4946	51.3338				
132				61.6632	51.8032				
133				61.889	51.9658				
134				62.2538	52.397				
135				62.5592	52.7656				
136				62.834	52.933				
137				62.9962	53.7274				
138					53.7528				
139					53.9298				
140					54.5858				
141					54.9508				
142					55.0056				
143					55.538				
144					56.1954				
145					56.566				
146					56.7526				
147					56.9364				
148					57.3728				
149					57.6874				
Age	cat15	cat19	1613	2013	1626	1850	1230	120B	1228
1	0.9244	0.4092	0.1936	0.3204	0.123	0.4438	0.4022	0.3584	0.1236
2	1.295	0.7464	0.3666	0.6964	0.2724	0.792	0.6964	0.552	0.6998
3	1.6664	1.1554	0.7886	1.0186	0.423	1.1228	1.3108	0.7626	0.8464
4	1.9752	1.3884	1.094	1.6014	0.7008	1.4576	1.7658	0.961	1.2474
5	2.1786	1.7672	1.346	2.0722	1.0056	1.682	2.057	1.191	1.5176
6	2.6516	2.0228	1.6826	2.6308	1.3308	2.0152	2.3452	1.445	1.9656
7	2.9566	2.3572	2.0876	3.0516	1.5434	2.5808	2.3698	1.6026	2.5098
8	3.4132	2.813	2.4404	3.3234	1.8446	2.9012	2.538	1.8256	2.9358
9	3.699	3.7782	2.7492	3.6196	2.2596	3.233	2.9096	2.2356	3.2032
10	3.986	4.3664	2.8432	3.8286	2.4684	3.663	3.4118	2.6108	3.4568
11	4.4396	4.9378	3.0198	4.0792	2.76	3.9156	3.7154	2.7568	3.6446
12	5.0858	5.3946	3.7242	4.2688	2.8086	4.17	4.1868	2.8692	3.9692
13	5.6906	6.278	4.3618	4.4222	3.1342	4.4284	4.4572	3.538	5.0622
14	6.5972	6.8468	4.8748	4.5568	3.8604	4.5176	5.0864	3.8266	5.2256
15	7.3236	7.7346	5.7046	5.122	4.0518	4.7658	5.411	4.1424	5.8982
16	7.7264	8.5242	6.2038	5.4316	4.7414	5.3992	5.8658	4.3112	6.1472
17	8.1412	9.147	6.7242	5.801	5.2356	5.6064	6.1748	4.4216	6.6734
18	8.609	9.3308	7.1912	6.1174	5.5982	5.724	6.7502	5.0106	6.893
19	9.1224	9.5352	7.5618	6.3944	5.9736	5.9844	6.8962	5.5444	6.9268
20	9.7652	10.2042	8.0716	6.651	6.6954	6.1672	7.5194	5.7958	8.0294
21	10.8752	10.7322	8.5242	6.993	7.781	6.3714	8.1162	5.8266	8.1866
22	11.6772	11.4584	9.4768	7.2618	9.0746	6.6122	8.505	6.4178	9.0466

23	13.0514	11.58	10.3098	7.7266	10.2782	6.8202	9.0298	7.002	9.9568
24	13.5068	11.7044	10.9872	7.7664	11.091	7.0118	9.4164	7.4452	10.781
25	14.5032	12.1838	11.3566	7.9472	11.3052	7.691	9.7464	7.9002	11.0744
26	14.9024	12.612	12.4436	8.4434	11.8412	7.914	10.252	8.255	11.724
27	15.2326	12.8696	13.2556	9.196	12.3282	8.2648	10.3452	8.2902	12.9188
28	15.5684	13.1022	13.7274	10.1116	12.9328	8.9776	10.9378	8.975	13.1454
29	15.8434	13.1748	14.0552	10.3832	13.715	9.1228	11.1024	9.3916	13.5112
30	16.7384	13.303	14.7854	10.5922	14.6544	9.4458	11.62	9.705	14.8316
31	17.2624	13.3884	15.3408	11.2908	14.8066	9.7326	11.9112	10.5764	15.7458
32	17.9008	13.8526	16.219	11.8438	16.1144	10.1644	12.1244	11.7484	16.3946
33	18.3122	14.0672	16.3376	11.9928	17.3242	10.433	12.3282	12.4792	16.8562
34	19.3356	14.5974	16.461	12.2834	18.0292	11.0008	12.8554	12.74	17.5268
35	20.363	15.393	16.7644	13.1996	19.158	11.1822	13.5452	12.7546	18.0714
36	21.083	15.9836	16.9936	13.5588	19.3912	12.1562	14.1996	13.0014	18.895
37	21.3496	16.7964	17.4866	14.1358	19.4158	12.3042	15.125	13.2916	19.7798
38	21.966	18.244	17.8292	14.6284	20.1454	13.06	15.4172	13.5332	19.9176
39	23.1408	19.0776	18.0422	15.0362	21.166	13.9166	16.2652	14.0478	21.6784
40	23.8468	19.562	18.4566	15.382	22.1986	14.0364	16.399	14.6756	22.7904
41	24.571	20.2234	18.9372	15.7114	22.7848	14.5934	16.5532	15.8402	23.7586
42	25.043	20.5732	19.6562	16.186	23.3128	15.1906	17.0842	17.072	25.3416
43	25.2658	21.1438	19.9336	16.3598	23.5844	15.5694	17.4434	17.4952	25.5564
44	25.595	21.6008	20.5846	16.6042	24.2176	15.7918	17.7318	18.6208	26.3812
45	26.2642	21.8974	21.2506	16.8098	24.7864	16.0238	18.4142	19.5256	27.5694
46	26.9038	22.1642	21.723	17.0118	25.4896	16.2294	18.7422	20.9192	28.9152
47	27.482	22.4624	22.1098	17.2024	25.9756	16.6906	18.8342	22.124	29.3606
48	27.9694	22.7016	22.2888	17.6492	26.5058	17.4974	19.1236	22.641	30.3162
49	28.5596	23.0094	22.6374	17.9232	26.8664	18.9634	19.613	23.5138	30.8046
50	28.8852	23.623	22.8872	18.1066	27.3024	19.3588	20.19	24.6424	31.7818
51	29.227	24.1734	23.349	18.4026	28.1756	19.3928	20.8218	26.1554	32.714
52	29.8802	24.7144	23.7274	19.0132	29.0192	19.4336	21.1466	26.7648	33.3624
53	30.267	25.604	24.118	19.2896	29.2464	19.4866	21.7254	27.7812	34.0354
54	30.597	26.4874	24.174	19.5954	29.5998	19.5342	21.9588	28.4786	34.5492
55	31.3724	27.0156	24.7916	19.9714	30.3242	19.5874	22.2192	29.2558	35.0346
56	32.1052	27.898	25.0026	20.009	30.8176	20.0192	22.6432	30.2046	35.2634
57	32.9882	28.4594	25.2756	20.257	30.9802	20.4708	23.0176	30.9926	36.2698
58	33.3734	28.8438	25.742	20.652	31.183	20.5034	23.2914	31.4362	37.5494
59	33.8866	29.3614	25.9402	21.125	31.4564	21.121	23.88	31.8472	38.0828
60	34.691	30.1672	26.397	21.3106	31.7844	21.7394	24.1752	32.156	38.663
61	35.517	30.486	26.9972	21.4674	32.0246	23.3788	24.9132	32.2162	39.5504
62	35.7464	30.638	27.1628	21.985	32.0476	24.1446	25.07	32.478	40.7986
63	36.5002	31.0664	27.5504	22.2884	32.1084	24.2936	25.3342	33.4286	41.2232
64	37.0332	31.5998	27.881	22.5144	32.819	24.3152	25.5906	34.2288	41.8054

65	37.672	31.7138	28.0968	22.6978	32.8492	24.3408	26.1074	34.5376	43.1064
66	38.1486	31.798	28.2434	23.4946	33.0222	25.5036	26.5612	34.99	43.6854
67	39.1678	31.9018	28.274	24.7234	33.2158	26.741	26.6192	35.4524	44.3234
68	39.8754	32.216	28.6102	24.9846	33.3724	27.7302	26.8002	36.0838	45.41
69	40.1638	32.6062	28.9778	25.0844	33.5712	28.6796	27.0984	36.38	46.4796
70	40.6874	32.759	29.0798	25.2142	34.1428	29.102	27.6616	36.646	46.9556
71	41.1326	33.3032	29.5202	25.2462	34.2288	29.172	28.098	37.0162	48.1446
72	41.8542	33.5964	29.9786	25.3746	34.2564	29.3904	28.2608	37.364	48.9118
73	42.4136	34.181	30.696	25.5014	34.5344	29.7016	28.9034	37.7362	49.0664
74	42.9652	34.9262	30.74	25.826	35.4024	29.9604	29.3998	38.2934	50.0214
75	43.2636	35.5818	31.3768	26.0446	35.889	30.0778	30.1998	38.5256	50.456
76	43.5536	36.124	31.8642	26.0698	36.7888	30.1102	30.3214	38.9658	51.0254
77	44.6142	36.4866	32.2716	26.2618	38.0712	30.5092	30.438	39.4558	51.5334
78	45.5648	37.142	32.5462	26.4	38.7422	30.9188	30.7378	40.3492	52.6168
79	46.433	37.5154	32.6032	27.0838	39.1488	31.4546	31.3218	40.5726	53.8006
80	46.634	37.5646	32.8774	27.3472	39.5514	31.5516	31.534	40.7494	54.87
81	46.9684	37.8912	33.3138	27.368	39.7846	31.8514	31.844	40.969	55.3898
82	47.6956	38.4548	33.3478	27.5708	40.1126	31.8934	32.0838	41.4068	56.5836
83	48.2616	39.2334	33.718	28.4908	40.5818	32.3736	32.6676	41.7732	56.841
84	48.7218	39.4998	34.4402	29.278	41.041	32.715	33.2126	42.559	57.7822
85	49.726	39.7452	34.8366	29.3848	41.2006	33.5592	33.4538	43.33	58.5964
86	50.3678	40.0816	35.2378	29.4884	42.2558	34.5422	33.6204	43.727	59.4706
87	51.2768	40.6026	35.4556	29.7292		35.1008	33.8558	43.9874	59.9928
88	52.2254	40.8518	35.7624	29.8934		35.8374	33.9118	44.234	60.7198
89	52.4356	41.171	36.3832	30.115		36.7596	33.9446	44.4644	61.4278
90	52.8006	41.4216	36.7306	30.3888		36.8816	34.3084	44.6544	62.5302
91	53.245	41.8148	37.1102	30.6914		37.6064	34.6826	44.8784	63.7742
92	53.8682	42.3902	37.3296	30.87		38.2174	34.9422	45.292	
93	54.4426	42.8696	37.7664	31.3442		38.6718	35.3904	45.9028	
94	54.913	43.4446	37.803	32.0638		39.5064	35.4792		
95	55.263	43.9368	38.2298	32.2596		39.9142	36.1324		
96	56.0598	44.0358	38.9766	32.9786		40.1982	36.3636		
97	56.6744	44.1766	39.008	33.129		40.674	36.6116		
98	57.229	45.0996	39.858	33.3798		41.7256	37.03		
99	57.8528	45.7602	40.3044	33.5294		42.0254	37.7358		
100	58.5616	46.7156	40.5018	34.0488		42.3106	38.5658		
101	59.8628	46.9576	40.6024	34.8136		42.3394	39.1292		
102	60.3742	47.3686	41.3558	34.9088		42.5488	39.792		
103	61.0682	47.9114	41.5994	35.2186		42.6386	39.9396		
104	61.5754	48.3302	41.629	35.553		42.8974	40.2272		
105	61.9202	48.8016	41.6938	35.6856		43.2864	40.5528		
106	62.8828	49.3156	42.4774	35.8278		43.7764	40.8382		

107	63.6976	49.7232	43.1242	36.383		44.2006	41.2236		
108	64.6094	50.3662	43.7608	36.5592		44.307	41.6296		
109	64.8686	50.6854	44.3482	36.9586		45.4406	41.8644		
110	65.1006	51.142	45.3	37.4848		45.8876	42.4064		
111	65.3748	51.4088	45.5932	37.9924		46.1028	42.7656		
112	65.8606	51.8856	45.8748	38.1372		46.4454	43.2612		
113	66.2736	52.4868	46.0736	38.2534		46.6258	43.4408		
114	66.8768	52.8704	47.006	38.3524		47.1004	43.5238		
115	67.497	53.166	47.638	38.6072		47.5914	43.806		
116	68.286	53.5128	48.5276	38.8736		47.7016	44.0256		
117	68.681	53.9002	49.6438	39.1834		48.0286	44.39		
118	68.9892	54.2788	50.348	39.3078		48.0986	45.035		
119	69.4444	54.6094	51.3836	39.3292		48.5006	45.5736		
120	70.307	55.1156	51.71	40.0374		49.191	45.8148		
121		55.5426	51.7642	40.5082		49.5604	46.206		
122		56.1726	51.833	40.9288		49.983	46.5368		
123		56.7062	52.2802	41.3882		50.1504	46.6132		
124		57.1492	52.874	41.506		50.205	46.8796		
125		57.45	53.2194	42.0352		50.292	47.2064		
126		57.5758	53.7756	43.302		50.437	47.4198		
127		57.8592	54.088	43.6678		50.4924	47.6672		
128		58.0832		43.806		51.2508	48.1692		
129		58.228		44.2862		51.6836	48.52		
130		58.823		44.804		51.7996	49.1224		
131		59.2974		45.4072		52.2314	49.4452		
132		59.645		45.8428		52.5706	49.908		
133		59.9366		46.031		52.764	50.033		
134		60.319		46.4986		53.4506	50.4404		
135		60.734		46.9692		53.5058	51.1192		
136		61.1768		47.9078		53.7656	51.2906		
137		61.6018		48.4084		54.444	51.4546		
138		61.7572		49.4138		54.8084	51.6542		
139		61.9234		50.1096		54.8346	51.6884		
140		62.1306		50.4		55.3478	51.838		
141		62.5608		51.0778		55.9896	52.0492		
142		62.9898		52.0436		56.4746	52.166		
143		63.2874		52.6582		56.611			
144		63.9706		53.0022		56.7694			
145		64.181		53.3218		57.2068			
146		64.3742		53.7862		57.5128			
147		64.5226		53.989					
148		64.6714		54.233					

149	65.2428	54.946
150	65.5412	55.467
151	65.8574	55.5624
152	66.3316	56.2868
153	66.6288	56.5918
154	66.8762	57.3304
155	67.1092	57.5444

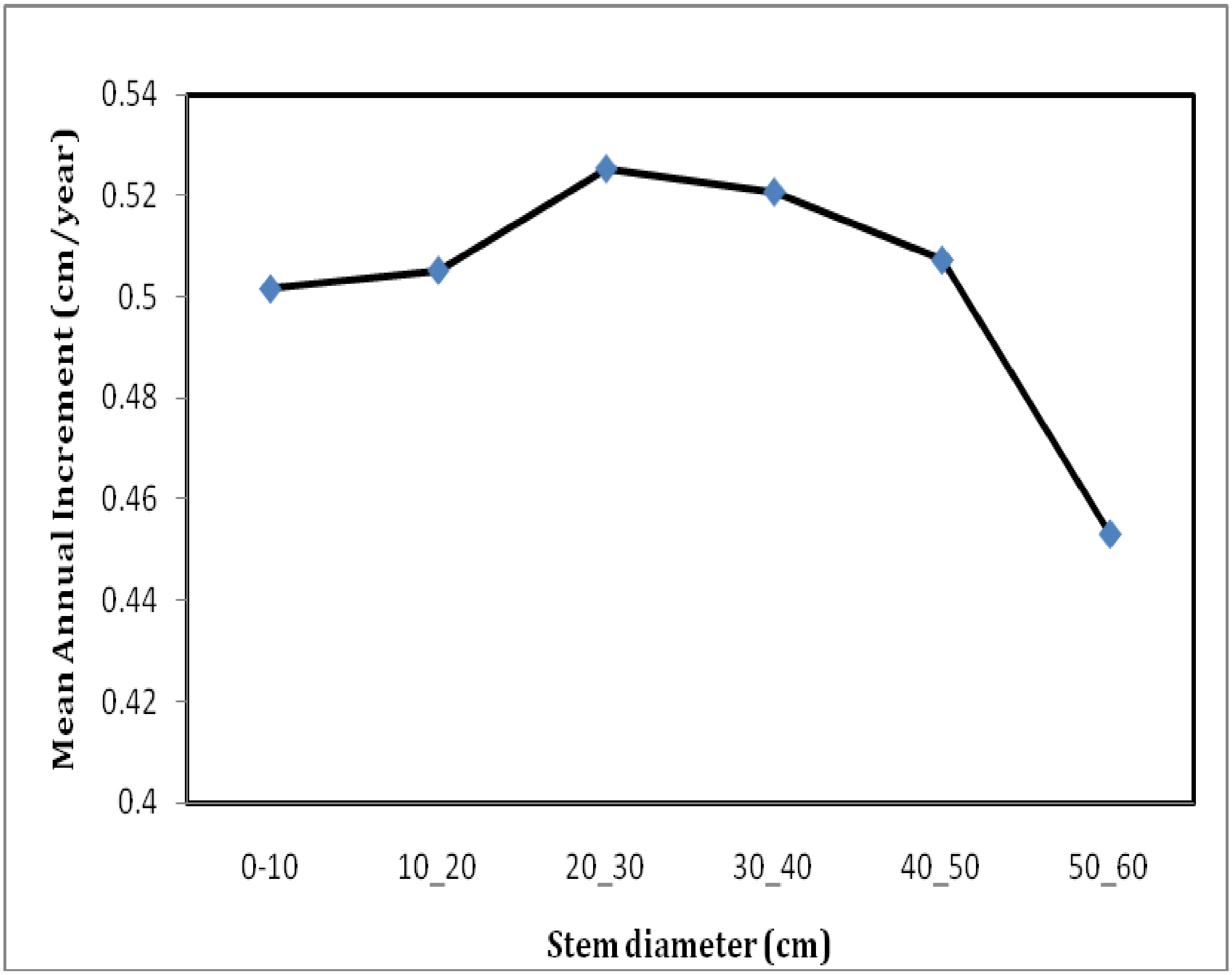
Age	1226	2145
1	0.3318	0.6978
2	0.8424	1.19
3	1.0458	1.5688
4	1.3424	2.2168
5	1.6856	2.4112
6	1.8902	3.0566
7	2.2622	4.0024
8	2.5744	4.3982
9	3.136	4.6076
10	3.3028	5.5044
11	3.9188	6.3962
12	4.4164	7.273
13	4.5608	7.9226
14	4.8546	8.7696
15	5.0804	9.129
16	5.8436	9.3142
17	6.9026	10.012
18	8.224	10.4966
19	9.1872	11.529
20	10.097	12.4564
21	10.2646	13.1356
22	10.6488	13.6896
23	11.1238	14.583
24	11.6314	15.2116
25	12.379	15.8978
26	13.1624	16.4538
27	13.3262	17.2042
28	14.6058	17.9834
29	15.9544	18.9238
30	16.726	19.9932
31	17.8636	20.366
32	18.41	20.4094
33	18.447	21.1912
34	19.2724	22.0332

35	20.5526	22.6402
36	21.5732	23.1602
37	22.1458	23.702
38	22.6108	24.3376
39	22.983	25.219
40	23.5696	26.015
41	24.0688	26.8378
42	24.8406	28.0938
43	25.336	28.4738
44	26.0106	28.836
45	26.4102	29.4794
46	26.702	29.9838
47	27.8864	30.5182
48	28.9286	31.157
49	29.1758	31.3976
50	29.3434	32.2608
51	29.7578	33.282
52	30.5508	34.4586
53	30.8374	35.5328
54	31.1142	36.0632
55	31.3926	36.3886
56	31.551	37.2756
57	31.775	38.2196
58	32.6742	38.6142
59	32.6884	38.864
60	32.9884	39.0486
61	33.5624	39.6766
62	34.3504	40.3658
63	35.3208	40.8922
64	35.5444	41.3782
65	35.7718	42.0834
66	35.8318	43.0218
67	36.1548	43.5224
68	37.2878	44.5276
69	38.103	45.5114
70	39.2602	46.0574
71	40.6884	46.6586
72	41.292	47.5078
73	41.97	48.4522
74	42.353	49.2194
75	42.5176	49.9952
76	42.5384	50.7806

77	42.8852	51.259
78	43.4394	51.7156
79	43.8744	52.574
80	44.7118	53.3168
81	45.544	53.912
82	45.544	54.7354
83		56.0186
84		57.0764
85		57.6386
86		57.772
87		57.956
88		58.2206
89		58.604
90		59.5268
91		60.3148
92		61.6054
93		62.481
94		63.2166
95		64.094
96		64.3594
97		64.5398
98		64.839
99		65.488
100		66.1356
101		67.0448
102		67.7124
103		67.7124

APPENDIX B

Diameter mean annual increment (MAI) dynamics over different diametric classes. Maximum MAI is reached at class size (30-40cm) and starts to decrease with the size increasing.



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Bachelor of Science-Honors in Forest Engineering, April 2010

Thesis Title:

Analysis of Annual Growth Patterns of *Millettia stuhlmannii*, in Mozambique

Major Professor: Dr. Matthew D. Therrell