Sokoine University of Agriculture

MSc Dissertation

Effect of Thinning on Selected Stand Parameters and Revenue Generation of *Tectona grandis* at Longuza Plantation, Muheza, Tanzania

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Effect of Thinning on Selected Stand Parameters and Revenue Generation of *Tectona grandis* at Longuza Plantation, Muheza, Tanzania

A Dissertation Submitted to Sokoine University of Agriculture in Fulfilment of the Requirements for the Degree of Master of Science in Ecosystems Science and Management

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EXTENDED ABSTRACT

Various researches have reported the effect of thinning on stand parameters of *Tectona grandis* in Tanzania. However, there is limited information on the effect of thinning on growth and yield, and revenue generation of *Tectona grandis* in Tanzania. This study assessed the effect of thinning on growth and yield and revenue generation of *Tectona grandis* at Longuza Forest Plantation. Data were purposely collected from 168 circular plots of 9.78 m radius (0.03 ha) distributed systematically in 9 thinned compartments. In each plot, all trees were measured for diameter at breast height (Dbh) and total height of three trees with largest, medium and smallest heights were measured. Compartment register provided information on planting and thinning year. Prices of wood volume at clear-felling, poles and expenses on establishment and management costs of the surveyed stands were collected. Growth and yield parameters described were Dbh, dominant height, volume per ha, and stand density. Adequacy of thinning was determined by calculating the remaining number of stems per hectare (ha) and the deviation from scheduled values expressed in percentages. Thinning timing was obtained by deducting the age the compartment was supposed to be thinned as indicated in the thinning schedule. An economic benefit was calculated by using discounting method whereas net present value (NPV) was used to determine the economic point of view. Thinning effect was assessed by comparing measured values with mean values of Teak yield table. One sampled t-test was used to compare if there were a significant difference between measured and Teak yield table values. The results have clearly showed that 88.9% of thinned compartments were understocked and 11.1% were well stocked. Furthermore, 100% and 75% of the first and second thinning were well-timed, whereas 25% of the second thinning was delayed by one year. Site classes I and II comprised 66.7% and 33.3% of the surveyed compartments. The effects of adequate and timely thinning on Dbh and volume were 2-42% and 9-53%, respectively. Heavy thinning in the first and second thinning schedule maximized economic benefit of climatic and ecosystem services provisioning goal by 181.5%. However, early heavy first and second-intensity thinning was found to be one of the essential treatments in producing higher financial returns but delayed thinning reduced the volume of logs produced with low quality and thus graded lowly. Heavy, timely and adequately thinnings are recommended. The results determines that *Tectona grandis* plantations play a crucial role in providing quality timber and storing carbon dioxide (carbon sink) from the atmosphere.

Keywords: Thinning; Climatic and Ecosystem provision; Revenue generation; *Tectona grandis*; Longuza

IKISIRI KUU

Tafiti mbalimbali zimeripoti matokeo ya uchenguaji (thinnings) kuhusu parameta za spishi ya msaji (*Tectona grandis*). Hata hivyo, kuna kiasi kidogo cha taarifa juu ya matokeo ya uchenguaji katika ukuaji na mavuno na uzalishaji wa mapato yatokanayo na spishi ya msaji katika nchi ya Tanzania. Utafiti huu unaangazia juu ya matokeo ya uchenguaji katika kuongeza mavuno na mapato ya spishi ya msaji katika shamba la miti Longuza. Ukusanyaji wa data ulifanyika katika viunga 9 vilivyochenguliwa na ploti za muda mfupi 168 za mduara zenye nusu kipenyo cha mita 9.78 sawa na eneo lenye hekta 0.03 zilizotawanywa kwa mpangilio zilianzishwa katika viunga hivyo.

Katika kila ploti miti yote ilipimwa kipenyo katika usawa wa matiti (Dbh) na miti mitatu (unene mkubwa, wastani/kati na mdogo) ilipimwa urefu kamili. Rejesta ya viunga ilitumika kupata taarifa ya upandaji na uchenguaji uliofanyika. Bei za ujazo wa mti, nguzo na gharama za kuanzisha na kusimamia kiunga zilikusanywa. Parameta za ukuaji na mavuno zilizofafanuliwa ni kipenyo (unene wa mti), urefu uliotawala, ujazo wa miti katika hekta na idadi ya miti katika hekta. Uchenguaji wa kutosha (adequate thinning) ulikokokotolewa kwa kutambua idadi ya miti iliyobaki katika kiunga kwa hekta na mchepuko (deviation) kwa kulinganisha na taarifa ya Teak yield table ikionyeshwa kwa asilimia. Uchenguaji uliofanyika kwa wakati (timely thinning) ulipatikana kwa kutoa umri wa kiunga uliofikia hatua ya uchenguaji na mwaka uliofanyika uchenguaji. Faida ya kiuchumi ilikokotolewa kwa kutumia mbinu ya punguzo (discounting) katika mtiririko wa faida na matumizi ambapo thamani halisi (NPV) ilitumika kutambua hatua ya kiuchumi iliyofikiwa. Aidha, athari ya uchenguaji ulipimwa kwa kulinganisha matokeo ya parameta zilizopimwa na matokeo ya parameta za jedwali la mavuno ya msaji (Teak yield table). One sample t-test ilitumika kulinganisha matokeo ya parameta zilizopimwa na matokeo ya parameta za jedwali la mavuno ya msaji (Teak yield table) ili kutafuta tofauti katika matokeo ya parameta zilizopimwa.

Matokeo yameonnyesha wazi kuwa asilimia 88.9 ya viunga vilivyochenguliwa vilikuwa na miti chini ya kiwango kilichopendekezwa na asilimia 11.1 ya viunga vilivyochenguliwa vilikuwa na idadi sahihi ya miti iliyopendekezwa. Aidha, asilimia 100 na 75 ya uchenguaji wa kwanza na wa pili ulifanywa kwa wakati ambapo asilimia 25 ya uchenguaji wa pili ulicheleshwa kwa mwaka mmoja. Viunga vilivyopimwa vinaonyesha kuwa asilimia 66.7 na 33.3 vinawakilisha daraja la kwanza na pili mtawaliwa.

Matokeo ya uchenguaji wa kutosha na uliofanyika kwa wakati kuhusu kipenyo na ujazo wa miti ulikuwa asilimia 2-4 na asilimia 9-53 mtawaliwa. Uchenguaji mkubwa katika ratiba ya kwanza na pili umeongeza faida za kiuchumi katika utoaji wa huduma ya kiikolojia na hewa ya ukaa kwa asimia 181.5. Hata hivyo, uchenguaji mkubwa wa kwanza na wa pili uliofanyika kwa wakati umeonyesha kuwa tiba muhimu katika kurejesha mapato ya juu lakini uchenguaji uliocheleshwa umeonyesha kupunguza ujazo wa magogo yakiwa na ubora na daraja la chini. Uchenguaji wa kutosha na mkubwa uliofanyika kwa wakati unapendekezwa.

Ufunguo wa maneno: Uchenguaji; Huduma za kiikolojia; Uzalishaji mapato; *Tectona grandis;* Longuza

DECLARATION

I Omari Shaban Mgoo do hereby declare to the senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

Omari Shaban Mgoo Date
(MSc. Candidate)

The declaration is confirmed;

Prof. S.A.O. Chamshama Date
(Supervisor)

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Dr. B.J. Temu Date
(Supervisor)

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DEDICATION

I dedicate this research study work to my lovely child, **Muneer O. Mgoo**, for whom I pray to Almighty God to be successful in his life and education carrier.

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ABBREVIATIONS, ACRONYMS AND SYMBOLS

a_i	Plot area
BA	Basal Area
cm	Centimetre
Dbh	Diameter at breast height
E	East
exp	Exponential
et al.	More than one
GPS	Global Position System
FAO	Food and Agriculture Organization
H	Height
ha	Hectare
I	One
II	Two
III	Three
KS	Kihuhwi Sigi
KL	Kolekole
KH	Kihuhwi
LG	Longuza
&	and
$\sum$	Summation
^oc	Degree centigrade
<	Below
>	Greater than
‘	Minutes
=	Equal
%	Percentage
ln	Natural logarithm
L.f	Lamiaceae family
MNRT	Ministry of Natural Resources and Tourism
Mr.	Mister
m	Meter
m^3	Cubic meter
mm	millimetre
N	Number of stems
NPV	Net Present Value
No.	Number

n	Number of plots
n_i	Number of stems per plot
pH	Acidity or alkalinity
SUA	Sokoine University of Agriculture
S	South
SAIF	South African Institute of Forestry
TFS	Tanzania Forest Services Agency
TZS	Tanzania Shillings
V	Volume
VMAI	Volume Mean Annual Increment

CHAPTER ONE

1.0 General Introduction

1.1 Background Information

Tectona grandis L.f. (Teak) is one of the valuable hardwood species planted in about 70 tropical countries throughout tropical Asia, Africa, Latin America and Oceania. It was estimated that Asia grows about 80% of Teak while Africa and America grow about 10% and 6% of Teak respectively (Kollert and Kleine, 2017). Large scale establishment of exotic forest plantations in Tanzania (Tanganyika by then) commenced under the British rule (1920 - 1961) (Nshubemuki *et al*., 2001). A commercial Teak forest plantation must be managed intensively to obtain maximum profitability (Méndez and Rico, 2019). Thinning is usually carried out in order to improve the economic output of the plantation (Pérez and Kanninen, 2005a). Both thinning schedules and intensity (proportion of stand cut to bring the growing stock to a desired level after thinning treatment) for Teak plantations worldwide are focusing on proper thinning regimes, as it has been clearly shown that high intensity thinning offers greater advantages than low intensity-thinning for saw timber production objectives (Pérez and Kanninen, 2005b). Thinning schedule of Teak is important for producing high quality timber which has higher value for national and international markets (Méndez and Rico, 2019). Thinning as one of the silvicultural managements has a tremendous effect on stand parameters and revenue generation which is influenced by adequate thinning and timing resulting into positive outcome of needed products. Thinning intensity opens more space for tree growth in diameter at breast height (Dbh), height, stand basal area (BA) and volume. On the other hand, thinning is an essential practice which facilitates proper growth, round bole (diameter) and higher and straight height when other factors such as soil fertility, temperature and rainfall are optimal (Pachas *et al*., 2019).

Furthermore, thinning intensity predicts growth rate which has impact on volume increment, proper thinned stand will have higher growth rate as compared to unproper thinned stand. It has been shown by various authors that proper thinning has direct relation to diameter increment, tree height and volume increment per hectare (ha) (Krishnapillay, 2000; Pachas *et al*., 2019). As a result, revenue generation will eventually rely on adequate and proper thinning intensity to produce round and straight tree bole with maximum height (Pachas *et al*., 2019). It has been confirmed that thinning has a strong effect on yield and quality timbers. Also stand BA has been showed to be achieved with thinning (Krishnapillay, 2000). It was evaluated by Pérez and Kanninen, (2005b) that tree growth and stand productivity is sensitive to thinning intensity and periods. They observed that BA was increasing for the intensely thinning practices. It was confirmed by Pachas *et al.* (2019) and Pérez and Kanninen (2005b) that thinning intensity and timing have impacts on stand BA and height of the dominant tree. They recommended that thinning should aim to remove approximately one half of the standing trees or one third of the standing BA, in order to have a positive impact on the standing BA and volume increments. They suggested that BA should be in the range of 18 to 24 m^2ha^{-1} and thinning should aim to remove 25 to 50% of the standing BA. Studies show that low growth rate, medium growth rate and higher growth rate have mean annual increment (MAI) of 3 m^3 ha^{-1} yr^{-1}, 5 m^3 ha^{-1} yr^{-1} and 8 m^3 ha^{-1} yr^{-1} respectively are influenced by intensity of thinning (Varmola and Carle, 2002).

Thinning intensity predicts growth rate, influencing volume increment, a properly thinned stand will have a higher growth rate than an improperly thinned stand. Several authors have demonstrated that proper thinning directly correlates with diameter increment, tree height, and volume increment per ha (Krishnapillay, 2000; Pachas *et al*., 2019). As a result, revenue generation will eventually depend on adequate and proper thinning intensity to produce round and straight tree boles with maximum height (Pachas *et al*., 2019). Similarly, tree growth and stand productivity are influenced by the intensity of thinning. On the other hand, various authors recommended that thinning intensity should aim to remove one-half and/ or one-fourth of the standing BA during consecutive thinning to open more space for the retained trees to grow (Krishnapillay, 2000; Pachas *et al.,* 2019; Pérez & Kanninen, 2005b).

1.2 Problem Statement and Justification

1.2.1 Problem statement

Monitoring growth and yield dynamics are essential to facilitate adequate management responses (Gumadi, 2019). The main sources of plantation hardwood raw materials and revenue generation in Tanzania are the Teak plantations. Their productivity is not sufficient enough to supply wood raw materials to local and foreign markets with the expectation of higher returns. As thinning influences stand diameter growth, yield and revenue, many studies have been conducted on stand response to thinning (Aiso-Sanada *et al.* 2019; Budiadi and Ishii, 2017; Hitsuma *et al.* 2021; Linkevičius *et al*., 2014; Pretzsch, 2020; Saarinen *et al.* 2020; Seo *et al.* 2019; Seta *et al.* 2021; Štefančík *et al.* 2018). In Tanzania Teak forest plantations, thinning regimes have been applied to increase resource productivity, but their operations are inadequately managed and inappropriately implemented. This is attributed to technical incompetence and inadequate competent staff and budgetary constraints having implications on the balance between manpower required to complete planned stand thinning on time. Late thinning is also constrained by the delay in disbursement of funds. However, little is known about the effects of thinning operations on the growth, yield and revenue generation of *Tectona grandis*. Gumadi, (2019) conducted a study on diameter and yield increment after thinning. Similarly, the study by Chamshama and Malimbwi (1996); Ngaga, (2011) and Nshubemuki *et al.* (2001) examined the effects of fewer and inappropriate thinnings on Dbh and yield growth. The studies found that thinning has significant positive Dbh and yield growth whereas there were negative effects for fewer and inappropriate thinnings. But since more information is needed to guide the investment in this species, information about growth, yield and revenue is of importance. Therefore this study is geared to address this gap by assessing growth of Dbh, yield and revenue generation for *Tectona grandis* grown at Longuza Forest Plantation.

1.2.2 Justification of the study

The results of this study will be used by Tanzania Forest Services Agency (TFS) and other private companies to properly thin Teak plantations to improve stand volume and forest revenue generation. Likewise, the results will be ideal for individual Teak growers to meet stand volumes and revenue collection in small areas and maximize individual income, thus reducing poverty.

1.3 Objectives

1.3.1 Main objective

To assess the effects of thinning on selected stand parameters and revenue generation of *Tectona grandis* in Longuza forest plantation.

1.3.2 Specific objectives

i. To assess the effects of thinning on Dbh and yield of *Tectona grandis* stand.

ii. To assess the effects of thinning on revenue generation in *Tectona grandis* stand**.**

1.4 Dissertation Organisation

This dissertation is divided into four major chapters and was developed in the format of publishable manuscripts. Chapter one consists of the introduction, which provides background information on the study, a problem statement and justification, along with the study objectives, and dissertation organization. Chapter two describes the first manuscript on the effects of thinning regimes on the growth and yield of *Tectona grandis* at Longuza forest plantation, Muheza District, Tanzania. Chapter three is presents the second manuscript which is on forest management optimization scenarios for climatic and economic benefits generated from a *Tectona Grandis* plantation in Muheza, Tanzania. Chapter four summarizes the key contributions of the study, general discussion, conclusion and recommendations for sustainable management of Teak forest plantation to improve thinning practices for better provision of ecosystem services and economic benefits.

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CHAPTER TWO

Manuscript One

Effects of Thinning Regimes on Growth and Yield of Tectona grandis at Longuza Forest Plantation, Muheza District, Tanzania

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Effects of Thinning Regimes on Growth and Yield of *Tectona Grandis* at Longuza Forest Plantation, Muheza District, Tanzania

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ABSTRACT

Thinning regime implies stands thinned at successive intervals, type, and intensity influencing growth and yield. Teak Forests in Tanzania are the main source of hardwood raw materials however thinning operations are not properly implemented. The purpose of this study was to determine whether thinned stands could impair the eventual projected growth and yield. Growth and yield data were collected from 168 purposively selected circular plots of radius 9.78 m distributed systematically in 9 thinned compartments in three thinning regimes. Thinning history, tree diameter, and total height of three fattest trees were recorded. Simple *t*-test was used to compare whether thinned stands were significantly different from Teak yield table values in Dbh, volume, and stocking. Results show that 88.9% and 11.1% of thinned compartments were understocked and well stocked respectively based on the Teak yield table. Also, 100% and 75% of first and second thinnings respectively were well timed whereas 25% of second thinning was delayed. Among surveyed compartments, 66.7% and 33.3% belong to site classes I and II respectively. Effects of adequate and timely thinning on Dbh and volume were 2-42% and 9-53% respectively. Thinning and timing promoted positively Dbh and Volume growth. Adequate and timely thinning treatments are recommended.

Keywords: *Tectona grandis* - thinning regimes - growth - yield - Longuza

INTRODUCTION

Teak (*Tectona grandis* L.f.) forest plantations are important in the world due to their production of valuable hardwood products. Teak is planted in about 70 tropical countries throughout tropical Asia, Africa, Latin America, and Oceania. Having good dimensional stability, high natural durability, and resistance to termites, fungus, water, and weather made the tree most valuable in the global timber market. Due to its successful cultivation, *Tectona grandis* plantations are estimated to occupy almost 7 million hectares (ha) globally (Kollert and Kleine 2017, Midgley *et al.* 2015, Seta *et al.* 2021) with about 80%, 10%, and 6% of the area contributed by Asia, Africa and America respectively (Carle *et al.* 2002, Dangal and Das 2018, Kollert and Cheburini 2012, Kollert and Kleine 2017). Moreover, the mean annual increment (MAI) of planted Teak forests ranges from 2 m^3 $ha^{-1}year^{-1}$ to 14 m^3 $ha^{-1}year^{-1}$. Regardless of extensive Teak cultivation, they have little contribution to global wood raw material production (Bauhus and Schmerbeck 2010). Therefore, there is a need to extend and improve the productivity of Teak plantations through using germplasm of high genetic quality and intensive management including thinning to maintain wood supply in the demanding market (Lautenschlager 2000, Seta *et al.* 2021, Pérez and Kanninen 2005).

The recent dependency on wood materials for building and construction purposes has increased the demand for higher quality poles, lumber, flooring, and furniture. Indeed, the increased demand for wood puts natural forests under pressure and results in deforestation and degradation hence the shrinking of natural forests (Bauhus and Schmerbeck 2010, Dudley *et al.* 2014). To avoid wood dependency on these natural forests, Teak forest plantations should serve the purpose (Bauhus and Schmerbeck 2010, Griess and Knoke 2011). Teak wood has gained a higher reputation due to its good appearance, texture, colour, and market demands making it valuable worldwide (Kanninen *et al.* 2004). On the contrary, various reports showed that thinning operations in many public plantations do not follow the prescribed schedules (Munishi and Chamshama 1994, Nshubemuki *et al.* 2001, Ngaga 2011). Thinning whenever carried out has been fewer and lighter than recommended, resulting in the standing volume being distributed on many small trees rather than a few ones of better value per cubic meter (Chamshama and Malimbwi 1996).

Monitoring growth and yield dynamics are essential to facilitate adequate management responses (Gumadi 2019). While the main source of plantation hardwood raw materials in Tanzania is the Teak plantation forests, their thinning operations are inadequately managed and inappropriately implemented. However, little is known on the effects of thinning operations on the growth and yield of *Tectona grandis* at Longuza Forest Plantation in Tanzania. This study aimed to fill the knowledge gap for *Tectona grandis* grown at Longuza Forest Plantation. The results are expected to provide basic information for future management practices of Teak plantations with regards to thinning to improve stand yield and utilization of Teak in woodlots.

MATERIALS AND METHODS

Location and Description of the Study area

This study was conducted at Longuza Forest Plantation, Tanzania which borders the foothills of the Eastern Arc Mountains (Figure 1). The plantation occupies an area of 3,496.31 ha. The planted area for *Tectona grandis* is about 2,025.82 ha, 1,032.05 ha is the natural forest, 430.81 ha is the extension area and 24.36 ha is planted with *Teminalia* sp, *Cedrela odorata,* and *Milicia excelsa.* The plantation is divided into four ranges which are under the management of the Longuza Forest Plantation Headquarter. Longuza (LG) range has a total area of 1,541.97 ha, Kihuhwi Sigi (KS) range has a total area of 921.43 ha, Kihuhwi range (KH) has a total area of 605.91 ha and Kolekole (KL) range has a total area of 303 ha. The KH range is further subdivided into sub-range of Kwani forest with a total area of 124 ha (MNRT, 2018). The study sites were in three ranges namely KH; KS and LG. The environmental characteristics of the study area are shown in Table 1

Table 1: Environmental conditions of Longuza Forest Plantation

Characteristic	Condition
Altitude (m, above sea level)	160-560
Precipitation (mm year^{-1})	1,500
Temperature (°C)	Maximum (26-32) - minimum (15-20)
Soil depth (cm)	shallow (<20)-deep (>120)
Soil (pH)	Neutral (4.5-5.0) – Acidic (6.6-7.3)
Soil type	Loam
Rock type	Pre – Cambrian

Source: Malimbwi *et al.* (1998), MNRT (2018), Ngaga (2011), Sibomana *et al.* (1997), Van Zyl (2005), Zahabu *et al.* (2015)

Study Design

In this study, the compartments were grouped into three age strata (5-9, 10-14, and >15 years) to obtain the correct age for the thinning schedule. The samples were drawn from compartments that match with age strata and thinning cycle. A total of 9 compartments, 2 compartments in the KH range, 3 in the KS range, and 4 in the LG range were selected purposively to draw samples. Each compartment was selected based on a thinning schedule.

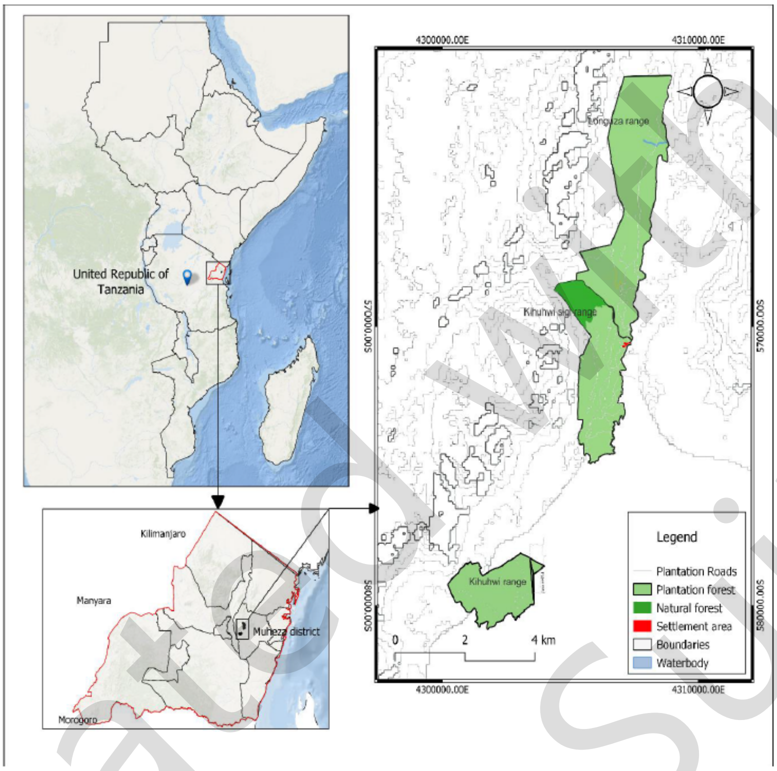

Figure 1: Map of Longuza Forest Plantation showing the location of study sites).

Sampling Design

Systematic sampling design as used to develop the Teak yield table by Malimbwi (2016) was adopted to establish; 1) circular shaped sample plots of radius 9.78 m, area of 300.33 m^2 (0.03 ha), 2) the accurate number of plots, 3) distance between plots, 4) transect distance and 5) appropriate sampling intensity to be applied for the surveyed compartment area. A reconnaissance survey was carried out in each compartment to decide the number of plots per compartment. The sampled compartment was surveyed before plot establishment to determine the correct area and to eliminate natural forests and swampy areas. Compartment maps were used to locate plots and lay out transects. Four transects were laid out in each sampled compartment. The distance between transects in a compartment was determined by dividing the distance of the widest part of the compartment by the number of transects and ranged from 100 m to 140 m. A total of 168 plots were laid out. The first plot was drawn randomly and the rest were laid out systematically at equal intervals of 100 m. The distance between plots was obtained by dividing the total transect length by the total number of plots (Table 2).

Table 2: Sampling procedure used in surveyed compartments

Thinning regime	Compartment	Age (years)	Area (ha)	Transect distance (m)	Sampling intensity (%)	Number of plots
1st Thinning	KH 12	6	33.8	120	0.02	23
1st Thinning	KH 13	7	28.1	120	0.02	23
1st Thinning	KS 1	8	47.3	140	0.025	31
2nd Thinning	LG 14	10	19.6	120	0.02	17
2nd Thinning	KS 11	11	23.6	140	0.03	19
2nd Thinning	LG 13	12	25.2	120	0.02	23
2nd Thinning	KS9B	13	5.4	100	0.02	6
2nd Thinning	LG 2	14	22.7	140	0.035	19
3rd Thinning	LG 13A	28	6.9	100	0.03	7

Data Collection

2.4.1 Growth and Yield of *Tectona grandis*

Forest inventory was carried out in each established plot in which Dbh (1.3 m above ground) of all trees was measured by using a caliper for compartments less than 10 years and compartments aged 10 years and above the Dbh was measured using diameter tape and counted. Height for the three fattest trees per plot was measured for total tree height using the Suunto hypsometer.

Thinning Adequacy and Timing

A compartment register was used to obtain data on the planting year and the age the compartment was supposed to be thinned. Through an interview, the Plantation Conservator provided information concerning thinning history, un-thinned, thinned and last thinning years on each selected compartment and were recorded.

Data Analysis

Growth and Yield of *Tectona grandis*

The stand parameters used to describe growth and yield were Dbh, dominant height, volume per ha, and stand density. Based on the Teak yield table for Longuza Forest Plantation produced by Malimbwi (2016), different models for tree and stand parameter estimation were adopted. The average Dbh was computed by summing Dbh (cm) in plots divided by the total number of trees measured. The estimation of height (H) for trees that were measured for Dbh alone was done by using Equation 1 (Table 3). The average dominant height estimation was done by summing the height of trees divided by the total trees measured. Stand volume per ha was estimated by using Equation 2 (Table 3). Stand density per ha was obtained by using Equation 3 (Table 3).

Table 3: Formulas used to estimate observed stand parameters

Equation	Equation no.	Source
$H = 1.3 + ((Dbh^2) \div (7.9693 + 0.03006 \times Dbh^2))$	1	Malimbwi (2016)
$V = \exp(1.033835 + 0.489679 \times \ln(H) + 0.9954 \times \ln(BA))$	2	Malimbwi (2016)
$N = 1/n((\sum ni)/ai)$	3	Malimbwi (2016)

Note: H is the total tree height, Dbh is the diameter at breast height, V is the volume, N is the number of stems, n is the number of plots surveyed, n_i is the number of stems per plot, a_i is the plot area, *ln* is the natural logarithm and *exp* is the exponential.

The measured values were compared to mean values obtained in the Teak yield table produced by Malimbwi (2016). However, the Teak yield table was developed meant to predict growth and yield for properly thinned stands. One sample t-test was used to test whether measured values differ significantly from the Teak yield table values.

Thinning Adequacy and Timing

Compartment tree density was computed to obtain the number of stems that remained after thinning. The tree density was determined by dividing the number of stems in a plot by plot area. The number of stems per ha that remained after thinning was obtained by dividing the number of stems in a plot by a plot area. Adequacy of thinning for thinned compartments was determined by calculating the remaining number of stems per ha and the deviation from scheduled values expressed in percentages. Thinning timing was obtained by deducting the age the compartment was supposed to be thinned as indicated in thinning schedule from the actual thinning age using the information from the Plantation Conservator and compartment register to determine whether the thinning was timely, earlier, or delayed. One sample t-test was used to test whether each compartment density after thinning differs significantly from the scheduled density in the thinning schedule.

Site Class Determination

The obtained dominant height and age were matched in the site index curves of the *Tectona grandis* produced by Malimbwi (2016) to determine site classes for the surveyed compartments (Figure 2). Site class I is the best, followed by site class II and lastly site class III. The corresponding site indices are 26, 22, and 18 m at the reference age of 20 years. All analyses were done using MS excel 2013 and SPSS software.

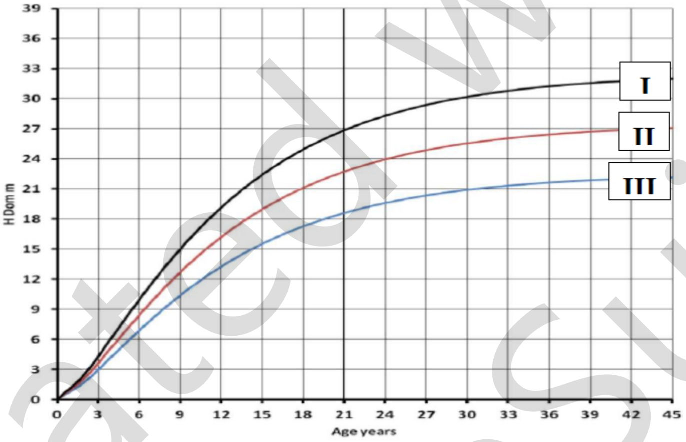

Figure 2: Site index curves for *T. grandis* in Tanzania. Roman I, II and III represent site classes one, two, and three respectively. ***Source***: Malimbwi (2016).

RESULTS

Thinning Adequacy and Timing

Results showed that in 9 surveyed compartments, 8 compartments were understocked with negative deviation ranging from 5% to 27%. However, overstocking was observed in one compartment aged 28 years. Compartments that received first and second thinning treatments had average stems per ha of 675 and 366 with an average negative deviation of 15.7% and 8.6% respectively whereas third thinning had stems per ha of 348 with a deviation of 16% (Table 4).

Results of One sample T-test showed that the mean of the observed stems per hectare values in three compartments (33.3%) of second thinning treatment of KS11, KS9B, and LG 2 was not statistically significant at the 0.05 level of significance ($p > 0.05$) from the test value = 400 of Teak yield table (Table 5).

Table 4: Post thinning results on stocking (stems ha^{-1}) for surveyed compartments in Longuza Forest Plantation

Thinning regime	Compartment	Age (years)	N/ha	*N/ha	Deviation	Deviation %
1st Thinning	KH 12	6	728	800	(72)	(9)
1st Thinning	KH 13	7	714	800	(86)	(11)
1st Thinning	KS 1	8	583	800	(217)	(27)
2nd Thinning	LG 14	10	365	400	(35)	(9)
2nd Thinning	KS 11	11	372	400	(28)	(7)
2nd Thinning	LG 13	12	357	400	(43)	(11)
2nd Thinning	KS9B	13	356	400	(44)	(11)
2nd Thinning	LG 2	14	379	400	(21)	(5)
3rd Thinning	LG 13A	28	348	300	48	16

Figures in (brackets) represent a negative deviation
* Stand for value scheduled in the Teak yield table for *Tectona grandis*

Table 5: One sample T-test Results on Stocking

Thinning regime	Compartment name	Mean	Standard Deviation	t-statistic	Degree of freedom	P-value	Mean Differences	95% Confidence interval of the Difference	
								Lower	Upper
2nd Thinning	KS 11	371.93	65.04	-1.881	18	0.076^{b}	-28.07	-59.41	3.28
2nd Thinning	KS 9B	355.55	54.43	-2	5	0.102^{b}	-44.44	-101.57	12.68
2nd Thinning	LG 2	378.95	48.69	-1.884	18	0.076^{b}	-21.05	-44.52	2.42

^{b} stands for insignificant p-values.

Results revealed that 7 compartments out of 9 received thinning treatments on time. Nevertheless, 100% of first thinning was done on time, and about 80% of second thinning was observed to be timely carried out while about 20% of second thinning and third thinning treatments in one compartment were delayed for one year (Table 6).

Site Classes of the Surveyed Compartments

Results revealed that 7 out of 9 surveyed compartments belong to site class I and 2 compartments belong to site class II. However, results indicated that 66.7% (141.7 ha), and 33.3% (70.9 ha) of surveyed compartments belong to site classes I, and II respectively. In addition, 52.5% (74.4 ha) are from the LG range, 43.7% (61.9 ha) are from the KH range and 3.8% (5.4 ha) are from the KS range and 100% (70.9 ha) of all site class II compartments are from KS range (Table 7 and Figure 3).

Table 6: Timing of thinning operations for surveyed compartments in Longuza Forest Plantation

Thinning regime	Compartment	Planting year	Age (years)	Actual stocking (N/ha)	Actual thinning year	Scheduled thinning year	Thinning timing (years)	Timing status
1st Thinning	KH 12	2015	6	728	2020	2020	0	Timely
1st Thinning	KH 13	2014	7	714	2019	2019	0	Timely
1st Thinning	KS 1	2013	8	583	2018	2018	0	Timely
2nd Thinning	LG 14	2011	10	365	2020	2020	0	Timely
2nd Thinning	KS 11	2010	11	372	2020	2020	0	Timely
2nd Thinning	LG 13	2009	12	357	2019	2019	0	Timely
2nd Thinning	KS9B	2008	13	356	2018	2018	0	Timely
2nd Thinning	LG 2	2007	14	379	2018	2017	+1	Delayed
3rd Thinning	LG 13A	1993	28	348	2008	2007	+1	Delayed

Table 7: Site classes of the surveyed compartments in Longuza Forest Plantation

Compartment name	Age (Years)	Area (ha)	Dominant height (m)	Site class	Thinning Status	Thinning regime	Range
KH 12	6	33.8	11.5	I	Thinned	1st	Kihuhwi
KH 13	7	28.1	12.4	I	Thinned	1st	Kihuhwi
KS 1	8	47.3	11.1	II	Thinned	1st	Kihuhwi Sigi
LG 14	10	19.6	19.5	I	Thinned	2nd	Longuza
KS 11	11	23.6	14.8	II	Thinned	2nd	Kihuhwi Sigi
LG 13	12	25.2	21.7	I	Thinned	2nd	Longuza
KS 9B	13	5.4	22.5	I	Thinned	2nd	Kihuhwi Sigi
LG 2	14	22.7	23.3	I	Thinned	2nd	Longuza
LG 13A	28	6.9	29.9	I	Thinned	3rd	Longuza

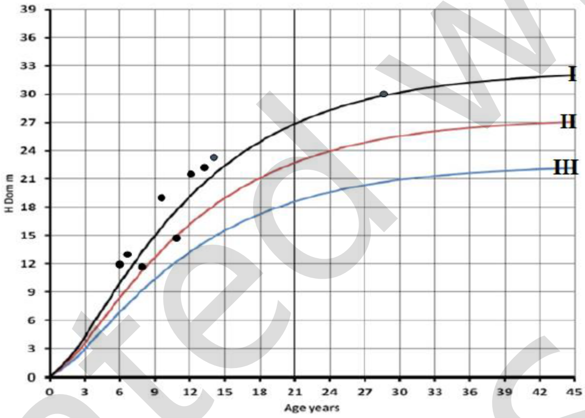

Figure 3: Site classes for the surveyed compartments. Roman I, II, and III represent site classes one, two, and three respectively

Effects of Thinning on Diameter Growth

In the first, second, and third thinned compartments, results revealed that thinning affects diameter growth. For site class I, results showed that observed values deviated from 20% to negative 36% in the first, second, and third thinning treatments. For site class II, results revealed that observed values deviated by 2% and 42% in the first and second thinnings respectively. (Table 8).

However, a statistical result of One sample T-test showed that the mean of the observed Dbh in five compartments in site class I revealed that first, second, and third thinning in compartments KH 12, KH 13, LG 13, LG 2, and LG13A was statistically significant at the 0.05 level of significance ($P<0.05$) from the test value = 9.8, 11.7, 22.7, 25.6 and 38.5 respectively of teak yield table values. The observed results of One sample T-test in three compartments of second thinning of KS9B, KS11, and LG 14 revealed that the mean of the observed Dbh was not statistically significant at the 0.05 level of significance ($P>0.05$) from the test value = 24.2, 17.6 and 19.3 respectively. Nonetheless, the statistical result indicated that the first thinning operation in compartment KS 1 was statistically significant at 0.05 level of significance ($P<0.05$) from the test value = 11.3 of teak yield table value while the second thinning operation in compartment KS 11 was not statistically significant at 0.05 level of significance from the test value = 17.6 of teak yield table value (Table 9).

Table 8: Summary of post-thinning results on diameter (cm) growth at Longuza Forest Plantation

Thinning regime	Compartment	Age (years)	Dbh (cm)	*Dbh (cm)	Deviation	Deviation %	Site class
1st Thinning	KH 12	6	13.7	9.8	4	40	I
1st Thinning	KH 13	7	14.0	11.7	2	20	I
1st Thinning	KS 1	8	16.1	11.3	5	42	II
2nd Thinning	LG 14	10	18.3	19.3	(1)	(5)	I
2nd Thinning	KS 11	11	17.9	17.6	0.3	2	II
2nd Thinning	LG 13	12	19.5	22.7	(3.2)	(14)	I
2nd Thinning	KS9B	13	23.9	24.2	(0.3)	(1)	I
2nd Thinning	LG 2	14	20.7	25.6	(5)	(19)	I
3rd Thinning	LG 13A	28	24.5	38.5	(14)	(36)	I

Figures in ( ) represent a negative deviation

* Stand for value scheduled in the Teak yield table for *Tectona grandis*

Table 9: One sample T-test Results on Diameter Growth

Thinning regime	Compartment name	Mean	Standard Deviation	t-statistic	Degree of freedom	P-value	Mean Differences	95% Confidence interval of the Difference	
								Lower	Upper
1st Thinning	KH 12	13.75	1.17	16.174	22	0.00^{a}	3.95	3.44	4.46
1st Thinning	KH 13	14.05	0.88	12.684	22	0.00^{a}	2.34	-109.24	61.77
1st Thinning	KS 1	16.05	1.90	13.92	30	0.00^{a}	4.75	4.05	5.45
2nd Thinning	LG 13	19.45	2.5	-6.129	22	0.00^{a}	-3.24	-4.34	-2.19
2nd Thinning	KS 11	17.89	1.46	0.884	18	0.38^{b}	0.29	-0.41	1.00
2nd Thinning	LG 2	20.74	1.74	-11.892	18	0.00^{a}	-4.85	5.71	-3.99
3rd Thinning	LG 13A	24.49	4.03	-9.19	6	0.00^{a}	-14.01	-17.74	-10.28

^{a} and ^{b} stand for significant and insignificant p-values respectively

Effect of Thinning on Stand Yield

Results revealed significant differences between observed values and Teak yield table values in 7 out of 9 compartments. In site class I compartments, the mean percentage deviation ranged from 9% to 53% while in site class II compartments, the percentage deviation ranged from negative 9% and 23%. First site class compartments had higher observed values than Teak yield table values ranging from 9% to 53%. In site class II, compartments KS 1 and KS 11 had a negative deviation percentage of 9% and 23% respectively (Table 10).

The results of One sample T-test indicated that in observed compartments, 85.7% of site class one in compartments KH 12, KH 13, LG 14, LG 13, KS 9B, and LG 2 was statistically significant at a 0.05 level of significance ($P<0.05$) from test value 52.1, 80.4, 128.5, 191, 223.7, and 256.8 respectively of Teak yield table values while statistical result in compartment LG 13A was not statistically significant at 0.05 level of significance ($P>0.05$) from test value = 508.9 of Teak yield table. In addition, compartment KS 1 was statistically significant ($P<0.05$) and statistically insignificant was observed in compartment KS 11 ($P>0.05$) at 0.05 level of significant from the test value 73.7 and 102.2 respectively of Teak yield table (Table 11).

Table 10: Summary of post-thinning results on volume yield (m³ ha⁻¹) in Longuza Forest Plantation

Thinning regime	Compartment	Age (years)	V (m³/ha)	*V (m³/ha)	Deviation	Deviation %	Site class
1stThinning	KH 12	6	72.9	52.1	21	40	I
1stThinning	KH 13	7	87.3	80.4	7	9	I
1stThinning	KS 1	8	56.8	73.7	(17)	(23)	II
2ndThinning	LG 14	10	196.1	128.5	68	53	I
2ndThinning	KS 11	11	93.5	102.2	(9)	(9)	II
2ndThinning	LG 13	12	253.1	191.0	62	33	I
2ndThinning	KS9B	13	271.6	223.7	48	21	I
2ndThinning	LG 2	14	314.5	256.8	58	22	I
3rdThinning	LG 13A	28	574.9	508.9	66	13	I

Figures in ( ) represent a negative deviation

* Stands for value scheduled in the Teak yield table for *Tectona grandis*

Table 11: One sample T-test Results on Stand Yield

Thinning regime	Compartment name	Mean	Standard Deviation	t-statistic	Degree of freedom	P-value	Mean Differences	95% Confidence interval of the Difference	
								Lower	Upper
1stThinning	KH 12	72.88	9.66	10.323	22	0.00 [a]	20.79	16.61	24.96
1stThinning	KH 13	87.25	14.09	2.331	22	0.29 [b]	6.85	0.76	12.94
1stThinning	KS 1	56.78	11.92	-7.899	30	0.00 [a]	-16.92	21.29	-12.54
2ndThinning	LG 14	196.06	72.12	3.862	16	0.01 [a]	67.56	30.47	104.64
2ndThinning	LG 13	253.06	63.52	4.686	22	0.00 [a]	62.06	34.59	89.53
2ndThinning	KS 9B	271.63	22.04	5.327	5	0.03 [a]	47.93	24.79	71.05
2ndThinning	KS 11	93.52	24.95	-1.516	18	0.14 [b]	-8.68	-20.71	3.35
2ndThinning	LG 2	314.45	74.74	3.363	18	0.00 [a]	57.65	21.63	93.68
3rdThinning	LG 13A	574.94	94.15	1.86	6	0.11 [b]	66.04	-21.03	153.11

[a] and [b] stand for significant and insignificant p-values respectively

DISCUSSION

Thinning positively affected stand growth parameters and yield. This may be the reduction of site growth competition among nearby trees. However, the study revealed that the implementation of thinning treatments timely relieves both horizontal and vertical competition. Furthermore, thinning practice reduced stand density which influenced the growth of stand parameters since Teak is a light demander and does not grow well in congested trees (Pandey and Brown 2000, Štefančík *et al.* 2018). It was noted that after a thinning treatment, reduced competition for light, nutrients, and moisture raised the growth of the remaining individuals especially radial growth as reported by Pérez and Kanninen (2005), Budiadi and Ishi (2017), Kokutse *et al.* (2010), Pandey and Brown (2000) and Seta *et al.* (2021).

Thinning Adequacy

In this study, understocked and overstocked stands were observed. However, 7 compartments had an allowable stem deviation of 10% as proposed by SAIF (2000) except compartments KS 1 and LG 13A with 27% and 16% respectively. On average, first and second thinning operations were adequately implemented indicating adherence to the Teak thinning schedule in the Technical Order. The observed differences were probably due to a lack of technical and competent skilled staff. Similar results were reported by Tewari *et al.* (2014) in Karnataka, India, and Laswai *et al.* (2016) in Tanzania which revealed thinning was lighter than recommended in the Technical Order. On the other hand, the study conducted by Pérez and Kanninen (2005a) in Costa Rica observed higher stand densities than recommended.

Thinning Timing

In this study, it was observed that all compartments that received first and three compartments that received second thinning were timely carried out as per the thinning schedule. However, results revealed that second thinning in one compartment and third thinning were delayed. The results are in agreement with the study by Kaninnen *et al.* (2004) and Gumadi (2019) who observed thinning delays for one year for the second and third thinnings. The observed delays are probably due to a lack of priority in planning thinning operations and technical incompetence and improper supervision, and a lack of commitment among staff (Gumadi, 2019). The study on thinning timing by Chamshama (2011) and Ngaga (2011) revealed that thinning delays are caused by a shortage of funds.

Growth and Yield of *Tectona grandis*

Results showed that thinning affected Dbh growth. Nevertheless, understocked compartments as a result of heavy thinning operation opened wider space reducing competition for raw materials which is beneficial for greater Dbh increment. These findings are in agreement with various researchers (Budiadi and Ishi 2017, Malimbwi *et al.* 1992, Maliondo and Chamshama 1996, Miller 2000, Kanninen *et al.* 2004, Mäkinen and Isomäki 2004, Pérez and Kanninen 2005, Kokutse *et al.* 2010, Pandey and Brown 2000, Rytter 2013, Saarinen *et al.* 2020, Seta *et al.* 2021, Simard *et al.* 2004). Meanwhile adequately and timely thinned stands can produce higher diameter increments as a result of a higher turnover rate of the crown as new leaves quickly adapt to the better environment (Malimbwi *et al.* 1992, Maliondo and Chamshama 1996, Kanninen *et al.* 2004). However, observed low diameters in compartments LG 2 and LG 13A were aggravated by delayed thinning.

The study found that early thinning had a positive influence on volume increment. Similar results were reported by Piotto *et al.* (2003), Simard *et al*, (2004), and Štefančík *et al.* (2018). There was a higher impact of volume increment in thinned compartments. Similar results were obtained by Aiso-Sanada *et al.* (2019), Cassidy *et al.* (2012), Perez and kanninen (2005), Saarinen *et al.* (2020), Seta *et al.* (2021) and Yahya *et al.* (2011) on the study of volume growth after thinning. The changes in volume were highly promoted by deduction in the number of stems after each consecutive thinning. However higher volume growth observed in compartment LG 13A was due to overstocking. Similar results were obtained by Chamshama and Malimbwi (1996) revealing that higher volumes are possible in stands with fewer and lighter thinning than recommended, resulting in the standing volume being distributed on many small trees rather than a few ones of better value per cubic meter.

CONCLUSION AND RECOMMENDATIONS

Conclusion

Generally, thinning operation and timing had a positive effect on the diameter growth and timber yield. The first and second thinning operations were over-thinned while the third thinning operation was lighter than specified in the Technical Order resulting in small diameter individuals whereas obtained higher volume was distributed in the small diameter stems. However, while timber volume increment drops after the first heavy thinning, it recovers quickly after the second thinning. Stand density in the first and second thinning operations was low except in the third thinning operation. The study revealed that thinning improved stand parameters. Although delayed thinning was performed in compartments LG 2 and LG 13A failed to attain the maximum Dbh as the Teak yield table recommends, the consequences would be loss of maximum yield as the crop attains commercial thinning and final harvesting age. The consequences

in the future would be a failure to meet revenue objectives.

Recommendations

Thinning is the integral silvicultural operation in a forest plantation. Moreover, thinning schedules for Teak are important for producing high-quality timber which has a higher value for national and international markets when implemented correctly. However, thinning schedules have to be implemented on time as stipulated in the Technical Order so that the estimated mean diameter of 40 cm at clear-felling is attained. To ensure positive effects of thinning regime as per Technical Order No 1 of 2021 the spacing of 3 m x 3 m is recommended as this will ensure reduced competition of resources of young growing individuals hence fast growth and maximum yield in the future for Longuza Forest Plantation.

However, as observed that the lack and or shortage of funds causes delays, it is recommended that sufficient funds be adequately allocated and disbursed timely.

Due to technical incompetence and inadequate competent staff, it is recommended to make close follow up and timely implementation of operations as recommended in the Technical Order.

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CHAPTER THREE

Manuscript Two

3.0 Forest Management Optimization Scenarios for Climatic and Economic Benefits Generated from Tectona grandis Plantation in Muheza, Tanzania

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Abstract

Consideration for multiple ecosystem services is increasingly becoming an important agenda in sustainable forest management. However, it is still unclear which forest management approaches would lead to an optimal level bundle of ecosystem services promoting sustainability. The purpose of this study was to determine whether the implemented three thinning schedule and 30 years rotation age has implications on the provision of ecosystem services and economic benefits of the *Tectona grandis* stands. Climatic and economic benefits of wood production and carbon sequestration were studied under five scenarios whereas 3 thinning schedule and 30 years rotation age were the baseline. Data were collected from 168 purposively selected circular plots of radius 9.78 m distributed systematically in 9 thinned stands. The thinned stands were implemented with intensities of 50%, 50%, and 25% in first, second, and third thinning schedules respectively. Results showed that decreasing 33.4% rotation age from the baseline while maintaining 3 thinning schedule maximized climatic and economic benefits of combined wood production and carbon storage goal by 181.5%. Implemented thinning schedules and rotation age affected wood production and carbon sequestration positively. Managing Teak forest plantation for combined goal of wood production and carbon sequestration is recommended.

Keywords: Forest management – Carbon sequestration – Wood production – Economic benefits – *Tectona grandis*

3.1 Introduction

Teak forest plantation being one of the crucial forests provides goods and services while mitigating climate change resulting from greenhouse gas emissions (Chayaporn *et al.,* 2021, Kesharwani *et al*., 2021, Nesha *et al.,* 2021). Teak forest plantations were established to replace and restore the lost tropical forest cover while serving the purpose of carbon sequestration and supplying woody materials to industries and residents (Chayaporn *et al*., 2021, Rahmawati *et al*., 2022, Zagade *et al*., 2022). Accordingly, the growing demand of Teak wood materials, production of higher quality timber, and fast growing ability with mean annual volume increment ranging from 2 m^3 $ha^{-1}year^{-1}$ to 14 m^3 $ha^{-1}year^{-1}$ attracts private and public sectors to establish Teak forest plantations (Mgoo *et al.,* 2022, Ounban *et al*., 2016, Payn *et al.* 2015., MacEwan *et al*. 2020, Zahabu *et al*. 2015). Globally, Teak forest plantation area is about 7 million ha (Kollert and Kleine 2017, Midgley *et al.,* 2015, Mgoo, *et al.,* 2022, Seta *et al.,* 2021). Further, Teak forest plantation accounts for 3.2 Gt CO_2 $year^{-1}$ of carbon sink (Nesha *et al.,* 2021). Although the quantity of Teak wood material production and carbon sink depends on age, volume ha^{-1} and number of stems ha^{-1} (Alexandrov, 2007, Behera and Mohapatra, 2015). On the other hand, increased uses and market value of high-quality poles, lumber, flooring, and furniture products raised the potential for Teak to be an important timber species for investment opportunity grown in farm plantations around the world (Kanninen *et al.* 2004, Seta *et al.,* 2021, Zahabu *et al.,* 2015). To optimize production of Teak wood and mitigating climate change, it is important to implement recommended silvicultural management regimes. Forest management practices have been recommended including thinning regimes, thinning intensity and time of final harvesting.

Thinning regimes reduces tree density providing early revenue and increases volume of individual trees. The time of stand establishment to harvest (rotation length) is used to manage timber yield and income from Teak plantations (Bauhus and Schmerbeck, 2010). In accordance with the Tanzania Technical Order of 2003 recommended three thinning regimes with intensities of 50%, 50%, and 25% in first, second, and third thinning treatments at the age of 5, 10 and 15 years respectively at spacing of 2.5 m x 2.5 m. The optimal rotation length is recommended at the age of 30 years in which clear-felling is advised to produce quality end products for targeted uses with a higher value for national and international markets (Méndez and Rico, 2019, MNRT, 2003). Until present, forest management practices in forest plantation is focused either on timber yield or carbon stock but little studies exists to assess thinning intensity and optimal rotation age that could provide the basis of understanding the importance of Teak forest plantation for carbon stock and wood production (Chayaporn *et al.,* 2021, Chanan and Iriany, 2014, Derwisch *et al*., 2009, Olayode *et al.,* 2015, Pichode and Nikhil, 2017). On the other hand, inadequately and inappropriately implemented thinning intensity and delayed thinning regimes would probably impair tree wood volume and may hamper the ability of Teak forest plantation to sequester carbon (Kaul *et al*., 2010, Mgoo *et al*., 2022).

According to Bauhus and Schmerbeck (2010), Dorner and Stein de Quadros (2019) and Hiesl *et al*. (2017), found that thinning intensity in Forest Plantation promoted higher economic values through production of quality wood and carbon sequestration. However, knowledge is rare about efficiency of different forest management practices (thinning intensity and optimal rotation age) in influencing provision of ecosystem services needed to maximize profits on carbon sequestration and round wood production in Teak Forest Plantation in Tanzania. Therefore, this study aimed to address this gap for *Tectona grandis* stands grown in Longuza forest plantation. The results are expected to provide the basic knowledge on thinning intensity and optimal rotation age with regards to profitability on Teak wood production and carbon sequestration promoting the economy of the private and public sectors involved in forest management.

3.2 Materials and Methods

3.2.1 Study sites description

The study was done in three ranges of Longuza forest plantation located in Muheza District Tanzania (Figure 3.1). The ranges were Longuza (LG), Kihuhwi Sigi (KS), and Kihuhwi (KH) with an estimated area of 1,541.97 ha, 921.43 ha, and 605.91 ha respectively (MNRT, 2018). The plantation total area is 3,496.31 ha whereby 2,025.82 ha are planted with *Tectona grandis,* 24.36 ha are planted with *Milcia excelsa, Terminalia spp,* and *Cederella odorata,* 1032.05 is the natural forest and 430.81 ha is the extension area. Native species dominated in natural forest are *Khaya anthotheca, Newtonia paucijuga, Albizia gummifera, Combretum schumanni, Brachystegia* sp., *Isoberlinia* sp., *Pterocarpus angolensis, Milicia excelsa*, *Antiaris* sp., *Zanha* sp., *Sterculia* sp. and *Acacia* sp. The plantation borders the Eastern Arc Mountains in the west. The plantation lies between Latitudes 4º55’ and 5º10’ South and Longitudes 38º 40’ and 390 00’ East. The altitude ranges from 160 m to 560 m above sea level.

The maximum temperature ranges between 26°C and 32°C and the minimum temperature ranges from 15°C to 20°C (Ngaga, 2011, Sibomana *et al*., 1997, Van Zyl, 2005). The study sites experienced two major seasons; the dry and wet seasons. The area received short and long periods of rainfall. Short rains begin from October to December while long rains begin from March to June. The amount of annual rainfall the study sites received is 1,500 mm. The dry season is between June and September (Van Zyl, 2005; Ngaga, 2011). The study sites have moderately deep soils ranging from 40 cm to 80 cm. The soil depth ranges from shallow (<20 m) to very deep (>120 m). The soil type is dominated by sandy clay loamy. The soil colour ranges from darkish brown to red (Malimbwi *et al.*, 1998; Ngaga, 2011, Zahabu *et al*., 2015).

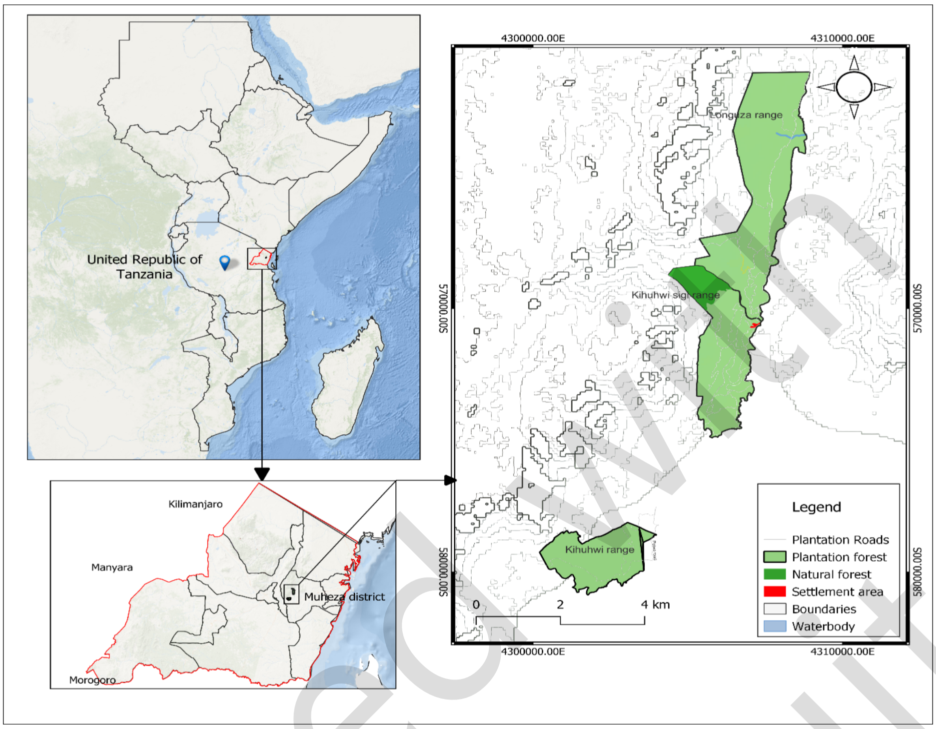

Figure 3.1: Map of Longuza Forest Plantation showing the location of study sites.

Source: Mgoo *et al.* (2022)

3.2.2 Study design

Thinning scenarios were developed to assess the role of forest management practices (thinning intensity, thinning regimes and optimal rotation age). A quasi-experimental research design was used to assess the effects of thinning intensity and optimal rotation age. In order to assess the effects of thinning two categories of ecosystem services were involved, provisioning services (wood production) and regulatory services (Co_2 sequestration). Provisioning services was assessed by quantifying stand volume and carbon dioxide sequestration was estimated by determining the capacity of a stand to transform atmospheric carbon dioxide into biomass through considering two carbon pools (the above and below ground biomass). The biophysical assessment of carbon sequestration in above ground biomass and below ground biomass was estimated as tons of Co_2 sequestered per ha using the variable tree volume increment (m^3 ha^{-1}) measured in stands after receiving thinning treatments.

Thinned stands were stratified into three age strata of 6-9, 10-14 and >15 years representing first thinning schedule, second thinning schedule, and third thinning schedule. Heavy thinning treatments were implemented in the first and second thinning schedule while moderate thinning was implemented in the third thinning schedule. The initial density of the measured stands was 1600 tree/ha. The treatments were (1) First heavy thinning; removal of 50% of the initial density 1600 tree/ha at age 5 years remaining density 800 tree/ha. (2) Second heavy thinning; removal of 50% of the remained trees after first thinning at age 10 years remaining density 400 tree/ha. (3) Third moderate thinning; removal of 25% of the remained trees after first and second thinning remaining density 300 tree/ha at age 15 years.

3.2.3 Sampling design

Systematic sampling design was done to lay out plots and transects. A reconnaissance survey was conducted to determine the number of plots per stand. Stands were surveyed using Global Positioning System to secure the actual stand area eliminating natural forests and wetlands. GPS and stand map was used to position and layout plots and transects. Four transects were laid whereby the distance between transects within a stand was determined by dividing the distance of the widest part of the stand by the number of transects and ranged from 100m to 140m. The first plot was laid at half distance from the compartment border to avoid edge effect. According to Malimbwi *et al*. (2004) and Malimbwi (2016) dictated that sampling intensity to be as low as 0.01% due to financial constraints, time limitation, purpose of forest stocking and sampled area. The distance between plots was determined by dividing the total length of four transects by the total number of plots. Then, 168 temporary circular plots of 9.78 m radius with 300.33 m^2 equivalent to 0.0300 ha (Malimbwi, 2016) were laid systematically in nine purposively selected stands (Table 3.1).

Table 3.1: Sampling intensity applied in surveyed areas

Thinning regime	Treatments (removals)	Age (year)	Area (ha)	Transect distance (m)	Sampling intensity (%)	Number of Plots
1stThinning	Heavy thinning (50%)	6	33.8	120	0.02	23
		7	28.1	120	0.02	23
		8	47.3	140	0.025	31
1st&2ndThinning	Heavy thinning (50%)	10	19.6	120	0.02	17
		11	23.6	140	0.03	19
		12	25.2	120	0.02	23
		13	5.4	100	0.02	6
		14	22.7	140	0.035	19
1st,2nd&3rdThinning	Heavy (50%), Heavy (50%) & Moderate thinning (25%)	28	6.9	100	0.03	7

3.2.4 Forest management scenarios

Forest management scenarios were developed connected to timber production and carbon sequestration. Assumptions were made based on rotation age and thinning intensity whereby five scenarios were defined and assessed. The objectives was to evaluate the efficiency of forest management practices in influencing provision of ecosystem services through maximizing net present value from timber production and carbon sequestration. The developed scenarios were noted and described as shown in Table 3.2.

Table 3.2: Description of Forest Management Scenarios

S/no.	Scenario type/name	Description
1	Business as usual (BAU).	Under this scenario, the management consider a tree rotation age of 30 years and three thinning schedules performed at age 5, 10, and 15 years.
2	Increasing rotation age by 10 years.	Under this scenario, the management consider a tree rotation age of 40 years and three thinning schedules performed at age 5, 10, and 15 years.
3	Decreasing rotation age by 10 years.	Under this scenario, the management consider a tree rotation age of 20 years and three thinning schedules performed at age 5, 10 and 15 years.
4	Increasing rotation age by 10 years	Under this scenario, the management

	and adopting two thinning schedules.	consider a tree rotation age of 40 years and adopts two thinning schedules at age 5 and 15 years only.
5	Decreasing rotation age by 10 years and adopting two thinning schedules.	Under this scenario, the management consider a tree rotation age of 20 years and adopts two thinning schedules at age 5 and 15 years only.

3.2.5 Data Collection

Financial data on establishment and management were collected through interview with the Longuza plantation management. The data included information on seedlings production, land preparation, tree planting, weeding, pruning, thinning and forest plantation protection. Selling price of removed stems was captured from Government published notes (GN NO. 59 of 2022), third commercial thinning and clear-felling volume price was provided by Plantation management from previous stored records while carbon price per ton of carbon dioxide equivalent (t/CO_2e) was obtained from the International Monetary Fund (IMF) Climate Report by Black *et al.* (2022). In addition, a forest inventory was conducted in 10 purposively selected stands aged 5, 6, 7, 8, 10, 11, 12, 13, 14, and 28 years whereby plots were established in each stand age and diameter at breast height (Dbh) of all trees and total tree height of three trees were measured and recorded. Diameter tape and Suunto hypsometer were used to measure dbh and tree height respectively (Malimbwi 2016, Zahabu *et al.,* 2016).

3.2.6 Data Analysis

Averages of expenses in Tanzania shillings (TZS) per ha were estimated to obtain the actual costs incurred to establish and manage stands. The estimation of expenses per ha was done by summing the costs of the stand surveyed divided by area. The average price of volume of the final harvests (clear-felling) was estimated by summing prices divided by years.

Yield and biomass values were estimated by using models presented in Table 3.3. The height of trees measured for Dbh was estimated by Equation number 1. Mean volume (MV) per ha was obtained by summing volume in plots divided by total plots and was done by Equation 2. Mean annual volume increment (MAVI) was done by dividing MV with age of the tree. Volume of the third commercial thinning schedule was calculated as a product of MV and stems removed. Estimation of tree biomass in kg for both above ground (AGTB) and below ground (BGTB) was done by Equation 3 and 4 respectively. Total biomass was obtained by summing AGTB and BGTB. Mean biomass (MB) was obtained as a ratio of total biomass and total number of measured trees. Mean annual biomass increment (MABI) was calculated as MB divided by age of tree. Carbon stock in kg was determined as 49% of the total biomass. Mean carbon (MC) was obtained by summing the individual tree carbon divided by total number of measured tree. Mean annual carbon increment (MACI) was done through dividing MC by age of the tree (Munishi *et al.*, 2000, Pokhrel and Mandal, 2019, Temu *et al.,* 2015). The estimation of values in ha basis was done by individual tree value divided by area of the sample plot.

Table 3.3: Models used to estimate yield, Stems removal and biomass

Equation	No	Source
$H=1.3+((Dbh^2)\div(7.9693+0.03006\times Dbh^2))$	1	Malimbwi (2016)
$V=\exp(1.033835+0.489679\times\ln(Hdom)+0.9954\times\ln BA)$	2	Malimbwi (2016)
$AGTB=0.1711\times Dbh^{2.0047}\times H^{0.3767}$	3	Zahabu *et al.* (2016)
$BGTB=0.0279\times Dbh^{1.7430}\times H^{0.7689}$	4	Zahabu *et al.* (2016)

Where: H is the total tree height, Dbh is the diameter at breast height, V is the tree volume in m^3, Hdom is the dominant height in m, BA is the basal area in m^2, *ln* is the natural logarithm, *exp* is the exponential, AGTB is the above ground tree biomass in kg and BGTB is the below ground tree biomass in kg.

The estimated information on prices and quantities of volume per ha, tons of carbon per m^3 and removed stems per ha was used to determine the benefits of the surveyed stands. The estimated information on costs and benefit was used to calculate net benefit for round wood production and carbon sequestered for total amounts estimated from AGB and BGB using data estimated from forest inventory. Estimation of carbon revenue was done by converting carbon stock into tCO_2e per ha by multiplying it by 44/12 the molecular weight over carbon (Chayaporn *et al.*, 2021, Temu *et al.,* 2015). The obtained volume in m^3 per ha and carbon in tCO_2e per ha quantities were converted into revenues by multiplying it with average price of each quantity. Net present value (NPV) was used to assess profitability of wood production and carbon sequestration. Discount rate of 9% was used to discount net benefit for NPVs of carbon sequestration and wood production estimation because it is the lending rate used in agriculture and forest projects in Tanzania. According to this criterion, an investment is economically efficient if the NPV is greater than zero. Equation 5 was adapted to estimate NPVs for Carbon storage and round wood production (Dorner Jr and Stein de Quadros, 2019, Seta *et al.,* 2021, Temu *et al.*, 2015).

$\mathbf{NPV = \sum ((Benefits - Costs)_t) \div ((1 + \mathit{r})^{\mathit{n}})}$----------------------Equation 5
Where, NPV = Net Present Value, r = Discount rate, t = Time (Year) of running project, $(\text{Benefits-Costs})_t$ = Net Benefits at Year t, n = Number of years in the project.

3.3 Results

3.3.1 Operating costs and selling prices

The average establishment expenses per ha observed of seedlings production was TZS 239,905.98, land preparation was TZS 178, 325.38, and planting was TZS 686,729.88. The average management expenses per ha observed of weeding was TZS 1,374,186.34, pruning was TZS 177,830.68, thinning was TZS 123,538.80 and protection was TZS 264,435.26 (Table 3.4). The selling prices of poles in the first and second thinning schedule was TZS 1,000/- and TZS 2,000/- respectively. However, the observed average selling price of commercial thinning volume in the third thinning schedule and final harvests (clear-felling) is TZS 67,500/- and TZS 743,129.20 respectively. Moreover, the global carbon average price was US$ 5 per tCO_2e which is equivalent to TZS 12,700/- (1US$ = TZS 2,540/- exchange rate of July, 2023).

Table 3.4: Average Establishment and Management Costs in TZS per ha

Cost item	TZS ha^{-1}	Rotation age (years)				
		20	30	40	20	40
		3 thinning schedule			2 thinning schedule	
Seedling Production	239,906.0	239,906.0	239,906.0	239,906.0	239,906.0	239,906.0
Land preparation	178,325.4	178,325.4	178,325.4	178,325.4	178,325.4	178,325.
Planting	686,729.9	686,729.9	686,729.9	686,729.9	686,729.9	686,729.
Weeding	1,374,186.3	13,741,863.0	13,741,863.0	13,741,863.0	13,741,863.0	13,741,863.
Pruning	177,830.7	355,661.4	355,661.4	355,661.4	355,661.4	355,661.
Thinning	123,538.8	370,616.4	370,616.4	370,616.4	247,077.6	247,077.
Protection	264,435.3	5,288,705.2	7,933,057.8	10,577,412.0	5,288,705.2	10,577,412.0
Total costs TZS		**20,861,807.3**	**23,506,159.9**	**26,150,514.1**	**20,738,268.5**	**26,026,975.3**

3.3.2 Yield, biomass and carbon sequestration

Forest management practices had a distinctive effect on wood volume, biomass and carbon sequestration. Among the management scenario the highest value of wood production was found in scenario S2 which was 821 m^3/ha whiles the lowest values of 249 m^3/ha was observed in scenario S5. Highest values of above ground biomass, below ground biomass and carbon sequestration was 18.7 m^3/ha, 4.3 t/ha and 41.3 t/ha respectively in S2 and S4 scenarios while the lowest values was 9.1 t/ha, 2.2 t/ha and 20.3 t/ha were observed in S3 and S5 scenarios in both implemented thinning schedules (Figure 3.2).

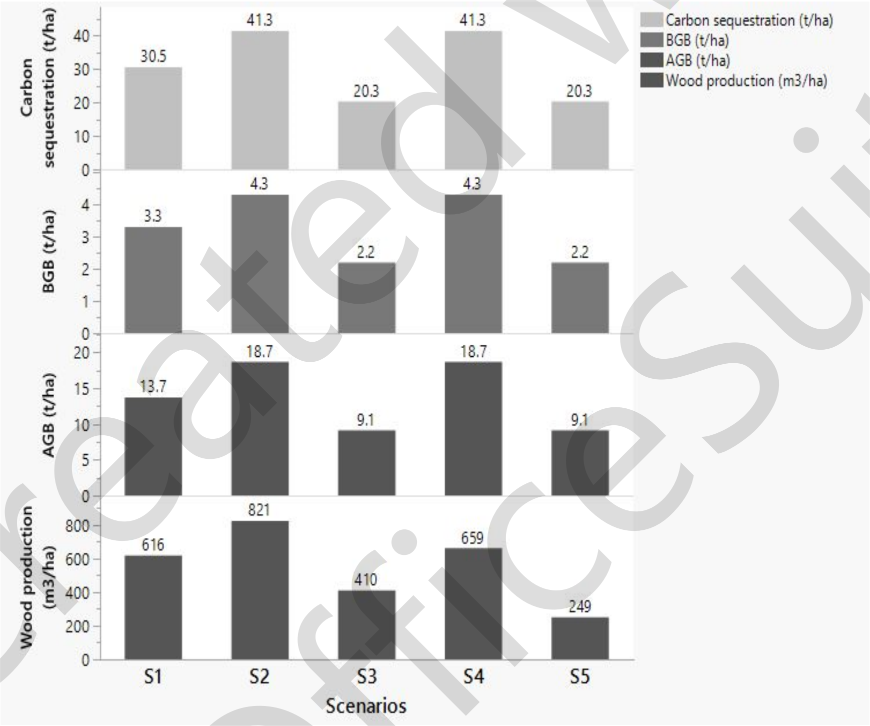

Figure 3.2: Wood volume, biomass and carbon sequestration under forest management scenarios.

S stand for scenario

3.3.3 Economic benefits

The results revealed that the NPV value of wood production in three implemented thinning schedules in the S1, S2, and S3 scenarios was TZS 22,917,213.8, TZS 7,714,474.7and TZS 43,088,012.5 per ha respectively. The NPV values of wood production in two implemented thinning schedules was TZS 3,627,693.8 and TZS 21,505,332.2 per ha in the S4 and S5 scenario respectively. The highest NPV value for wood production was found in scenario S3 while the lowest NPV value was observed in scenario S4. However, the NPV values of the combined wood with carbon in the three implemented thinning schedules was TZS 24,300,963.0, TZS 9,317,621.6 and TZS 44,104,826.5 per ha in S1, S2, and S3 scenarios respectively. The NPV values of the combined wood and carbon in the two thinning schedule was TZS 5,179,901.1 and TZS 22,471,206.5 per ha in S4 and S5 scenarios respectively. Values of NPV for wood production and combined wood production and carbon sequestration were observed to be highest in three implemented thinning schedules of scenario S3 than in S4 and S5 scenarios of the two thinning schedules. The NPV for carbon sequestration was negative for all scenarios (Figure 3.3).

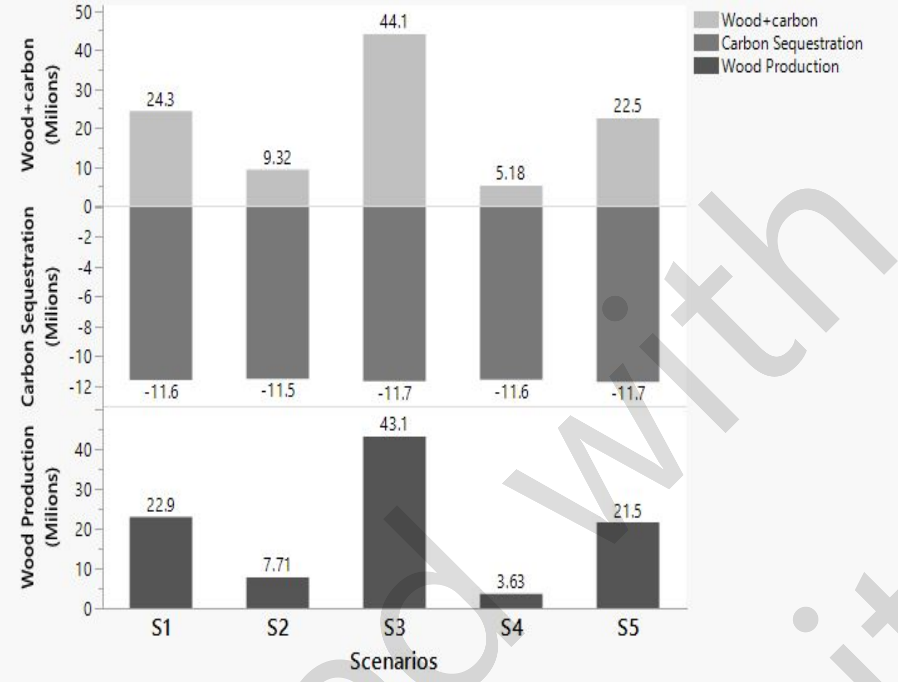

Figure 3.3: Net Present Values (in TZS/ha) under forest management scenarios

S stands for scenario

3.4 Discussion

Forest management practices had a clear effect on provision of ecosystem services and economic benefits in the study area. This study revealed that scenario S3 is more reliable in Teak forest management for combined wood production and carbon sequestration in the study area. In general, increased wood production and carbon sequestration of Teak forests lead to higher climatic and economic benefits was influenced by forest management practices. Hiltunen *et al.* (2021) and Kolo *et al.* (2020) reported that forest management practices maximized the economic benefits and climatic amelioration. However, Forest management practices in S2 and S4 scenarios improved the ability of Teak forests to produce wood biomass and consequently sequester carbon compared to business as usual in scenario S1. Although, both scenarios showed that wood production and carbon stock was increasing as thinning schedule increases regardless of rotation age which affected wood biomass and carbon sequestration positively as results of implementing heavy thinning intensity. The observed results of this study could be compared with findings of the study conducted by Mendez and Rico (2019), Palleto *et al. (*2017) and Rahmawati *et al*. (2022) who observed heavy thinning intensity practices enhances highest wood production and carbon sequestration. Moreover, it have been found in results of scenario 3 that implementing heavy thinning intensity and three thinning schedule with 20 years optimal rotation age improved NPV value of combined wood production and carbon sequestration positively. The results of this study are supported by the findings of Derwisch *et al*. (2009), Kanninen *et al*. (2004), Mendez and Rico (2019), Mgoo *et al*. (2022), Wirabuana *et al*. (2022), and Zagade *et al*. (2022) who reported that for Teak wood production and carbon storage objectives heavy thinning intensity in the first and second thinning schedules offer greater advantage than moderate thinning intensity. Yet, on the other hand investing in wood production only has greater returns than investing in carbon sequestration although the study showed that carbon sequestration can be achieved high with management goals to maximize wood production. The study conducted by Dai *et al.* (2017), Häyhä *et al*. (2015), Keleş, (2010), and Pohjanmies *et al*. (2017) explained that maximizing wood production also increases carbon storage and they found that wood production are positively correlated with carbon storage.

3.5 Conclusion and Recommendations

3.5.1 Conclusion

Generally, decreased clear-felling age with 3 thinning regimes was the most suitable management for *Tectona grandis* stands when climatic and economic benefits managed together. The climatic benefit gained from forest management decreased the NPV when carbon stock was prioritized. However, high NPV could be simultaneously achieved by targeting combined goal of wood production and carbon stock. The findings depict that the climatic and economic benefits was probably influenced by thinning intensity implemented in the first and second regimes. The study revealed that adopting S2 scenario had high value increment of wood production, AGB, BGB and carbon sequestration while low NPV in contrast to S3 scenario. Also, the study found that S3 and S5 scenarios had similar values of AGB, BGB and carbon sequestration but high value of wood production and NPV in S3 scenario. The study revealed that forest management practices improved both climatic and economic benefits.

3.5.2 Recommendations

To ensure better provision of ecosystem services and climatic benefits it is recommended that plantation managers to consider a tree rotation age of 20 years and 3 thinning regimes at age 5, 10 and 15 years. However, to ensure better returns from a thinned commercially Teak forest plantation it is recommended that heavy thinning in the first and second regimes be carried out to encourage large diameter tree which promises high profitability. Furthermore, it is recommended that the current Technical Order No. 1 of 2021, the recommended 2 thinning regimes for spacing of 2.5 x 2.5 m be changed to 3 to ensure better gain in volume but also to store carbon to a great extent. It is also recommended that Teak forest plantation owners should engage in carbon business because it gives net revenue and NPV when considering a combined goal of timber production and carbon stock compared to a plantation managed for one objective of timber production only.

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CHAPTER FOUR

4.0 Key Contribution, Conclusion and Recommendations

This chapter describes the key contributions made by the study to the body of existing knowledge. Furthermore the chapter narrates the conclusions and highlights recommendations of the study.

4.1 Key Contribution of the study

This study has made contribution to the existing knowledge of forest management practices of Teak plantation on stand parameter growth, yield and economic benefits. In chapter two the study has shown that diameter growth is low without adequate and timing of thinning operation. However, the study found that implementing thinning treatments on time alleviates horizontal and vertical competition. The study provides the understanding of the satisfactory stems needed to utilize resources in each consecutive thinning and during the clear-felling time. The study also predicts that better diameter growth is influenced by site classes and effective thinning done by competent technical staff.

In chapter three the study revealed that the employed thinning intensity procedure and rotation age suggests high revenue gain. The study predicts that thinning schedules and rotation age contributed more to the economic benefit of climatic and wood production. The study revealed that the NPV of the Carbon storage and wood production was increasing as intensity increases and rotation age decreases. This study found that establishment and management costs are decreasing as rotation age decreases influencing high NPV.

4.2 Conclusion and Recommendations

4.2.1 Conclusion

Generally, thinning had a positive effect on growth and revenue generation of *Tectona grandis* stands at Longuza forest plantation. Based on the findings, the study concluded that adequate and timely thinning operations improved growth and climatic and wood benefits of the plantation. Forest management practices had a significant effect on profitability. The results demonstrated that *Tectona grandis* plantation is profitable under management of heavy thinning intensity and three thinnings however delayed and inadequate thinning operations impede the diameter growth due to congested stems resulting to high yield of thin trees and failure to meet revenue goals.

4.2.2 Recommendations

i. Thinning operations should be implemented at the right time and required intensity as scheduled in the Technical Order No 1 of 2021. It is evident that timely and intensive thinning implementation leads to better results in improving timber quality and maximising income, so it should be prioritised in managing Teak forest plantations.
ii. To ensure sufficient growth and yield forest management professionals and woodlot owners should better understand site class before establishing forest plantations and woodlots.
iii. Heavy thinning in the first and second thinning, short rotation age and three thinnings should be given top priority in Teak Plantation to ensure better provision of ecosystem services, climatic and economic benefits.
iv. Competent technical staff and adequate and timely disbursement of fund are recommended to ensure close follow up and minimize thinning operations delays.
v. In future studies, I recommend study to be conducted on evaluating thinning intensity and timings on enhancing stand resilience to climate related stresses

Kuhusu Tasnifu Hii

Utafiti huu ulifanyika katika Msitu wa Hifadhi wa Shamba la Miti ya kupandwa jamii ya msaji la Longuza lililopo katika Wilaya ya Muheza, ukilenga kubaini athari ya uchenguaji kuhusu parameta za viunga zilizochaguliwa na uzalishaji wa mapato yatokanayo na msaji. Taarifa kuhusu unene wa kipenyo cha mti katika usawa wa matiti, urefu wa miti mitatu yenye unene tofauti katka kila ploti, gharama za kuanzisha na kusimamia viunga, bei za nguzo katika uchenguaji wa kwanza na pili, hewa ukaa, ujazo wa miti katika uchenguaji wa tatu na iliyofikia hatua ya kuvunwa zilikusanywa. Faida za kiuchumi ulikokotolewa kwa mbinu ya punguzo katika mtiriko wa faida na matumizi. Utafiti huu ulibaini kuwa uchenguaji ulisababisha ukuaji wa kipenyo, mavuno ya ujazo wa mti na uzalishaji wa mapato yatokanayo na mchanganyiko wa hewa ukaa na mazingira ya kiikolojia. Utafiti kuhusu uchenguaji katika spishi ya Msaji kukabiliana na matatizo yatokanayo na mabadiliko ya tabia nchi unapendekezwa.