THINNING COMPLIANCE AND EFFECTS ON GROWTH AND YIELD OF *TECTONA GRANDIS* AT MTIBWA FOREST PLANTATION, MOROGORO, TANZANIA

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A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF MASTER OF SCIENCE IN FORESTRY OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

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ABSTRACT

Tectona grandis L.f., a valuable hardwood grown in plantations in about 70 tropical countries. Teak long term market prospects are promising. This study assessed thinning compliance and effects on growth and yield of Teak at Mtibwa forest plantation because there is limited detailed information. Study results will be useful to TFS and other forestry stakeholders with regard to tending operations. The plantation was stratified into 4 age groups (6-10, 11-15, 16-20 and >20 years) capturing all age classes for thinning. Ninety two circular plots of 9.78 m radius were laid out in 23 purposively selected compartments. Compartment thinning history, heights for 3 fattest trees, Dbh and stem quality of all trees in a plot were recorded. Results show 57% and 43% of thinned area is overstocked and understocked respectively as opposed to the thinning schedule. On average, second and third thinnings have significantly higher ($P<0.05$) SPH deviations of 39% and 26% respectively whereas, first thinnings have 13% ($P>0.05$) deviations closer to the allowable 10%. Results show that 20% and 80% of first thinnings are delayed for one and two years respectively. Second thinnings are well-timed by 25% but delayed for one and two years by 37.5% each. Third thinnings are delayed for one and two years by 50% each. Site class I results indicate inadequate thinning affects Dbh growth by 6-10% but dominant height is unaffected. Stocking, basal area, and volume are higher by 15-69%, 4-118% and 3-149% respectively. However, VMAI results are lower by 5-26%. Results indicate 73-80% of trees in compartments have stem quality 2. The effect of thinning on stem quality is not established. Compliance to the thinning schedule is recommended to attain the projected mean 40 cm Dbh at rotation age. Future yield predictions for management planning must include relative correction factors ranging from 0.57–2.18.

DECLARATION

I, JEREMIAH MGANGA GUMADI, 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.

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DEDICATION

This work is dedicated to my beloved parents, Mganga Jeremiah Kazi and Devota Mganga Kazi, who wholeheartedly played a role in laying down the foundation for my education and secondly to my offspring as an inspiration for their academic life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PLATES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND SYMBOLS

Cm	centimetre
Comp	Compartment
Dbh	Diameter at breast height (cm)
DCAI	Dbh current annual increment
DMAI	Dbh mean annual increment
FAO	Food and Agriculture Organization of the United Nations
FBD	Forestry and Beekeeping Division
FP	Forest plantation
FRIM	Forest Research Institute Malaysia
G	Basal area per hectare (m^2/ha)
GPS	Global Positioning System
Ha	Hectare
HCAI	Height current annual increment (m/year)
Hdom	Dominant height (m)
HMAI	Height mean annual increment (m/year)
ISTF	International Society of Tropical Foresters
KVTC	Kilombero Valley Teak Company
M	Metre
M^3	Cubic metre
MNRT	Ministry of Natural Resources and Tourism
N	Number of stems per hectare
NACRML	Nepal Australian Community Resource Management and Livelihoods Project
P	Project
RS	Relative spacing index
SPH	Stems per hectare
Spp	Species
V	Volume per hectare (m^3/ha)
VMAI	Volume mean annual increment (m^3/ha/year)
VPAI	Volume periodic annual increment (m^3/ha/year)

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Tectona grandis L.f. (Teak) is one of the few emerging valuable hardwood species that has been grown increasingly in planted forests in about 70 tropical countries throughout tropical Asia, Africa, Latin America and Oceania (Kollert and Kleine, 2017). Global Teak plantations are estimated to cover 4.35 to 6.89 million hectares (ha) of which more than 80% grow in Asia, about 10% and 6% in Africa and tropical America respectively. On the other hand, natural Teak forests though substantially declining cover an estimated area of 29 million ha in India, Lao PDR, Myanmar and Thailand, nearly half of which are from Myanmar (Kollert and Kleine, 2017). Total log production is predicted to 6.6 billion m^3 by 2025 (Mollick *et al*., 2005).

Large scale establishment of exotic forest plantations in Tanzania (Tanganyika by then) commenced under the British rule (1920 - 1961) and was mainly based on species and provenance trials, and successful inoculation with suitable mycorhiza (Nshubemuki *et al*., 2001). The most important industrial plantation species are Pines (*P. patula*, *P. elliottii* and *P. caribaea*), *Cypress* sp, *Eucalyptus* sp and *Tectona grandis*. Total plantation area in Tanzania mainland is 554 500 ha (MNRT, 2015). Public Teak plantations cover about 2 874 ha (planted): 1 346 ha, 1 354 ha and 174 ha in Longuza, Mtibwa and Rondo forest plantations respectively (Ngaga, 2011). The dominant Teak private sector player, Kilombero Valley Teak Company (KVTC) covers 8 150 ha of planted Teak (CDC, 2019).

Teak plantations are known to exhibit a wide range of origin related variation in growth and wood characteristics. Most of the plantations, however, were established with seeds of uncertain origin and quality and more recently with clones being produced in countries such as Brazil, Costa Rica, Côte d’Ivoire, India, Indonesia, Malaysia, Tanzania and Thailand (Kollert and Kleine, 2017). Teak is rather flexible to soil requirements as it grows on a variety of soils of different geological formations, yet the quality of its growth depends on depth, structure, porosity, drainage and moisture holding capacity of the soils. Generally, deep soils with good drainage are most desired (Kollert and Kleine, 2017).

The selection of the initial spacing is the first critical activity, as it determines future standing stock management, plant production needs, and soil preparation operations. Nevertheless, off season planting due to budgetary limitations and lack of planning are common sources of failure, mainly in public projects (Kollert and Kleine, 2017).

The opportune execution of weeding and pruning is crucial including also the first thinning which should be made shortly after canopy closure (Kollert and Kleine, 2017). In the simplest terms, thinning is an effort to increase the growing space available to the residual trees. This allows the site's growing potential to be captured on fewer, larger trees instead of many small trees (Scanlon, 1992; Evans, 1992 in Chamshama and Malimbwi, 1996; FAO, 2002; Kanninen *et al*., 2004). In dense Teak plantations, the first thinning should be made as early as possible (between age 3 and 8 years) depending on site quality, initial spacing/survival, and expectations of any commercial products (e.g. biomass, poles). In Latin America, where short rotations are desired (16 - 25 years), a first non-commercial early thinning is recommended at ages 3 - 6 years (Morataya *et al*., 1999). Criteria other than age are used to prescribe thinning operations. These include average height, which accounts for the effect of site quality on stocking. In Costa Rica, first thinning is recommended when trees reach 8.0 m height, at 3 - 6 years old (Chaves *et al*., 2016); and 9 - 9.5 m in Malaysia (Krishnapillay, 2000). In Tanzania, first thinning for Teak public plantations is recommended at age 5 years and later at ages 10 and 15 years

(FBD, 2003) and differs from private plantations (Appendix 1). In dense stands, after canopy closure, tree crown length and lateral expansion are rapidly reduced, leading to a notorious reduction in diameter increments if thinning is delayed for too long or inadequately done (Morataya *et al*., 1999).

In view of the declining supply of quality Teak from natural forests, the long term market prospects of plantation grown Teak appear promising provided that wood quality and yield can be improved through the use of superior planting material, proper site selection and best management practices (Kollert and Kleine, 2017). This study will look at thinning compliance and effects on growth and yield of Teak grown at Mtibwa forest plantation.

1.2 Problem statement and justification

Yield and predominantly the quality of Teak timber will be the two overriding commercial factors in future (Chaix *et al*., 2008). Monitoring growth and yield dynamics is essential to facilitate adequate management responses.

Thinning being an important silvicultural operation, must be done at the right time, in the right way, and with the right intensity. On the contrary, various reports show that the operation in many public plantations in Tanzania does not follow the prescribed schedules (Munishi and Chamshama, 1994; Nshubemuki *et al*., 2001; Balama, 2010 in Ngaga, 2011; Kiangi, 2010 in Ngaga, 2011). Thinnings whenever carried out have been fewer and lighter than recommended, resulting to standing volume distribution on many small trees rather than just few of better value per cubic meter (Chamshama and Malimbwi, 1996).

However, little detailed information on thinning compliance and effects on growth and yield for Tanzanian Teak plantations is available. This study aims at filling the gap for Teak grown at Mtibwa forest plantation.

Study results will be ideal for use by Tanzania Forest Services Agency (TFS) and other stakeholders in the forestry sector with regards to forest productivity. They will highlight issues requiring attention in the management of Teak plantations in order to meet expected revenue objectives from small harvesting units while maximizing unit area profits and meeting world demands.

1.3 Objectives

1.3.1 Main objective

To assess thinning compliance and effects on growth and yield of *Tectona grandis* at Mtibwa forest plantation.

1.3.2 Specific objectives

i) To assess level of compliance to Teak thinning schedule;

ii) To assess growth and yield on thinned and unthinned stands of Teak; and

iii) To assess stem quality of Teak in thinned and unthinned stands.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Thinning intensity and types

The development of a forest plantation is not only determined by natural tree growth, but also by the weight and type of the prescribed thinning operations. Thinning operations reduce stand density and modify its structure, consequently influencing subsequent medium and long-term stand development (Gadow and Hui, 1998). Numerous efforts have been made over the years to develop a terminology for describing different types of thinnings. Some authors use graphs such as Fig. 1 to define a thinning operation (Dengle, 1982; Kramer, 1988 in Gadow and Hui, 1998).

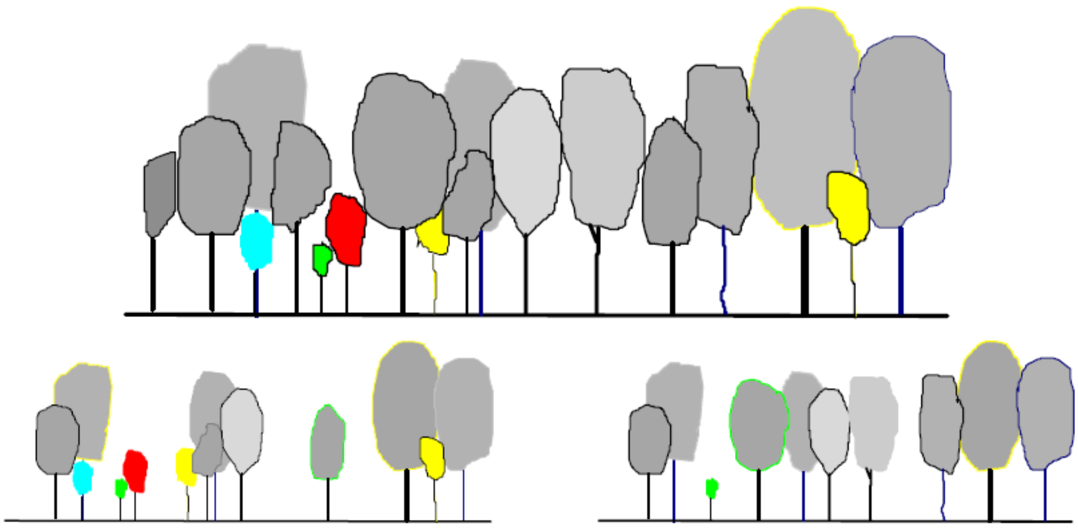


Figure 1: Schematic representation of two different thinning operations in an even-aged beech stand. Above: stand before the thinning; below left: after a heavy high thinning; below right: after a moderate low thinning

Source (Dengle, 1982; Kramer, 1988 in Gadow and Hui, 1998)

The number of terms that can be used to describe different thinning operations is limited. One of the first authors to recognize this problem was Franz (1972) in Gadow and Hui (1998), who introduced a thinning factor for describing simultaneously the type and weight of a thinning. Within the framework of a stand model, it is necessary to use variables defining the weight and others characterizing the type of a thinning (Gadow and Hui, 1998).

2.1.1 Thinning weight/intensity measures

A measure for quantifying thinning weight at the stand level, which is sometimes used in conjunction with a yield table, is the reduction in the degree of stocking (B°) caused by the thinning. The degree of stocking is the basal area per hectare (ha) expressed as a proportion of some normal basal area, defined by a yield table. Kramer (1990) in Gadow and Hui (1998) presents a practical method for estimating thinning yields based on the reduction of B°.

Another popular measure for defining the thinning weight is the change in relative spacing first introduced by Hart (1928) in Gadow and Hui (1998), also known as the Hart-Becking spacing index or Spacing percent. Relative spacing is defined by the average distance between the trees, expressed as a proportion of dominant stand height (Equation 1) if square spacing is assumed (Gadow and Hui, 1998).

$$RS = \frac{10\,000}{Hdom\sqrt{SPH}} \quad \text{……………………....Equation 1}$$

Where,

RS = relative spacing or spacing percent,

Hdom = stand dominant height (m), and

SPH = stems per ha.

Equation 1, when used for developing thinning guides where RS is being specified, must be solved for SPH.

A spacing percent of 16%, 19%, 22% and 25% is considered as light thinning, moderate thinning, heavy thinning and very heavy thinning respectively. Spacing percent is simple to follow and is not closely related to either age or site quality. It is sometimes used for constructing thinning ranges which define the maximum and the minimum number of trees for a given stand height. Gadow and Hui (1998) provided a hypothetical thinning range (Fig. 2).

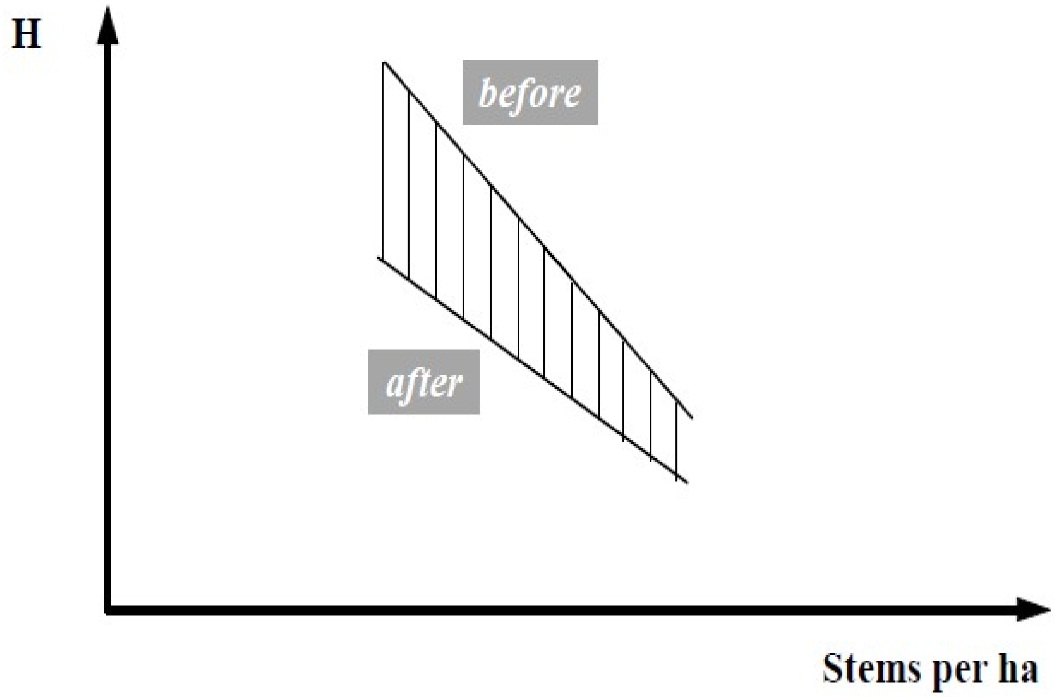


Figure 2: Hypothetical thinning range defining the maximum and minimum number of trees for a given stand height
Source (Gadow and Hui, 1998)

When a stand has reached the line marked *before*, it should be thinned to avoid undesirable crowding and associated instability. The difference between the *before* and *after* ordinate values for a given height defines the thinning weight, i.e. the stems per ha that should be removed during the thinning. Examples of thinning ranges for even-aged forests are given by Abetz (1975) in Gadow and Hui (1998) for European spruce, by Lewis *et al*. (1976) in Gadow and Hui (1998) for Australian *Pinus radiata* and by Gadow and Bredenkamp (1992) in Gadow and Hui (1998) for pine plantations grown in the summer rainfall areas of South Africa.

Specific thinning ranges may be developed to facilitate the planning of silvicultural operations. However, these decision aids should be used with caution because the weight of a thinning does not only depend on the tree species and the silvicultural objectives. Adjustments should also be made to accommodate abnormal stand conditions such as overcrowding (Gadow and Hui, 1998).

2.1.2 Thinning types

The future development of a forest is not only influenced by the weight, but also by the type of thinning, which is defined by the selective removal of specific members of the population (Gadow and Hui, 1998).

Thinning type refers to the crown class of the trees removed in relation to the ones retained (Chamshama, 2014). The main thinning types are systematic and selective thinning (NACRMLP, 2006). The type of thinning is also reflected by the change of the diameter distribution. At the stand level, diameter distributions are usually not available. In this case, the SG-ratio may be used (Equation 2) (Gadow and Hui, 19Equation 2

$$SG = \frac{(N_{thn}/N_{tot})}{(G_{thn}/G_{tot})}$$ Where:

SG = stocking-basal area ratio,

N_{thn}, N_{tot} = removed and total number of stems,

G_{thn}, G_{tot} = removed and total basal area.

2.1.2.1 Systematic thinning

This is also known as mechanical or line thinning. Under systematic thinning, predetermined spacing or pattern dictates the selection of trees to be removed (Chamshama, 2014). Trees are thinned following an objective and systematic procedure in which individual tree quality is not considered. It aims at removing every second or third row, etc. in a stand. Systematic thinning only reduces the number of stems per hectare without considering the quality of removed stems (NACRMLP, 2006). However, systematic thinning is the cheapest form of thinning as (a) little specialist knowledge is required (b) the need for supervision is small (c) trees do not need marking before thinning (d) take-down and extraction of felled trees is easier (Evans and Turnbull, 2004 in Chamshama, 2014). Besides the possibility of machinery use, systematic thinning is most suited to first thinning.

2.1.2.2 Selective thinning

Selective thinning is the type of thinning where trees are cut or left depending on the subjective judgment of the person marking the trees for removal. Contrary to systematic thinning, selective thinning can cause variation of both number of trees remaining and the kind of trees favoured. Selective thinning is therefore important in species with poor performance, so that best stems can be favoured (NACRMLP, 2006). This is the thinning type adopted at Mtibwa forest plantation. The operation is semi mechanized. Felling and crosscutting is done by chainsaws whereas delimbing and terrain transport (skidding) is done by manual labour (MNRT, 2018).

A tree classification system or a thinning assessment procedure must be in place to successfully implement the identification of which trees to remove and retain.

This eliminates as far as possible subjectivity engaged in marking trees for removal (Gadow and Hui, 1998). However, in practice at Mtibwa forest plantation, a tree to be removed is judged in terms of its stem quality (form, growth), spacing factor and diseased or abnormality (MNRT, 2018). Selective thinning is categorised into five main types as follows:

a) Low thinning

Commonly termed as thinning from below, entails removing weak trees from the lower crown positions allowing space for healthy taller, larger-crowned trees to grow. Dead or dying, suppressed or smaller less vigorous and dominant malformed trees are removed first, followed by the other crown classes upwards until the desired intensity is attained (Chamshama, 2014). It can be termed as light, moderate or high low thinning to refer to the intensity of a thinning.

Low thinning is costly as it involves removing many small trees, though marking trees for thinning is not difficult and as small trees are mainly cut, difficulties with take-down are not great. Low thinning tends to realize the highest site growth potential and, in the long term, are the most profitable (Evans and Turnbull 2004 in Chamshama, 2014).

b) High/crown thinning

Commonly termed as thinning from above, where by the removals are first chosen from among the dominant and co-dominant trees and only a limited number of the best dominants is left, common for old stands. Crown thinning favours a limited number of potentially excellent trees capable of producing the highest rate of value increment. However, it focuses more on removing immediate competing trees in the dominant and co-dominant classes (Wiedemann, 1935 in Gadow and Hui, 1998; NACRMLP, 2006). One of the characteristics of the method is the fact that the best trees (target trees) are re-evaluated at each thinning, since the relevant quality attributes of a target tree could change between successive thinning operations (Gadow and Hui, 1998). Fig. 3 shows the effects of a low thinning and a high thinning, in a 0.1 ha sample plot situated in a 60 year old beech stand (Gadow and Hui, 1998).

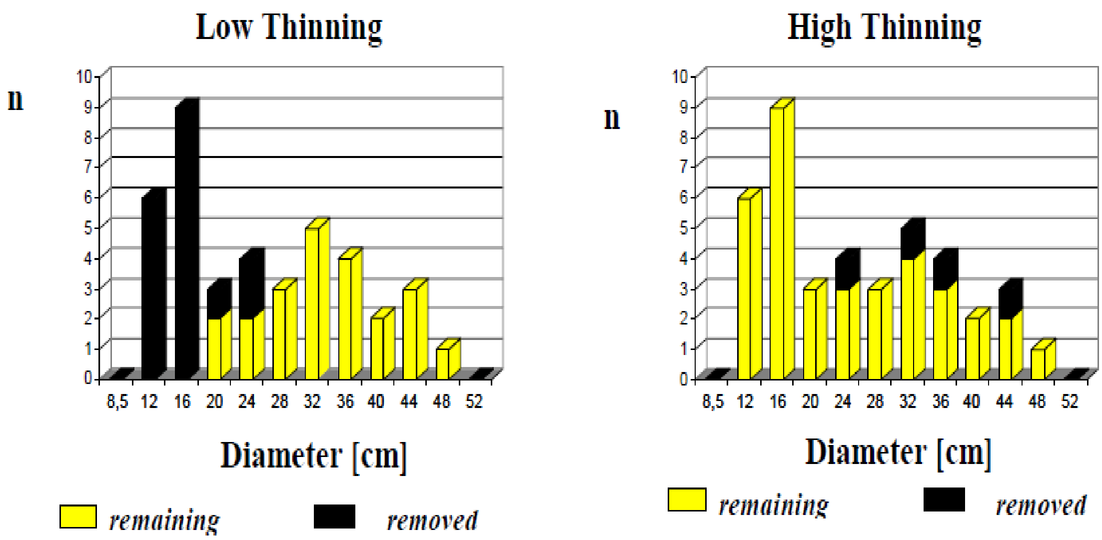


Figure 3: Change in the diameter distribution of a 60 year old beech stand, resulting from a low thinning (left) and a high thinning (right)
Source: (Gadow and Hui, 1998)

The weight of the two thinnings was approximately the same, with 15% of the basal area removed in the low thinning and 16% in the high thinning. However, the low thinning removed 45 % of the trees, the high thinning only 10 %, the difference being due to the type of thinning implemented (Gadow and Hui, 1998). Apart from being time consuming in tree marking, but when applied in younger stands it results into poor quality of final harvest as best trees are harvested during intermediate thinning operations.

c) Free thinning

This form of thinning involves a combination of approaches, removes trees from all crown classes and aims at favouring the development of selected evenly spaced trees from all classes (Chamshama, 2014).

d) Selection thinning

Also called extreme crown thinning, it favours trees of the best quality and may remove larger trees of marketable dimensions. It often results in larger average diameter of the thinned material than that of the remaining material (Chamshama, 2014). However, it is not widely practised in commercial plantations.

e) Queensland selection system

Before the first thinning final crop trees are selected (e.g. 400 SPH). In marking trees to cut during first thinning, the marker works along each row aiming to remove three out of a group of seven trees. A form of crown thinning is applied. Trees to remove are selected in the following order of priority: diseased or badly deformed; poor dominants and co-dominants competing with selected trees; trees with double or multiple leaders; any other trees competing with selected trees. The second thinning removes all remaining trees not selected, while the following thinnings remove poorer selected trees according to low thinning principles.

2.1.3 Measures of thinning type

Various objective measures of thinning types exist. The relation between mean diameter of removed trees (d) to mean diameter of the trees before thinning (D) has been used by a number of researchers (Braathe 1957, Joergensen 1957, Braastad 1975 in Chamshama, 2014) as described below.

When: d/D is 0.70 the thinning is low

d/D is 0.70 - 0.90 the thinning is severe low to light crown d/D is 0.90 - 1.00 the thinning is crown

d/D is over 1.00 the thinning is selection.

The relationship between percentage of number of trees removed (t) to percentage of volume removed (v) has also been used as a measure of thinning type (Vezina, 1963 in Chamshama, 2014) as described here under.

When: 1.40 or more, it is low thinning,

Around 1.00, it is crown thinning, and

Below 0.60, it is selection thinning.

Bevege (1967) in Chamshama (2014) put forward his Queensland thinning ratio as the ratio between mean basal area of thinnings and mean basal area of the stand before thinning. He classified the types of thinning as follows.

When: 0.43 - 0.56, it is low thinning,

0.57 - 0.81, it is severe low to light crown thinning,

0.82 - 1.00, it is severe crown thinning, and

Over 1.00, it is selection thinning.

Grayson and Johnson (1970) in Chamshama (2014) reported the use of the ratio between the average volume of the thinnings (v) to average tree volume before thinning (V) as a quantitative measure of thinning as follows.

When: 0.60, it is very low thinning,

1.00, it is neutral thinning, and

1.20, it is crown thinning.

Generally, all quantitative measures of thinning type are useful guides, but the d/D measure is used most and is the simplest. For the first thinning however, where many small trees are removed, the indices may not give a clear picture of the type of thinning (Braathe, 1957 in Chamshama, 2014).

2.2 Thinning timing

Hashim (1996, 2002) in Hashim (2003) suggests at 4 and 5 years based on the intersection of height mean annual increment (HMAI) and height current annual increment (HCAI) curves to commence the first thinning. The intersection equally applies for Dbh mean annual increment (DMAI) and Dbh current annual increment (DCAI) and volume mean annual increment (VMAI) and volume periodic annual increment (VPAI) curves (Hashim, 2003). The points of intersection of the curves indicate the optimum height, diameter and volume increments and the best time to conduct the first thinning (Hashim, 2003). In addition, this is most likely the onset of inter tree competition as suggested by Sibomana *et al*. (1997) to be between 4 and 5 years. Kanninen *et al*. (2004) in Costa Rica established based on the remaining stand volume (after thinning), tree size and rate of recovery the best thinning timing to be at 4 years removing 40 – 60% of the trees, or consecutively at 4 and 5 years removing 25% of standing trees in each year.

A heuristic modelling study in Venezuela by Quintero-Méndez and Jerez-Rico, (2017) showed that the minimum age for the first thinning is 5 years offering a small amount of commercial products. Earlier thinnings before 5 years have no scientific justification for financial optimality. In addition to that, very frequent and lighter thinnings are expensive and detrimental to growth response of the remaining trees. Moreover, the majority of the best thinning regimes obtained by the model consisted of two or three thinnings. The best thinning regime for both wood production and carbon sequestration consisted of three thinnings at 5, 10, and 19 years, removing 46.5%, 47.7%, and 29% of the total basal area, respectively.

In Thailand, for coppice teak based on DCAI decrease, slightly contrasting results suggested first thinning when the DCAI decreased at 5 – 6 years. Similarly, for stump-planted teak, the CAI analysis indicated after 5 years, silvicultural intervention might be required to increase the growth rate (Auykim *et al*., 2017).

The recovery of basal area and volume is faster in well-timed thinning operations than in delayed ones. This effect was evident just 2 years after thinning (Kanninen *et al*., 2004). Delaying thinning could impose intense inter-tree competition that eventually jeopardises stand growth and yield.

2.3 Thinning schedules and compliance

Teak, a premier wood was grown on rotations of 80 – 100 years unlike currently on shortened rotations of 20 – 25 years for commercial wood production (ISTF, 2009). Many countries employ shorter rotations for both veneer and sawlog production for relatively quick returns (Ball *et al.,* 1999).

Zaman (1985) in Kanninen *et al*. (2004) on Teak spacing and thinning guidelines study in Bangladesh reported that aging trees use canopy space less efficiently. This suggests intensive and frequent thinnings as stands age with time. However, SAIF (2000) proposes an allowable 10% deviation on the number of stems per ha (SPH) to be retained against scheduled values on thinning operations.

In Costa Rica, a density of 1111 stems per ha (SPH) at 3 m × 3 m spacing is now commonly accepted in place of the former 1600 SPH (Pérez and Kanninen, 2005a). Pérez and Kanninen (2005a) observed that despite heavy thinnings, some stand densities were still higher than the recommended for young teak stands in Costa Rica.

At Cepu, Eastern Java, an initial density of 3 300 SPH on open lands under Taungya agroforestry system is applied. About eleven frequent thinnings are conducted to 60 years resulting in 100 – 150 SPH that are clear felled at 80 years (Tanaka *et al*., 1998).

In Nilambur, Kerala, India, the Kerala Forest Department thinning schedule prescribes a first mechanical thinning at 5 years removing every alternate row to facilitate growth space. This is followed by selective thinnings removing at 10, 15, 20, 30, and 40 years 1 739, 318, 126, 103, 40 and 19 SPH respectively. Clear felling is carried out at 50 years with at most 155 SPH (Sreejesh *et al*., 2013).

At Karnataka State Forest Department, India, Teak forests are managed based on decade wise approved working plans. An initial spacing of 2 x 2 m and a rotation of 120 years is prescribed. Mechanical (systematic; row thinning) and silvicultural thinning regimes are prescribed as follows (Tewari *et al*., 2014);

i. First mechanical thinning in the 6th year (retaining about 1700 – 1800 SPH);
ii. Second mechanical thinning in the 12th year (retaining about 1000 – 1100 SPH);
iii. First silvicultural thinning in the 18th year (retaining about 700 – 800 SPH);
iv. Second silvicultural thinning in the 30th year (retaining about 500 – 550 SPH);
v. Third silvicultural thinning in the 38th year (retaining about 300 – 350 SPH); and
vi. An elite thinning at the end of 80th year (retaining about 150 SPH).

However, the prescription is not always rigorously adhered to. One of the many reasons is tree damage by elephants leading to extraction of such trees every year. However, many plantations are in a state of neglect (Tewari *et al*., 2014).

Ghana applies Ivory Coastan thinning schedules and yield tables due to similarities in soil and climatic conditions. An initial spacing of 3 m × 3 m with 1111 SPH, a 20 years rotation, and 2 – 4 thinnings before clear felling is prescribed (Wanders and Tollenaar, 2017).

The first tentative Teak thinning schedule for Tanzania prescribed 5 thinnings at ages 4, 8, 12, 16 and 20 years with initial and final stockings of 1680 and 250 SPH respectively and a rotation of 60 years (Appendix 2) (Ahlback, 1986). The current Teak thinning schedule for public plantations was issued in Technical Order No. 1 of 2003 (FBD, 2003). Chamshama (2016) in Malimbwi (2016) opined that the schedule was rather still tentative. It prescribes 3 thinnings at 5, 10 and 15 years with initial and final stockings of 1600 and 300 SPH respectively and a rotation of 30 – 40 years (Appendix 1).

From the private sector, Kilombero Valley Teak Company schedule (KVTC) prescribes 3 thinnings at ages 8, 13 and 20 years including an initial removal of multiple stems at age 2 years. It prescribes an initial stocking of 2500 and 1111 SPH before and from the year 2000 respectively a final stocking of 250 – 280 SPH respectively and a rotation of 30 – 32 years (Appendix 1).

Generally, the public sector schedule appears to be relatively heavier than that for KVTC because it has a higher initial stocking due to narrower spacing but the final stocking is similar to that of KVTC.

Most reports have found thinning schedules to be improperly carried out in many public plantations than in private sector plantations. Angyelile (2010) and Kiangi (2010) in Ngaga (2011) found no thinning was carried out at Sao Hill and Ukaguru plantations. The main reasons given for the neglect of thinnings were shortage of funds, lack of markets for unsawn thinnings, lack of plantation management skills and experience, traditional attitude by foresters against waste and lack of processing plants (Chamshama, 2011; Ngaga, 2011). Scientific or personal observations evidence for thinning schedule neglect in Teak plantations is undocumented, but they may not be an exception given the reasons above.

2.4 Effect of Site Quality and Thinning on Teak growth and yield

Tree and stand growth is limited by site quality and light interception (Scanlon, 1992). Forest site quality is relatively measured by site index based on the dominant height of trees at a specific age (Nugroho *et al*., 2015). Site index at 10 years of 21.71 m or more for better site and 18.08 m or less for low site have been reported (Ugalde and Vásquez, 1995 in Radío and Delgado, 2014). However, there is a high variability between 5 to 10 years, with a remarkable relation between the youngest plantations and site index from medium to good. The maximum and minimum site indices of 25 m (excellent) and 10 m (low) were respectively found for a 10 years old Teak plantation (Ugalde and Vallejos, 1998 in Radío and Delgado, 2014). For ages above 10 years a maximum and minimum of 28 m (excellent) and 20 m (good) respectively with an average of 24 m (excellent) has been observed, implying most plantations in Panama are in high quality sites. Plantations older than 25 years can be expected in an excellent site height up to 26 m (Gómez and Ugalde, 2006). Site index curves for Tanzanian Teak are shown in Fig. 4. 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 respectively at the reference age of 20 years (Laswai *et al*., 2016).

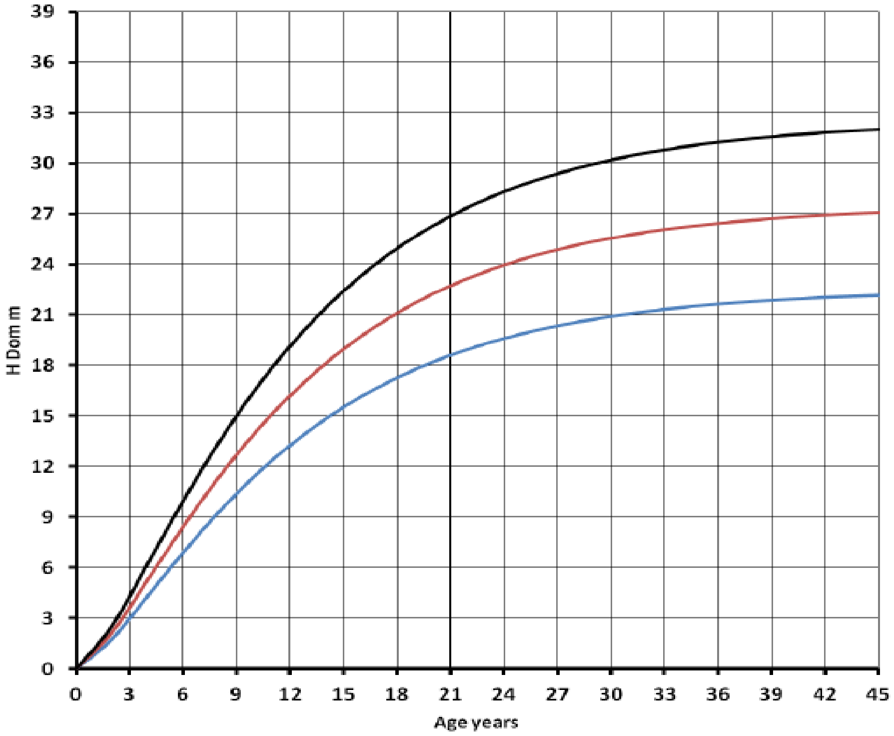


Figure 4: Site index curves for *T. grandis* in Tanzania (black, red, and blue colours in curves represent site classes I, II and III respectively)
Source: (Laswai *et al*., 2016)

Thinning is important so that tree can better utilize the site potential. Thus thinning is designed to leave the most desirable trees with improved stem form, diameter size and height and to provide intermediate financial returns from the sale of thinnings (Evans, 1992 in Chamshama and Malimbwi, 1996; FAO, 2002; Pérez and Kanninen 2005b). Thinning at an early age is important for stand hygiene, avoiding stress levels that may encourage pest and disease attack, increasing foliage biomass, sustaining rapid diameter growth and altering stand composition (Scanlon, 1992; Evans, 1992 in Chamshama and Malimbwi, 1996; FAO, 2002; Kanninen *et al*., 2004).

Thinning a stand reduces the number of trees competing for light, soil moisture, and nutrients therefore increasing growing space for both roots and crowns thus leading to increased canopy light levels for photosynthesis (Chamshama, 2014). Moreover, after thinning, more light reaches beneath the canopy and there is usually a resurgence of weed growth, increased breakdown of litter, and sometimes epicormic shoots on tree stems. Also the water table may rise and the ground becomes wetter, due to less demand for soil moisture and less interception of the rain by the canopy (Nebeker *et al*., 1985).

According to NACRMLP (2006) lessening of competition between trees has three main effects:

i. Lowering natural mortality: Natural mortality of trees in thinned stands is uncommon as trees survive longer and the ones becoming suppressed are usually thinned out anyway;
ii. Deeper crowns on remaining trees: The shaded lower branches of a tree receive more light and remain alive longer; therefore trees in thinned stands have deeper crowns; and
iii. The increased growing space surrounding a tree after thinning induces active growth of shoots, foliage and roots leading to crown expansion.

The effects of points (ii) and (iii) above result in a greater photosynthetic area on each remaining tree, thus increasing trees growth potential. If however, thinning is heavy and large gaps occur in the canopy, which only slowly become occupied, the total interception of light energy by the stand is less than optimal and some loss in total production could be expected.

Teak growth rate is highest during the first 10 years followed by a decline from 15 years on (Radío and Delgado, 2014). However, higher growth rates may expose the trees to risks of bending after the first thinning, as in certain sites in Costa Rica for trees with height/basal diameter ratio greater than 120 (Kollert and Kleine, 2017).

2.4.1 Diameter and basal area growth

Several studies have found that diameter of Teak stands increases with increased spacing after thinning (Ola-Adams, 1990; Kanninen, *et al*., 2004; Yahya *et al*., 2011). Thinning, like wider spacing, produces larger individual trees since they have larger crowns and eventually produce more wood. Certainly, there is generally a close relationship between crown diameter and stem diameter. Since the response to thinning is mainly diameter growth with height usually little affected, thinning changes tree shape causing the trunk to taper more rapidly (NACRMLP, 2006). All these effects of thinning only continue while the tree is expanding into the newly available growing space and before between tree competition again becomes intense. Therefore, if rapid growth of individual trees is sought, thinning is repeated at pre-determined intervals during the life of a stand (Chamshama, 2014).

Unthinned and unprunned Venezuela Teak trees were in the range of 25 – 35 cm dbh at 20 years (ISTF, 2009). At the same age, Malimbwi (2016) simulated for thinned stands quadratic mean Dbh to range from 22.7 - 33.8 cm at 20 years in Tanzania implying either wider espacement in Venezuela or relatively slow Teak diameter growth in Tanzania despite thinning interventions. However, highest dbh between 35 and 40 cm were reported by Kanninen *et al*. (2004). On the best sites in Myanmar and India, 50 year old plantations exhibited dbh of 60 cm (Krishnapillay, 2000). However, Pérez and Kanninen (2005b) in Costa Rica reported final mean dbh of 24.9 – 47.8 cm depending on rotation length and site quality. Zahabu *et al*. (2015) reported Dbh of 15.95, 20.79 and 25.9 cm at

2 x 2, 3 x 3 and 4 x 4 spacings respectively in a 14 years trial stand. However, at the same age but at 2.5 x 2.5 m spacing, Malimbwi (2016) simulated quadratic mean Dbh values of 17.2, 21.4 and 25.6 cm for site classes III, II and I respectively.

Heavily thinned Teak stands with wide spacing are able to produce higher diameter increment and consequently increased size of logs over low-thinned or unthinned stands due to higher turnover rate of the crown as new leaves quickly adapt to the better environment (Malimbwi *et al*., 1992a; Maliondo and Chamshama, 1996; Kanninen *et al*., 2004). In Malaysia, teak grown by the Forest Research Institute Malaysia (FRIM) shows an increment in diameter of 1.5 – 2 cm year^{-1} and 25 – 35 cm Dbh at 15 years (Radío and Delgado, 2014). In Guanacaste, Costa Rica the DMAI was from 1.5 or less and 2.0 year^{-1} or more in a low and high productivity site respectively (Ugalde and Vásquez, 1995 in Radío and Delgado, 2014). However, Malimbwi (2016) simulated relatively similar DMAI values of 1.3 - 1.9 cm year^{-1} and relatively lower dbh values of 19.1 - 28.4 cm at 15 years after commercial thinning in low and high productivity sites respectively.

In Guanacaste, Costa Rica basal area of more than 20 and less than 15 m^2 ha^{-1} in better and poor sites were reported respectively (Ugalde and Vásquez, 1995 in Radío and Delgado, 2014). Pérez and Kanninen, (2005b) reported stands with a full canopy closure with no evident extreme competition to have basal area varying between 13.5 and 21 m^2 ha^{-1}. These values are difficult to fairly compare because of missing age. Zahabu *et al*. (2015) reported different non-significantly differing basal area values of 17.38, 22.76 and 18.84 for 2 x 2, 3 x 3 and 4 x 4 spacings respectively for a 14 years old trial. Nevertheless, Malimbwi, (2016) simulated relatively lower basal area values of 9.3, 14.4 and 20.7 m^2 ha^{-1} for site classes III, II and I respectively at the same age.

On the contrary, Vincent (1962) in Hashim (2003) showed that Teak grown on alluvial soil had a basal area of 16.2 m^2 ha^{-1} at 9 years which is 36.2% higher than the basal area in Hashim, (2003). Equally higher basal area values of 17.3 and 13.1 at 9 years were reported by Sibomana *et al*. (1997) for 2 x 2 and 3 x 3 m spacings respectively than simulated values of 6.6, 10.3 and 14.7 m^2 ha^{-1} at 2.5 x 2.5 spacing for site classes III, II and I respectively at the same age (Malimbwi, 2016).

In Panama, Gómez and Ugalde (2006) reported basal area MAI (GMAI) of 2.6 and 1.3 m^2 ha^{-1} $year^{-1}$ for plantations aged less than 5 and greater than 15 years respectively. Conversely, Malimbwi, (2016) simulated relatively lower GMAI of 0.4 - 0.8 and 0.6 - 1.3 m^2 ha^{-1} $year^{-1}$ at ages 5 and 15 years respectively after thinning. Generally, heavy thinnings cause a drastic and difficult to recover reduction in basal area (Pérez and Kanninen, 2005b).

2.4.2 Height growth

Research on thinning versus height growth has established that height growth of the trees themselves is usually little affected or not affected by thinning at all (Malimbwi *et al*., 1992b; Malimbwi, 1997, NACRMLP, 2006). The slight differences in height growth may be explained by the removal of smaller trees during thinning operations.

Average stand heights of 6.7 m at 2 years, 21 m at 18 to 20 years, and 31 m at 84 years have been reported by Tanaka *et al*. (1998). On the best sites in Myanmar and India, 50 year old plantations exhibited heights of up to 30 m (Krishnapillay, 2000). Malimbwi (2016) simulated stand dominant height values of 18.2, 22.2 and 26.3 m at 20 years for site classes III, II and I respectively. However, Pérez and Kanninen (2005b) in Costa Rica reported mean total heights between 23.0 and 32.4 m, depending on rotation length and site quality. Zahabu *et al.*, (2015) reported average heights ranging from 19.52, 23.09 and 24.05 m for a 14 years stand under 3 spacing regimes: 2 x 2, 3 x 3 and 4 x 4 respectively.

However, at the same age but at 2.5 x 2.5 m spacing, Malimbwi (2016) simulated slightly lower dominant height values of 14.8, 18.1 and 21.4 m for site classes III, II and I respectively. Dominant heights of 21.7 m or more and 18.1 m or low at 10 years have been reported in highly and less productive places respectively (Ugalde and Vásquez, 1995 in Radío and Delgado, 2014). Conversely, Malimbwi (2016) reported relatively lower dominant height values of 11.4 and 16.5 m for poor and better sites respectively at 10 years.

In Panama, Gómez and Ugalde (2006) reported HMAI of 2.7 and 1.2 m year^{-1} for plantations aged less than 5 and greater than 15 years respectively. On the contrary, Malimbwi (2016) reported HMAI ranging from 1.1 - 1.6 and 1 - 1.5 m year^{-1} for thinned plantations aged 5 and 15 years respectively. The two studies indicate that younger stands in Panama grow relatively faster in height that those in Tanzania and vice versa for 15 years old and above stands.

2.4.3 Volume MAI and volume growth

Teak stand productivity is usually assessed by estimating total volume yield (m^3 ha^{-1}) or mean annual increments in volume (VMAI). For teak, VMAI of 15 – 20 m^3 ha^{-1} year^{-1} are considered excellent; whereas, MAI below 6 m^3 ha^{-1} year^{-1} is at the lower limit for profitable plantations (Kollert and Cherubini, 2012). However, in Teak plantations, VMAI should be interpreted with caution and be accompanied with additional explicit information on average tree dbh and age, as volume yields are affected by stand density. High VMAI can be associated with small average tree diameters, i.e. high volume increments per ha are easy to obtain in unthinned plantations (Fig. 5) (Kollert and Kleine, 2017).

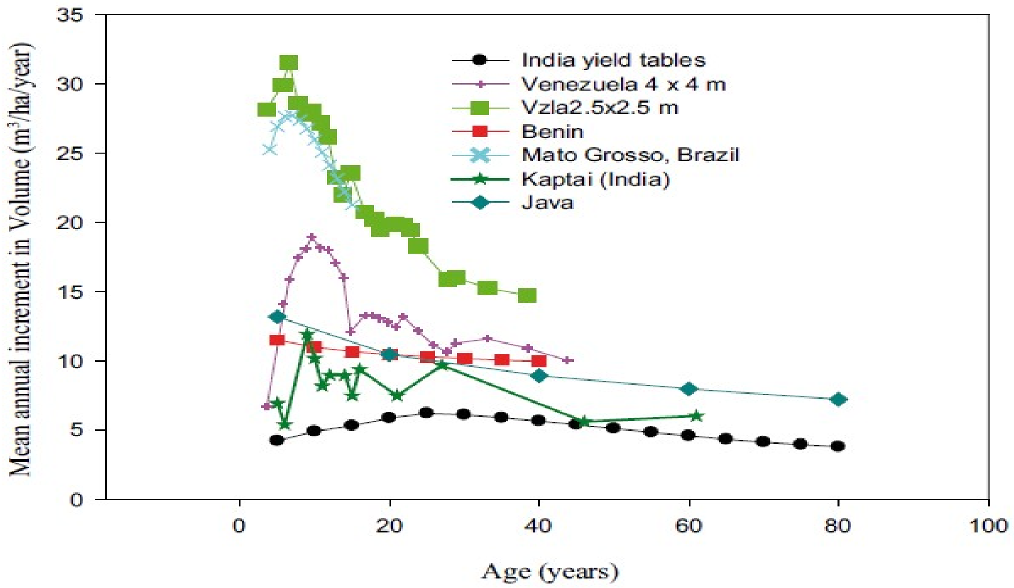


Figure 5: Volume mean annual increment for thinned and unthinned stands

Source: (Kollert and Kleine, 2017)

Teak plantations under favourable conditions exhibit growth rates varying between 10 and 20 m^3 ha^{-1} $year^{-1}$ in the first years. However, growth falls to the general reported level of 4 to 8 m^3 ha^{-1} $year^{-1}$ as the plantation ages (Htwe, 1999; Cao, 1999 in Krishnapillay 2000). A study by Yahya *et al*. (2011) in a 10 years old Teak plantation found VMAI to increase with increasing thinning intensities (Table 1).

Table 1: Teak volume and MAI increase with thinning intensity

Parameters	**T1**	**T4**	**T3**	**T2**
Volume (m^3 ha^{-1})	107.60 – 117.25	86.00 - 97.76	92.72 – 110.87	92.83 – 108.05
VMAI ($m^3 ha^{-1} year^{-1}$)	9.84 – 10.24	16.35 – 16.66	17.66 – 18.45	20.73 – 21.15

T1, T2, T3 and T4 = unthinned (0), 200, 300 and 400 stems ha^{-1} respectively.

Source**:** Yahya *et al*. (2011)

In addition to fine growth characteristics and superior timber qualities, Teak is reported to have a VMAI of 4 to 18 m^{3} ha^{-1} yr^{-1} on good sites (Evans, 1982) in Jayasankar *et al*. (1999). In Guanacaste, Costa Rica VMAI of 12 or less and 18 m^{3} ha^{-1} year^{-1} or more in low and high productivity sites were respectively reported (Ugalde and Vásquez, 1995 in Radío and Delgado, 2014). However, Pérez and Kanninen (2005b) in Costa Rica reported depending on rotation length and site quality VMAI of 11.3 to 24.9 m^{3} ha^{-}1 year^{-1}. In Ghana, Teak has a growth rate of 15 m^{3} ha^{-1} year^{-1} (Wanders and Tollenaar, 2017). In Panama, VMAI between 12.2 m^{3} ha^{-}1 year^{-1} in trees over 15 years to 15.8 m^{3} ha^{-}1 year^{-1} in trees younger than 5 years has been reported by Gómez and Ugalde (2006).

In Tanzania, Madoffe and Maghembe (1988) reported VMAI ranging from 13.7 to 19.6 m^{3} ha^{-1} year^{-1} for 10 provenances planted at a spacing of 1.83 × 1.83 m. In Tanzania, yield tables for thinned Teak (Malimbwi, 2016) indicate maximum VMAI of 27 m^{3} ha^{-1} year^{-1}, 16 m^{3} ha^{-1} year^{-1} and 9.5 m^{3} ha^{-1} year^{-1} between ages 15-20 years and minimum VMAI of 9 m^{3} ha^{-1} year^{-1}, 6 m^{3} ha^{-1} year^{-1} and 3.5 m^{3} ha^{-1} year^{-1} at age 5 years for site classes I, II and III respectively.

The VMAI for Mtibwa plantation in 1986 inventory was 12.28 m^{3} ha^{-1} year^{-1}. In the year 2000 mini-inventory, VMAI was calculated to be 7.87 and 7.06 m^{3} ha^{-1} year^{-1} for Mtibwa and Lusunguru blocks respectively (MNRT, 2018). Most of information on MAI is provided without indicating ages, making a critical and fair interpretation and comparison difficult.

Total volume estimations of up to 250 m^{3} ha^{-1} in 33 years plantations have been reported (Gómez and Ugalde, 2006). However in Tanzania at the same age, Malimbwi (2016) simulated total volume between 211.9 and 560.9 m^{3} ha^{-1} for poor and better sites respectively.

Hashim (1996) in Hashim (2003) reported that the total volumes of a Teak stand grown on deep alluvial soil at ages five and 10 years were 81.45 and 163.9 m^3 ha^{-1} respectively. Malimbwi (2016) simulated at ages five and 10 volumes between 17.6 – 30.3 and 74.8 – 198 m^3 ha^{-1} for poor and better sites respectively before thinning. Stand volumes between 200 and 300 m^3 ha^{-1} are normal (Kanninen *et al*., 2004). However, Pérez and Kanninen (2005b) in Costa Rica reported depending on rotation age and site quality a total volume of 268 - 524 m^3 ha^{-1}.

A combination of appropriate site selection coupled with good germplasm material and by adopting the right silvicultural practices could increase the yield and quality of Teak plantations (Bekker *et al*., 2004; Kollert and Kleine, 2017) to 8 – 10 m^3 ha^{-1} $year^{-1}$ that will be realistic on a short rotation of 20 years for better economic returns (Kollert and Kleine, 2017). Teakwood productivity has been reported to significantly increase by as much as 75% as a consequence of improved planting material by way of tree improvement programmes (Siswamartana, 2008) coupled with sound silvicultural techniques.

2.5 Effect of thinning on stem quality

Stem quality is an important factor when selecting stands to be felled for production of a particular type of timber and for production recovery in sawmilling. Stem quality can be viewed in two ways: the external quality and internal quality. External quality includes dimensions like diameter and height, roundness, straightness of the stem, number and size of the branches (Kellomaki, 1980 in Mtakwa, 2014). Diameter is considered to be the most fundamental characteristic of stem quality across all the factors which help to determine the value of the product. Tree diameter is the one which can be appreciably modified by a forester through thinning (Shepherd, 1986). Trees of greater diameter are considered to be of higher quality except for certain special uses such as pitprops, poles and others. Also a tree of large diameter lends itself to much greater variety of uses than a small sized tree. It is important, therefore, to describe a stand by its stem diameter distribution (Brazier, 1997 in Mtakwa, 2014). Stem straightness is a quality requirement for poles. It contributes to superior grades of sawn timber and irrespective of end use whether it is pulp, particle board, fuel wood or charcoal saves costs and increases the recovery from plantation management through harvesting to conversion (Bamess and Gibson, 1986 in Mtakwa, 2014). Crooked and logs with eccentric pith cause wastage in veneer and plywood industry. Extremely crooked boles add to costs of debarking and chipping in the pulp industry (Hans, 1982). Bayley (2004) observed a similar phenomenon that defective logs cause problems and losses in nearly all harvesting, transporting and processing operations.

Apart from affecting the quantity of usable timber from a stand, thinning also affects the quality. Removal of leaning and misshapen trees and those with basal sweep or crooked stems reduces the amount poor quality wood remaining in the stand and the trees left to grow on will have a higher percentage of utilization (Shepherd, 1986). Also, because the remaining trees are encouraged to grow to larger sizes, their sawlog and veneering potential is improved since less of the log is wasted (NACRMLP, 2006).

Little is known about the effect of thinning on Teak stem quality. Okama and Chamshama (1988); Maliondo and Chamshama (1996) found that delayed thinning, too light thinning, lack of serious quality consideration during thinning, poor care of trees by taungya farmers and cattle grazing in young stands resulted in seedling damage and poor stem quality in general for *C. lusitanica* and *Pinus patula*.

However, Madoffe and Maghembe (1988) in a Teak provenance trial reported Mtibwa provenances to be the most straight, with good self-pruning properties and branch free boles by more than 50% free.

2.6 Practical application of yield tables

A yield table is essentially a tool of long term planning for even-aged stands. It lists growth and expected productivity/volumetric yield for a given age, site or crop quality and sometimes other indices such as density. Thus, yield tables.

Owing to the enormity of information they contain, yield tables can be put to many uses in management or silvicultural practices (Parthiban *et al*., 2016): (a) determination of site quality or fractional site quality, (b) estimation of total yield or growing stock, (c) determination of increment of stand, (d) determination of rotation, (e) preparation of stock-map by site qualities, and (f) as a guide to silvicultural thinnings. However, the use of yield tables in yield forecasting for management planning should take into consideration adjustments for small deviations between yield table estimates and actual compartment values. This is because they are originally meant to predict yield for properly thinned stands (Malimbwi, 2016).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Location and description of the study area

The study was conducted at Mtibwa Forest Plantation covering an area of 16 106.19 ha: Existing 3 156.19 ha and new extension area 12 950 ha. The plantation lies between latitude 6^0 - 6^0 10'S and longitude 37^0 40' - 37^0 45' E approximately 640 m.a.s.l. and about 110 km from Morogoro town along the Morogoro – Dumila – Handeni road (MNRT, 2018).

The area receives long rains from March to May. These are followed by a long dry season lasting October. Short rains are from November to December. The average mean annual rainfall is 1217 mm. Since this is marginal for teak growth, it is supplemented by sub surface underground water. Temperatures are high particularly in the months of January to March. Mid-day temperatures vary from 14 ^{0}C to 36 ^{0}C (MNRT, 2018).

The plantation is divided into three blocks that are separated by strips of village land:

i) Mtibwa block

The block has a total area of 894.93 ha. It is surrounded by three villages: Madizini in the South, Kunke in the South East, and Lusanga in the West.

ii) Lusunguru block

The block has a total area of 2264.26 ha. It is surrounded by three villages: Dihinda in North East, Lusanga in North West and Kunke in North East.

iii) Pagale block

The block has a total of 12 950 ha, previously a forest reserve until 2018 when planting activities commenced. It is surrounded by three villages: Mlumbilo in the South East, Kaole in the North East, Dihinda in the North West and it is bordered with Wami Mbiki in the East and Wami River in the South East.

Mtibwa block is almost flat while Lusunguru and Pagale blocks are dominated by gentle slopes and a number of low lying hills. The soils in Lusunguru are smooth and fairly strong compacting. They are progressively more fertile down the catena. The soils of Mtibwa and Pagale block are alluvial and fertile. Also more fertile down the catena, the soils are rich in calcium and have pH of 5 - 8, though pH of 6 - 7 is more common throughout the plantation area. The soils in both blocks have high capacities for water retention and at the same time very poor drainage (MNRT, 2018).

Mtibwa and Lusunguru blocks were taken for the study because they had compartments that met age requirements for sampling. The study area is as shown in Fig. 6.

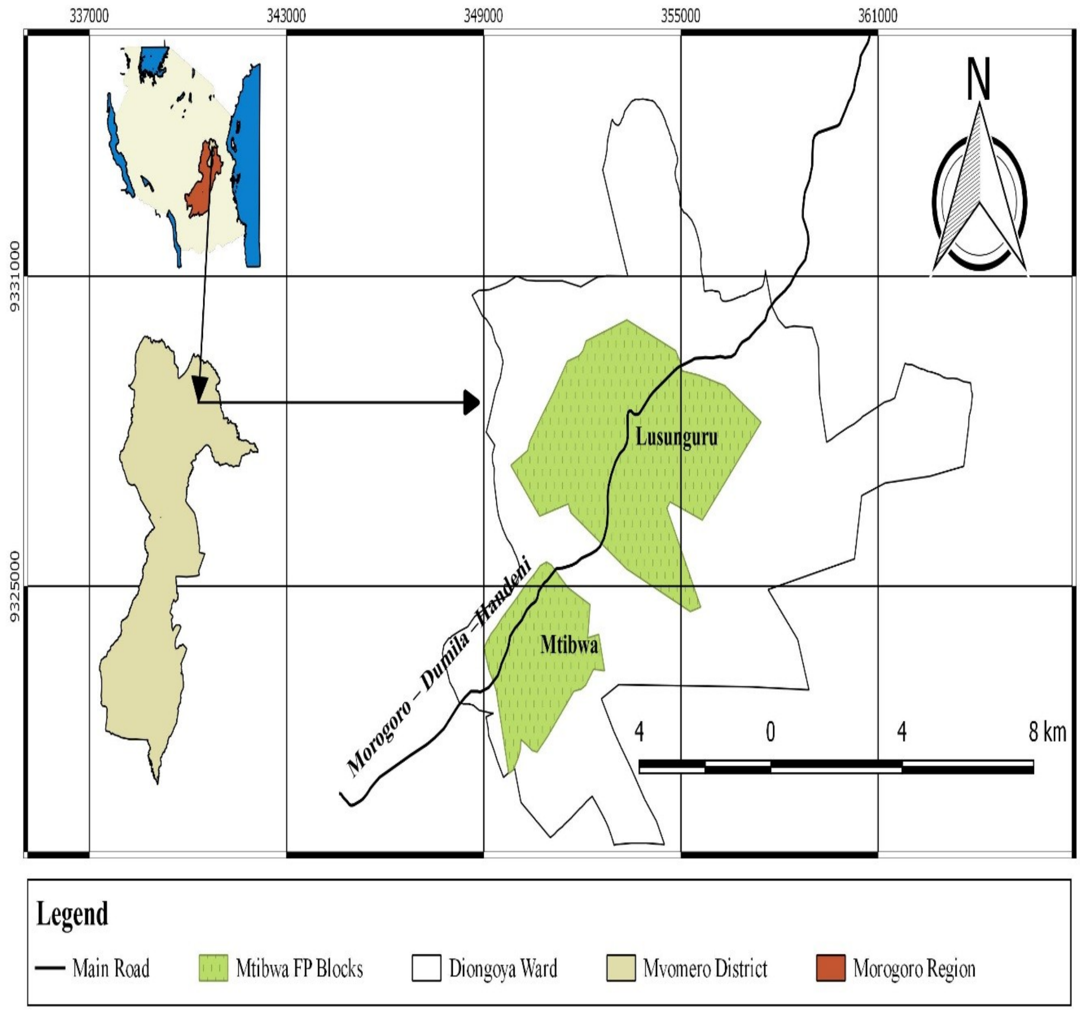


Figure 6: Map showing location of Mtibwa and Lusunguru blocks at Mtibwa forest plantation

3.2 Sampling design

In this study, the plantation (Appendix 3) was stratified into 4 age groups (6-10, 11-15, 16-20, and > 20 years) in order to capture all age classes for thinning. Compartments less than 5 ha were not considered for the study, because most of them were established from flying nurseries in the past (MNRT, 2018).

The objective way of determining number of plots that involves determination of coefficient of variation (CV) by estimating basal area using few random sample trees for each sampled compartment, with a sampling error of 10% at 5% probability level was not used. This was due to time and fund constraints. Instead, 92 plots were laid out in 23 (12 and 11 from Mtibwa and Lusunguru blocks respectively) purposively selected compartments that capture all age classes.

Plantation map of 2010 and QGIS programme version 2.16.3 were used in transect layout and plot allocation prior field work. In order to get accurate stems per ha (SPH), basal area per ha and volume per ha estimates, all sampled compartments were GPS surveyed to obtain shapefiles for actual area determination prior data collection, this involved eliminating water lodged sections with no trees which is typical in Lusunguru block compartments. Four transects and circular plot of 9.78 m radius (giving 3 fattest trees for dominant height estimation) were laid out (Malimbwi, 2016) in each sampled compartment. In QGIS, transects were laid out in each compartment shapefile along the long side of the 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 (4). In transect laying out, the first transect was laid at half transect distance from the compartment boarder. The distance between plots in a compartment was determined by dividing the total length of 4 transects by the number of plots (4) (Malimbwi, 1997). The actual positions of plots in the forest were located by Global Positioning System (GPS) device by using extracted location coordinates from the QGIS programme.

3.3 Data collection

In each plot the following measurements and attributes were recorded:

i. Thinning history: Thinned (with last thinning year) or unthinned,
ii. Diameter at breast height (Dbh) of all trees to the nearest 10^{th} of a cm using a calliper for compartments less than 10 years and girth using a sewing tape measure for compartments older than 10 years (later converted to Dbh by dividing by PI (3.14)),
iii. Stem quality of all trees using four quality classes (Table 2). Stem quality classes by Mugasha *et al*. (1996) were not adopted because they were found to fit better for Pines than Teak, thus they were slightly modified for this study. Stem quality assessment in the field took into consideration the merchantable height and tree form.

Table 2: Stem quality classification

Description	Stem quality class
a) Straight to the top and good stem form b) Straight and good stem form but with straight top forks	1
a) Straight and good stem form but with one slight bend less than 1 m in length b) Straight and good stem form but with slightly bent or crooked mid/top forks c) Straight and good stem form but with buttresses within 1 m height	2
a) Slight bends less than 1 m at bottom and at top with straight middle part b) One slight bend more than 1 m in length c) Slight crook, slight taper, buttressed within 2 m height	3
a) Serious crook, excess taper and buttressed beyond 2 m height	4

iv. Heights for 3 fattest trees per plot using SUUNTO hypsometer,
v. GPS coordinates of the plot centre,
vi. General remarks about the plot (e.g. silviculture operations carried out, invasive spp, etc.).

Various tools and equipment were used for data collection (Appendix 4). Field data were recorded in special forms (Appendix 5) for easy subsequent entry and analysis into the computer.

3.4 Data analysis

Data were analysed using R version 3.4.2 and Ms Excel 2013.

3.4.1 Compliance to teak thinning schedule

The total number of thinned and unthinned compartments was determined and corresponding hectarage determined. Adequacy of thinning for thinned compartments was determined by calculating the remaining number of stems ha^{-1} and the deviation from scheduled values were expressed in percentages. In addition, a paired Student's t-test was run at plot level to test for significance in differences between measured and scheduled SPH. Lastly, thinning timing was computed by deducting the age the stand was supposed to be thinned from the actual thinning age to determine whether it was timely, earlier or delayed.

3.4.2 Growth and yield for thinned and unthinned teak trees

Yield tables for Teak by Malimbwi, (2016) were used to compare with study stand parameters (Dbh, SPH, dominant height (Hdom), basal area (BA), volume (Vol), mean annual increment (MAI)) for sampled compartments. However, quadratic mean diameter was used instead of arithmetic mean in making comparison, because yield table Dbh is quadratic mean Dbh derived from the per-hectare basal area and the number of stems per hectare (Equation 3) (Gadow and Hui, 1998). Deviations between measured and yield table values were calculated for each site class and presented in percentages.

(Equation 3)

$$Dg = \frac{\sqrt{BA}}{0.0000785 \times SPH}$$

Where: Dg = quadratic mean diameter (cm),

BA = stand basal area (m^2/ha),

SPH = number of stems per ha.

In site index, tree height, tree volume, stand volume and basal area calculations, the following equations were used:

a) Site index for compartments was determined by using Equation 4 by Malimbwi (2016):

$$Hdom = 1.25 \times Site \times \left(1 - \exp\left(-0.101319 \times Age\right)\right)^{1.504122} \quad \text{……..(Equation 4)}$$

Where: Hdom = measured stand dominant height (m),

Site = stand site index (m),

Age = stand age (years).

b) Height (H) for trees that were measured for dbh alone was estimated using Equation 5 by Malimbwi (2016):

$$H = 1.3 + \frac{Dbh^2}{7.9693 + 0.03006 \times Dbh^2} \quad \text{…………………………………(Equation 5)}$$

Where: H = estimated tree height (m),

Dbh = measured diameter at breast height (cm).

c) Stand volume was estimated by using Equation 6 by Malimbwi (2016):

$$Vol = \exp\left(1.033835 + 0.489679 \times \ln(Hdom) + 0.9954 \times \ln(BA)\right) \quad \text{..(Equation 6)}$$

Where: Vol = estimated stand volume,

Hdom = stand dominant height (m),

BA = stand basal area (m^2/ha).

d) Stand basal area growth was estimated by using Equation 7 by Malimbwi (2016):

$$BA = \exp(-7.36466 + 0.62616 \times \ln(N) + 2.16723 \times \ln(Hdom)) \quad \text{...(Equation 7)}$$

Where: BA = stand basal area (m^2/ha),

N = stand number of stems per ha,

Hdom = stand dominant height (m).

In comparing stand parameters with yield tables:

a) Average Hdom per compartment was calculated,

b) Appropriate site class for each compartment by using the site index Equation 4 by Malimbwi (2016) was determined. The chosen site class was the basis for selecting which yield table section to use for comparison.

However, Teak yield tables were meant to be used to predict yield for properly thinned stands, Equation 8 will be used in determining the relative correction factor that should be applied to adjust the measured values when predicting future yields of the compartments.

$$f = \text{basal area of the compartment} / (\text{basal area yield table}) \quad \text{..........(Equation 8)}$$

Where: f = relative correction factor.

3.4.3 Stem quality of teak in thinned and unthinned stands

Percentage of trees in each of the four quality classes was computed for both thinned and unthinned stands.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Compliance to teak thinning schedule

4.1.1 Adequacy of thinning

Results indicated that Comp no. MT IV was the only unthinned of all the surveyed compartments at the time of data collection and Comp no. MT VII A was just being marked for second thinning. However, in terms of thinning adequacy, results showed 321.59 ha (57%) and 242.83 ha (43%) of all thinned compartments are overstocked and understocked respectively as presented in Appendix 6. Nevertheless, no compartment had an allowable SPH deviation of 10% as proposed by SAID (2000) except MT VII B with 8%. On the other hand, out of the 23 sampled compartments, only seven (30%) had SPH values that are statistically significantly different ($P<0.05$) from scheduled values namely MT X A, MT X B, LR XVII i & ii, LR XIII I, LR XIII iv & v, LR XIII vi and LR XII ii & iii (Appendix 6).

Overstocking was observed in 15 stands aged 20 years and below agreeing with Pérez and Kanninen (2005a) in Costa Rica who observed higher stand densities than the recommended for young Teak stands notwithstanding heavy thinnings. Whereas, understocking was observed in eight stands aged above 20 years as shown in Fig. 7. This trend could possibly be due to reported illegal cutting and wind throw in older compartments.

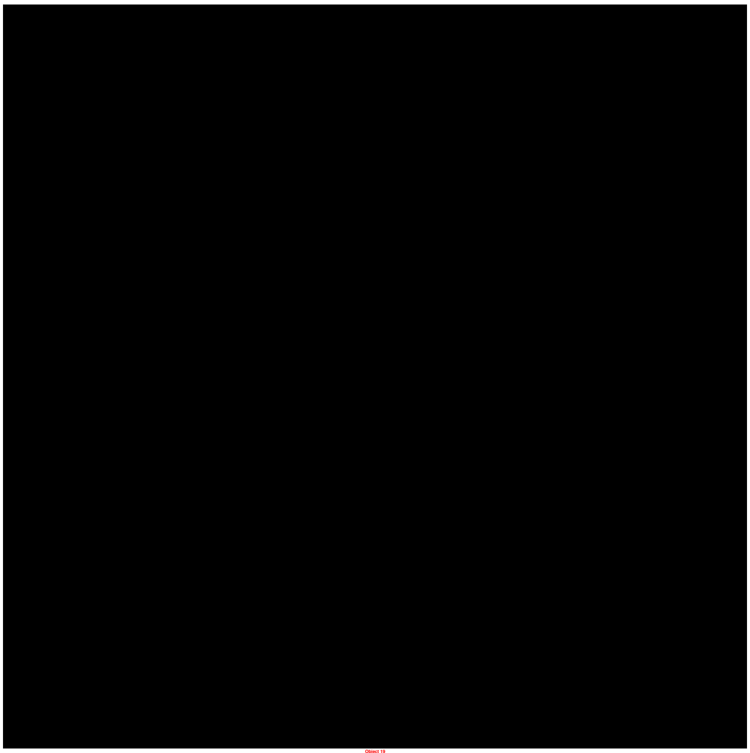


Figure 7: Measured and expected stems per ha by age groups at Mtibwa Forest Plantation

On average, second and third thinning operations are not adequately implemented. SAIF (2000) suggests an allowable 10% deviation of the prescribed SPH. This was at least observed in first thinning operations with 13% and statistically insignificant ($P>0.05$) but second and third operations had significantly ($P<0.05$) higher deviations of 39% and 26% respectively as summarised in Table 3 indicating low adherence to thinning prescriptions. These results are in agreement with Tewari *et al*. (2014) in Karnataka, India and Laswai *et al*. (2016) in Tanzania that revealed thinning prescriptions were lighter and not always rigorously adhered to. Compartments aged > 20 years are > 5 years past the third and final commercial thinning, so a substantial deviation in their SPH could possibly be due to observed illegal and wind throw.

Table 3: Stems per ha deviation by age groups in percentage at Mtibwa Forest Plantation

SN	Age group	Number of compartments	SPH Deviation (%)	P-value
1	6-10 years (n = 24)	6	13	0.08
2	11-15 years (n = 28)	7	39	0.00
3	16-20 years (n = 8)	2	26	0.04
4	>20 years (n = 32)	8	(30)	0.00

4.1.2 Timing of thinning

Results revealed that most thinning operations were delayed for one and two years as shown in Appendix 7. About 80% of all first thinnings were delayed for two years with MT IV being delayed for one year already and yet unthinned. Second thinnings were observed to be timely carried out by 25%. However, one and two years delays for second thinnings were by 37.5% each. Third thinnings were delayed for one and two years by 50% each. Two years delays were also observed in Cost Rica by Kanninen *et al*. (2004). The observed delays in Mtibwa Forest Plantation are due in the main to lack of priority in planning thinning operations and technical incompetence. Other reasons are shortage of funds and lack of markets for unsawn thinnings especially first thinnings (Chamshama, 2011; Ngaga, 2011).

4.2 Effect of site quality and thinning on teak growth and yield

Results indicated 37% (231.53 ha), 54% (332.63 ha) and 9% (54.46 ha) of surveyed compartments to belong to site classes I, II and III respectively. In addition, 98% (225.77 ha) of all site class I compartments are from Mtibwa block whereas 46% (152.79 ha) and 100% (54.46 ha) of all site class II and III compartments are from Lusunguru block respectively as summarised in

. This indicated relatively poor growing conditions in Lusunguru block due to gentle slopes and a number of low lying hills with fairly strong compacted soils (MNRT, 2018).

4.2.1 Effect of thinning on teak growth and yield in site class I compartments

Results indicated various agreements and deviations of measured parameters from scheduled parameters. A graphical perspective is provided in Fig. 8 and in addition, a tabular summary with deviations in percentage is shown in Appendixi 9

Results as shown in Fig. 8a indicate that inadequate thinning affects diameter growth by 6 to 10% with few exceptions at 6, 8 and 12 years due to existence of older coppice sprouts and natural regenerants in compartments numbers MT IV, MT V C, and LR XXIV and LR XXVI respectively (Plate 1). Adequately thinned Teak stands with wide spacing are able to produce higher diameter increment and consequently increased size of logs over low-thinned or unthinned stands due to higher turnover rate of the crown as new leaves quickly adapt to the better environment (Malimbwi *et al*., 1992a; Maliondo and Chamshama, 1996; Kanninen *et al*., 2004).

Fig. 8b shows that dominant heights obtained in this study agree with yield table values. However, few exceptions were observed probably due presence of coppice sprouts and natural regenerants as described in preceding paragraph. These results are in agreement with most research (Malimbwi *et al*., 1992b; Malimbwi, 1997) on thinning versus height growth as height growth of trees is usually little or not affected by thinning at all. They also demonstrate the ability of the yield tables to predict growth.

Plate 1: Older unmanaged coppice sprouts and natural regenerants in MT IV at Mtibwa Forest Plantation

Stocking results indicate that all compartments are variously overstocked from 15 to 69% except compartment number MT V C as shown in Fig. 8c which is understocked by 30%. This exception is due to poor survival, no blanking and serious *Senna siamea* invasiveness in the compartment. However, overstocking indicated inadequate thinning due to several reasons including technical difficulties in thinning stands established through coppice sprouts and natural regenerants management (Kwame *et al*., 2014) and lack of markets for first and second thinnings as already observed. MT V A, MT V B and MT V C were established through coppice and natural regenerants management due to heavy rains in 2009/10 prohibiting satisfactory land preparation following first rotation harvesting in the compartments (Katety, H. H. personal communication, 2018).

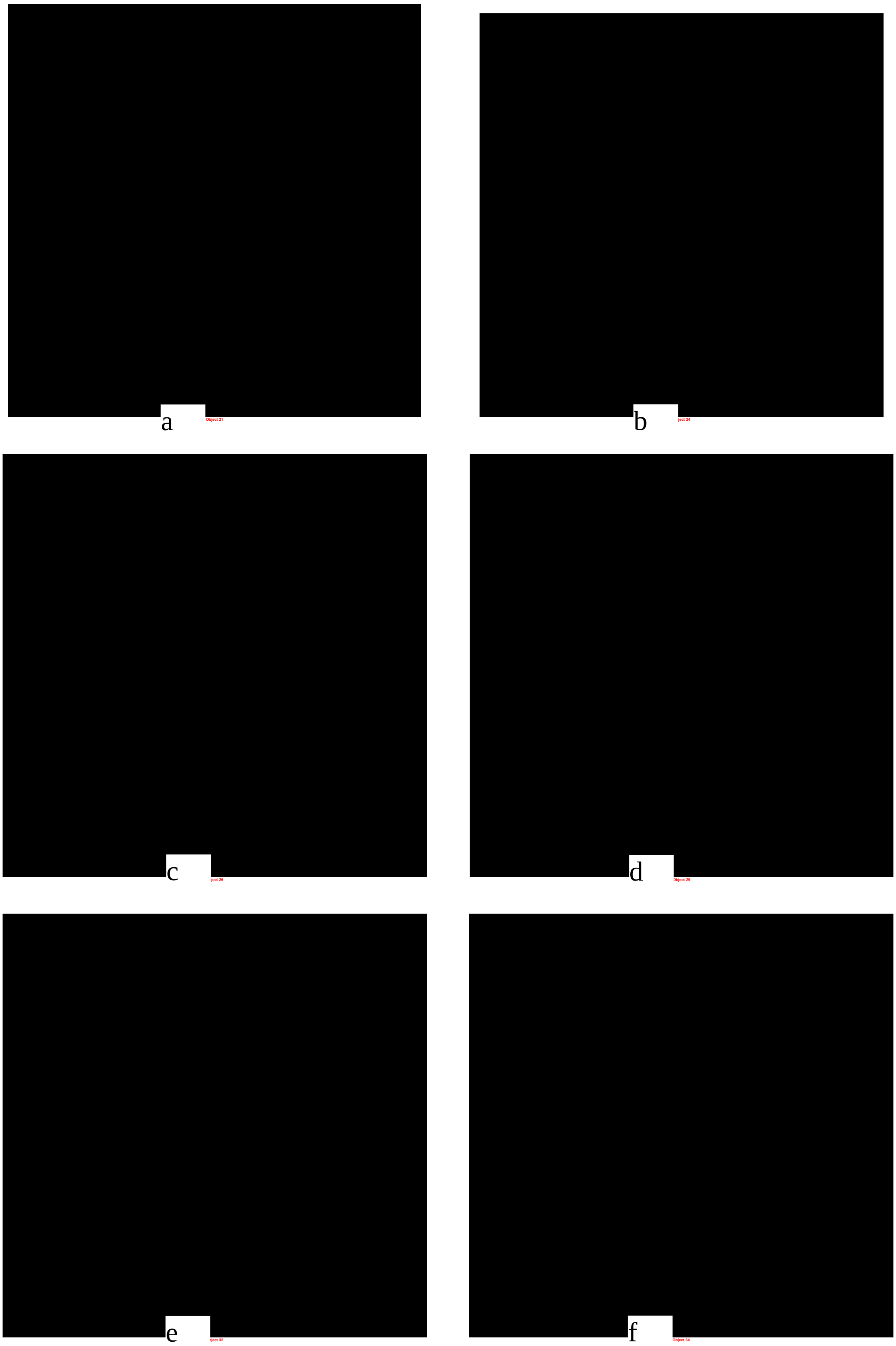


Figure 8: Effect of thinning on quadratic mean diameter (a), dominant height (b), SPH (c), basal area (d), volume (e) and VMAI (f) for site class I at Mtibwa Forest Plantation

Stand basal results indicated that most compartments have values beyond yield table values by 4 to 118% except for compartment number MT V C which is lower by 13% due to reasons given earlier as shown in Fig. 8d.

Furthermore, a similar trend was observed for stand volume as shown in Fig. 8e because basal area is directly related to stand volume (Malimbwi, 1997). The higher values indicated the effect of inadequate thinning on younger stands signifying that there were many small sized trees resulting in standing volume distribution on many small trees rather just few of greater value per cubic metre (Chamshama and Malimbwi, 1996).

Volume mean annual increment (VMAI) results (Fig. 8f) indicated most compartments to have figures below yield table figures by 5% to 26% except for unthinned compartments number MT IV with figure higher by 74% because high volume increments per ha are easy to obtain in unthinned stands (Kollert and Kleine, 2017). Another exception was MT VII A with equal VMAI figure yet somewhat coppiced and just timely marked for second thinning. The general trend observed was due to inadequacy in thinning operations making it difficult for trees to fully utilize site potential for growth which is meant following thinning (Evans, 1992 in Chamshama and Malimbwi, 1996; FAO, 2002; Pérez and Kanninen 2005b).

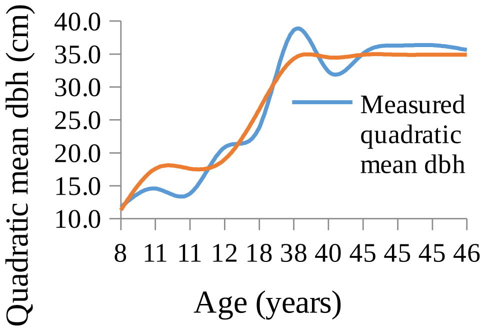
4.2.2 Effect of thinning on teak growth and yield in site class II compartments

Results indicated various agreements and deviations of measured parameters from scheduled parameters. A graphical perspective is provided in Fig. 9 and in addition, a tabular summary with deviations in percentage is shown in

.

Results in Fig. 9a for Dbh almost indicate intersection points at ages 8, 12 and 45 years for compartments numbers MT V D, MT VII B, LR XII i, LR XIII ii and iii, LR XIII iv and v and LR XIII vi. This agreement between measured and scheduled quadratic mean diameters was likely due to presence of almost prescribed SPH at given ages in the compartments. However, relatively lower values by 6% were observed in compartment number LR XVII i and ii aged 40 years because the compartment was relatively overstocked and even serious in compartments numbers MT X A by 17% and MT X C by 21% which had almost double the SPH than the prescribed ones at 11 years. On the other hand, a relatively higher value by 13% was observed at age 38 years for compartment number LR XXI i because it was relatively understocked. All these results agree with various studies (Malimbwi *et al.*, 1992a; Maliondo and Chamshama., 1996; Kanninen *et al.*, 2004).

Fig. 9b shows that study dominant heights agree with yield table values. However, few exceptions were observed. Relatively lower values by 9% were observed in compartments number MT X C at 11 years possibly due to observed high soil variability in the compartment and by 6% in LR XIII iv and v at 45 years possibly due to reported high/crown thinning in the past (Katety, H. H. personal communication, 2018). Besides, a relatively higher value by 8% was observed in compartments number MT VII B at 12 years possibly due to edge effect as the compartment is at the edge of the plantation. These results are in agreement with most research (Malimbwi *et al.*, 1992b; Malimbwi, 1997) on thinning versus height growth as height growth of trees is usually little or not affected by thinning at all. They also demonstrate the ability of the yield tables to predict growth.



a

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b

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c

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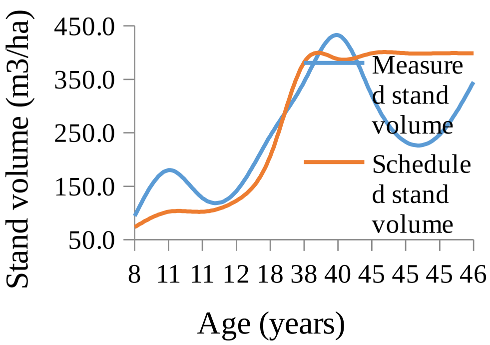
d



e

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f

Figure 9: Effect of thinning on quadratic mean diameter (a), dominant height (b), SPH (c), basal area (d), volume (e) and VMAI (f) for site class II at Mtibwa Forest Plantation

Stocking results indicate that all compartments are overstocked except compartments MT VII B aged 12 years with an almost the same SPH as prescribed, LR XXI i aged 38 years, LR XIII iv and v, LR XIII vi both aged 45 years and LR XII i aged 46 years that are understocked due to wind throw and illegal cutting as shown in Fig. 9c. Generally, overstocking indicated inadequate thinning due to several reasons including technical difficulties in thinning stands established through coppice sprouts and natural regenerants management, e.g. MT V D aged 8 years, MT X A and MT X C both aged 11 years and traditional attitude by foresters against waste aggravated by lack of reliable market for third thinnings in LR II aged 18 years.

Stand basal results indicated that most younger compartments have values beyond yield table values from 11% to 78% except for understocked compartments LR XXI i aged 38 years, LR XIII ii and iii, LR XIII iv and v, LR XIII vi all aged 45 years and LR XII i aged 46 years due to reasons given earlier for stocking (Fig. 9d).

Moreover, a similar trend was observed for stand volume as shown in Fig. 9e because basal area is directly related to stand volume (Malimbwi, 1997). The higher values from 12% to 76% indicated the effect of inadequate thinning on stands signifying that there were many relatively small trees resulting in the standing volume distribution on many small trees rather than just few of greater value per cubic metre (Chamshama and Malimbwi, 1996).

Results for VMAI indicated most compartments to have figures below yield table figures between 8% to 52% except for critically inadequately thinned compartment number MT X A aged 11 years with over double the prescribed SPH and the both overstocked and somewhat coppiced and naturally regenerated MT V D as shown in Fig. 9f. This is because high volume increments per ha are common in unthinned stands (Kollert and Kleine, 2017). The general trend observed was due to inadequacy in thinning operations making it difficult for trees to fully utilize site potential for growth which is meant following thinning (Evans, 1992 in Chamshama and Malimbwi, 1996; FAO, 2002; Pérez and Kanninen 2005b).

4.2.3 Effect of thinning on teak growth and yield in site class III compartments

Results indicated various agreements and deviations of measured parameters from scheduled parameters. A graphical perspective is provided in Fig. 10 and in addition, a tabular summary with deviations in percentage is as shown in Appendix 11.

Quadratic mean diameter results as shown in Fig. 10a indicated relatively higher values by 27% and 20% for compartment number LR XIII i aged 45 years and LR XII ii & iii aged 46 respectively possibly due to understocking allowing space for dbh growth. However, relatively lower values by 14% were observed in LR III aged 19 years due to overstocking leading to low site potential utilization for growth.

Fig. 10b shows relatively lower Hdom values by 10% in LR III aged 19 years possibly due to reported third crown thinning. A relatively higher value by 11% in LR XIII i aged 45 years possibly due to edge effect and over maturity and a similar value in LR XII ii aged 46 years indicating the ability of the yield tables to predict growth.

The SPH for compartments LR XIII i and LR XII ii and iii aged 45 and 46 years respectively are relatively lower by 50 % and 61 % respectively than the prescribed most likely due to wind throw and illegal cutting in these over matured stands as shown in Fig. 10c.

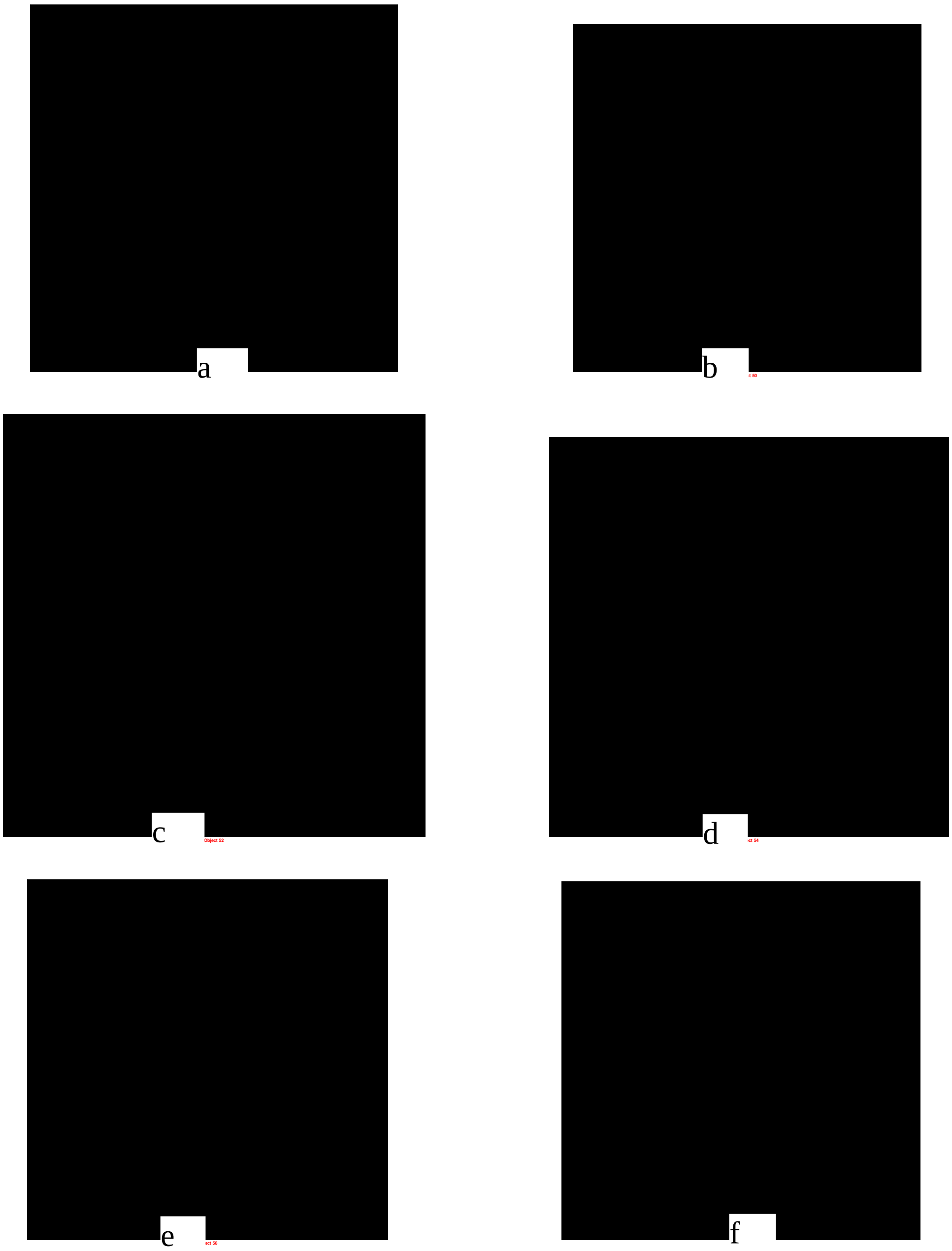

Figure 10: Effect of thinning on quadratic mean diameter (a), dominant height (b), SPH (c), basal area (d), volume (e) and VMAI (f) for site class III at Mtibwa Forest Plantation

Relatively lower stand basal area values by 13% to 43% were observed for all three compartments as shown in Fig. 10d. This was due to understocking by about 50% and 61% in LR XIII i and LR XII ii and iii aged 45 and 46 years respectively.

A similar trend was observed for stand volume as shown in Fig. 10e because basal area is directly related to stand volume (Malimbwi, 1997).

Values for VMAI were relatively lower than prescribed ones (Fig. 10f). This could possibly be due to inadequate thinnings in the past. Inadequate thinnings create a difficulty for trees to fully utilize site potential for growth which is meant following thinning (Evans, 1992 in Chamshama and Malimbwi, 1996; FAO, 2002; Pérez and Kanninen 2005b).

4.2.4 Application of yield tables and relative correction factors

Results for relative correction factor (f) vary from 0.57 – 2.18. Site class I compartments have a relatively higher average value of 1.29 followed by site class II (1.05) and site class III (0.75) (Appendix 12). The magnitude of deviations increases with site improvement indicating that better sites are likely to be more affected by thinning negligence. This implies that, unless compartments are properly thinned and brought to normal as per the yield table, future yield predictions must be made by multiplying the relative correction factor by the scheduled values (especially BA and V). Thus ensuring reliable future yield estimates at respective ages and site classes for management planning (Malimbwi, 2016).

4.3 Effect of thinning on stem quality

Results indicated most of the stems in compartments to have stem quality 2 as shown in Fig. 11 with 76%, 73%, 80% and 74% for age groups 6 - 10, 11 - 15, 16 - 20 and > 20 years respectively. However, compartments in age groups 6 – 10 and 11 – 15 showed to possibly respond to their first and second thinnings by having 9% and 16% stem quality 1 stems respectively. On the other hand, compartments in age groups 16 – 20 and > 20 years showed to have 19% and 20% respectively of stems with stem quality 3 possibly due to past high thinnings in those compartments, most of them being in Lusunguru block (Katety, H. H. personal communication, 2018). In addition, the presence of stems (3%) with stem quality 4 for compartments aged 6 – 10 years and 3% for compartments > 20 years possibly signals the effects of improper selection of stems for removal, lack of serious quality considerations especially in compartments MT V B and MT VII A and high thinning respectively.

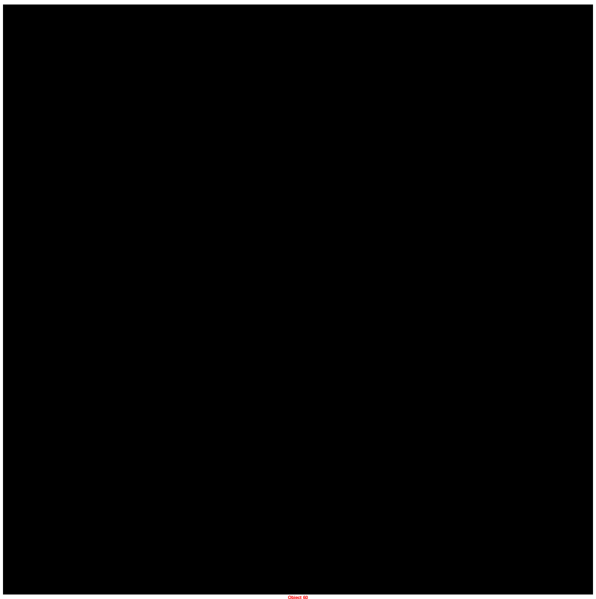

Figure 11: Stem quality percentage distribution by age groups at Mtibwa Forest Plantation

In comparing stem quality between Mtibwa and Lusunguru blocks, results indicated 74% and 76% of stems with stem quality 2 respectively as shown in Fig. 12. However, Mtibwa block had 13% of stems with stem quality 1, three times higher than Lusunguru block possibly due to presence of most of the younger compartments (< 20 years) in Mtibwa block. This trend is evidenced by the presence of 18% of stems in Lusunguru block with stem quality 3 because of the presence of older stands (> 20 years). This is possibly a result of lack of serious quality consideration during previous thinning operations (Okama and Chamshama, 1988; Maliondo and Chamshama, 1996).

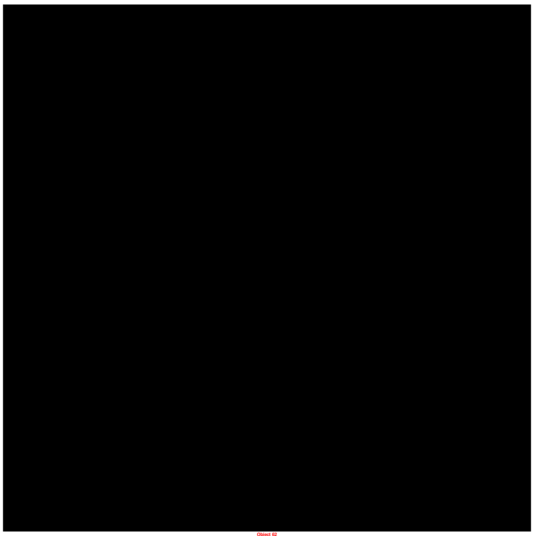

Figure 12: Stem quality distribution in percentage by blocks at Mtibwa Forest Plantation

Generally, it was difficult to establish the effect of thinning on stem quality because there were no enough unthinned compartments. Even compartment number MT IV that was unthinned at the time of data collection had an average stem quality 2. The noticed difficulty was perhaps due to reports that Mtibwa provenances were most straight, with good self-pruning properties and branch free boles by more than 50% (Madoffe and Maghembe, 1988).

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

i) Though thinning operations appear to be performed, they are delayed and still lighter than recommended in the thinning schedule.

ii) The effect of inadequate thinning on stand quadratic mean dbh, basal area, stocking, volume and VMAI has been observed to be serious. The consequences in the future would be failure to attain maximum dbh of 40 cm and meet revenue objectives thus low sawmill recovery given the fact that the plantation is primarily managed for timber and not poles production. In addition, relative correction factors appeared to increase in magnitude with site improvement.

iii) It was difficult to establish the effect of thinning on stem quality because there were no enough unthinned compartments for comparison. Most of the compartments had stems with stem quality 2 same as for the only unthinned compartment number MT IV.

5.2 Recommendations

i) On each thinning, preference should be given to the retention of the prescribed and most vigorous trees (dominants, straight stem, no diseases or stem defects, well-formed crown), besides selecting trees to keep a relatively even spacing. This obliges technicians to concentrate, observe and have a good sense of spacing.

ii) Delayed thinnings would cause unnecessary inter-tree competition, which could reduce wood production and quality. Thus, planting with satisfactory land preparation and thinning need to be scheduled and implemented at the right time to ensure high productivity of the plantation.

iii) Due to the fact that lack and or shortage of funds causes delays and in some instances inadequate thinning operations, it is recommended that sufficient funds for thinning and other silvicultural operations be adequately allocated and disbursed timely.

iv) It is recommended that a close follow up on the implementation of Technical order No. 1 of 2003 with regard to thinning schedules be conducted. This is important because, the Forest Policy (1998) advocates production of quality products from forest plantations.

v) In case coppice and natural regenerants management is opted, then careful sprout selection in a good point of origin (preferably in the lower level) and minimal degree of sweep in the first year of growth can minimize future wood quality problems associated with early tension wood formation.

vi) Unless compartments are properly thinned and brought to normal as per the yield table, future yield predictions must be made by multiplying the relative correction factor by the scheduled values to have reliable future yield estimates at respective ages and site classes for management planning.

vii) Finally but not least, the following studies are recommended: the effect of inadequate or lack of thinning on revenue generation and the allowable safe deviations in Dbh, Hdom, stand BA, stand Vol and Stand VMAI like the available 10% for SPH.

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APPENDICES

Appendix 1: Thinning schedules for industrial public and private teak forest plantations in Tanzania

Species	Age (years)	Stems per ha
T. grandis (planted at 2.5 x 2.5 m spacing) in public plantations	0	1600
	5	800
	10	400
	15	300
	30-40	0
T. grandis at KVTC (planted at 2 x 2 m from 1993 – 1999 and 3 x 3 m since 2000+)	2	Remove multiple stems
	8	650
	13	400
	20	250-280
	30-32	0

Source: FBD, (2003) and Ngaga, (2011)

Appendix 2: Tanzanian first Teak thinning schedule

Age (years)	Stems per ha
0 (planted at 2.44 x 2.44 m spacing)	1 680
4	1 125
8	875
12	625
16	375
20	250
60	0

Source: Ahlback, (1986)

Appendix 3: Mtibwa forest plantation compartment register

SN	Block	Compt.	Area (ha)	Spp	P/Year	Age	SPH	Basal area (m^2/ha)	Vol (m^3/ha)	Total stems	Total Vol (m^3)	Mean Dbh (cm)	Mean H (m)	H Dom (m)
1	Lusunguru	TP64C	1.4	*TG*	1964	54	405	32.4	341.28	567	477.79	29.3	20.7	22.7
2	Lusunguru	LR12A	79.4	*TG*	1972	46	433	16.2	162.01	22 893	8 558.76	20.5	15.5	20.7
3	Lusunguru	FN73B	3.4	*TG*	1973	45	430	25.6	254.18	1 462	864.20	27.7	23.4	25.7
4	Lusunguru	LR13	102	*TG*	1973	45	183	16	171.63	18 716	17 506.25	33.8	22.8	23.9
5	Lusunguru	LR14	18.2	*TG*	1974	44	372	18.3	177.82	5 597	2 677.90	25.7	21.8	24.6
6	Lusunguru	LR15	32.6	*TG*	1975	43	303	12.6	121.09	9 882	3 947.61	22.1	17.4	19.3
7	Lusunguru	LR16A	46.6	*TG*	1977	41	485	25	251.08	17 723	9 169.24	23.5	18.6	22.2
8	Lusunguru	LR16B	48.6	*TG*	1977	41	319	21.6	225.85	4 022	2 849.78	28.5	20.2	23.8
9	Lusunguru	FN76	2.4	*TG*	1978	40	505	29.2	292.32	1 212	701.57	25.9	19.4	22.6
10	Lusunguru	FN78A	1.6	*TG*	1978	40	425	30.2	308.83	680	494.12	29.7	19.9	21.4
11	Lusunguru	FN78B	3.1	*TG*	1978	40	525	30.4	303.69	1 628	941.45	26.5	18.9	21.6
12	Lusunguru	LR17	53.4	*TG*	1978	40	282	19.8	202.78	9 039	6 507.31	29.3	21.4	23.7
13	Lusunguru	LR18	98	*TG*	1979	39	255	24.4	264.60	7 691	7 969.72	35.5	24	26.5
14	Lusunguru	LR21	50	*TG*	1980	38	263	18.9	198.36	11 629	8 787.22	30.5	20.7	23.2
15	Lusunguru	LR80	60	*TG*	1980	38	200	15.5	162.74	5 431	4 419.08	29.5	20.3	21.5
16	Lusunguru	FN75	1.4	*TG*	1990	28	835	18.7	174.73	1 169	244.62	16.7	14.6	19.4
17	Lusunguru	FN90	0.5	*TG*	1990	28	500	38.2	395.13	250	197.56	31.3	20.3	21.9
18	Lusunguru	LR12B	20	*TG*	1999	19	218	11.3	110.24	4 364	2 204.76	27.3	19.1	20.2
19	Lusunguru	LR12C	10	*TG*	2000	18	254	11.2	106.37	2 536	1 063.66	23.2	17.4	19.1
20	Lusunguru	TP2006	22.5	*TG*	2006	12	545	14.5	124.94	12 263	2 811.21	19.1	15.2	16.5

SN	Block	Compt.	Area (ha)	Spp	P/Year	Age	SPH	Basal area (m^2/ha)	Vol (m^3/ha)	Total stems	Total Vol (m^3)	Mean Dbh (cm)	Mean H (m)	H Dom (m)
21	Lusunguru	LR1	27.26	*TG*	2011	7	57	0.8	5.94	1 558	161.85	13.5	9.9	9.8
22	Lusunguru	LR3	10.7	*TG*	2011									
23	Lusunguru	LRX111	24.01	*TG*	2011	7	927	5.5	42.73	22 264	1 025.87	7.7	10.3	11.1
24	Lusunguru	LR99	10	*TG*	1999									
25	Lusunguru	FN77	4	*TG*	2012	6	1,540	7.6	48.74	6 160	194.97	7.8	10.6	10.2
26	Lusunguru	KWA	46.09	TG	2013	5	348	0	-	16 027	-	3.8	2.8	
27	Lusunguru	KWB	64.98	TG	2013	5	235	0	-	15 302	-	4.8	3.1	
28	Lusunguru	KWD	57.8	TG	2014	4	862	0	-	36 200	-	4.2	3.9	
29	Lusunguru	KWC	49.46	TG	2014	4	408	0	-	20 384	-	1.2	1.1	
30	Lusunguru	NY2015	80	TG	2015	3	463	0	-	37 073	-	2.6	2.6	
31	Lusunguru	KY2015	70	TG	2015	3	204	0	-	14 300	-	0.9	1.1	
32	Lusunguru	LR2016	96	TG	2016	2	443	0	-	12 236	-	0.2	1	
33	Lusunguru	NY 2016	100	TG	2016									
34	Lusunguru	LR2018	20	TG	2018									
35	Lusunguru	S/OCHARD MIKONGO	6	AQ	2018									
36	Lusunguru	SEED OCHARD MVULE	3.5	ME	2016									
37	Lusunguru	SEED OCHARD TEAK	14.5	TG	2011									
38	Lusunguru	SEED OCHARD MIKANGAZI	7	KA	2011									
	Sub Total		**1346.4**											

SN	Block	Compt.	Area (ha)	Spp	P/Year	Age	SPH	Basal area (m^2/ha)	Vol (m^3/ha)	Total stems	Total Vol (m^3)	Mean Dbh (cm)	Mean H (m)	H Dom (m)
1	Mtibwa	MT10C	16	*CO*	1999	19	156	9.1	82.71	2 223	1 180.50	30	13.6	14.6
2	Mtibwa	MT7C	5	*TG*	2001	17	380	21.3	208.33	1 900	1 041.66	28.4	19.1	20.2
3	Mtibwa	MT7D	15	*TG*	2002	16	218	7.2	65.34	3 275	980.17	20.6	16.2	17.6
4	Mtibwa	MT7B	30	*TG*	2006	12	720	16	135.01	21 609	4 050.35	16.6	15.9	18.4
5	Mtibwa	MT8	80	*TG*	2006	12	748	18.6	159.00	59 800	12 719.60	17.8	16	18.7
6	Mtibwa	MT10A	42	*TG*	2007	11	621	11.7	95.95	26 100	4 029.96	15.3	14.7	16.8
7	Mtibwa	MT10B	28	*TG*	2007	11	839	15.9	131.07	23 500	3 670.00	15.4	14.6	16.3
8	Mtibwa	MT10B	4.44	*CO*	2007									
9	Mtibwa	MT11A	36.4	*CO*	2008	10	117	2.9	22.07	4 247	803.31	17.6	10.2	11
10	Mtibwa	MT11B	106.6	*TG*	1971									
11	Mtibwa	MT3	31.8	*TG*	2008	10	530	11	94.44	16 854	3 003.10	16	14.1	16
12	Mtibwa	MT7A	43	*TG*	2008	10	840	14.6	118.88	36 110	5 111.69	15	14.8	17.7
13	Mtibwa	MT5A	32	*TG*	2010	8	343	3.2	23.82	10 987	762.20	10.2	10.8	12.4
14	Mtibwa	MT5B	27	*TG*	2010	8	548	5.6	41.60	14 798	1 123.07	10.6	11.4	13.2
15	Mtibwa	MT5C	30	*TG*	2010	8	831	9.2	68.86	24 926	2 065.79	11.5	11.9	13.2
16	Mtibwa	MT5D	17	*TG*	2010	8	890	9.7	71.90	15 135	1 222.25	11.3	12.2	13
17	Mtibwa	MT4	54.8	*TG*	2012	6	676	5.1	35.71	37 043	1 956.65	8.6	10.5	11.9
18	Mtibwa	MT6A(I)	5.84	*CO*	1966									
19	Mtibwa	MT6A(II)	37.2	TG	2014	4	1,540	0	-	71 524	-	6.8	6.3	
20	Mtibwa	MT2	30	TG	2014	4	1,033	0	-	31 000	-	5.7	5.5	
21	Mtibwa	MT1	38.6	TG	2014	4	879	0	-	33 927	-	4.7	4.3	
22	Mtibwa	MT9B	45.4	TG	2016	2	859	0	-	39 003	-	0.3	0.9	
23	Mtibwa	MT9A	43.4	TG	2016	2	786	0	-	34 128	-	1.1	1.4	

SN	Block	Compt.	Area (ha)	Spp	P/Year	Age	SPH	Basal area (m^2/ha)	Vol (m^3/ha)	Total stems	Total Vol (m^3)	Mean Dbh (cm)	Mean H (m)	H Dom (m)
24	Mtibwa	MT6B	30	TG	2017	1	1,384	0	-	41 531	-	0.1	0.8	
	Sub Total		**829.48**											
1	Pagale	PGA1	20	TG	2018	1	0	0	-	33 200				
2	Pagale	PGA2	20	TG	2018	1	0	0	-	33 200				
3	Pagale	PGA3	20	TG	2018	1	0	0	-	33 200				
4	Pagale	PGA4	40	ME,GA, KA,AQ	2018	1	0	0	-	58 100				
5	Pagale	PGA5	40	AQ,GA, KA, ME	2018	1	0	0	-	66 400				
6	Pagale	PGA6	8.5	GA, ME	2018	1				14 110				
7	Pagale	PGA8	40	TG	2018	1				66 400				
8	Pagale	PGA9	35	GA, AQ, ME	2018	1				58 100				
9	Pagale	PGA10	53	TG	2018	1				83 000				
10	Pagale	PGA11	35	TG	2018	1				61 420				
11	Pagale	PGA12	20	TG	2018	1				33 200				
12	Pagale	PGA13	56	TG, KA,AQ, GA	2018	1				92 960				
13	Pagale	PGA14	73	TG, KA	2018	1				121 180				
14	Pagale	PGA15	0											
15	Pagale	PGA16	35.8	TG	2018	1				59 428				
16	Pagale	PGA17	38	TG	2018	1				63 080				
17	Pagale	PGA18	21	TG	2018	1				34 860				
	Sub Total		**555.3**											

Grand Total	**2 731.18**

Appendix 4: Tools and equipment used for data collection

SN	Tool/Equipment	Specification
1	Caliper	65 cm length
2	Sewing tape measure	150 cm length
3	Tape measure	50m length
4	Hypsometer	Suunto
5	Compass	Suunto
6	GPS	Gps Map 64S
7	Clipboard and pencil	Various

Appendix 5: Inventory field form

Date……………………...

Plot Data

Block name……………… Compartment name……..… Compartment age (yrs)……

Compartment area (ha)…….. Plot number.………

Thinning history……….........…*Thinned/Unthinned*…… Last thinning year………...

Plot coordinates: Easting……………… Northing…………………Elevation……..…

Tree data

S/ N	Tree no.	Branch no.	Diameter (cm)	Height (m)	Stem quality	Remarks
1						
2						
3						
-						
-						
30						

Plot remarks

Appendix 6: Adequacy of thinning for thinned compartments at Mtibwa Forest Plantation

SN	Comp name	Comp age (years)	Comp area (ha)	Present stocking (SPH)	Scheduled stocking (SPH)	Stocking deviation (SPH)*	Stocking deviation (%)
1	MT IV	6	54.3	1133	800	333	42
2	MT V A	8	17.95	950	800	150	19

3	MT V B	8	27.84	908	800	108	14
4	MT V C	8	32.86	558	800	(242)	(30)
5	MT V D	8	37.3	925	800	125	16
6	MT VII A	10	41.83	1033	800	233	29
7	MT X A	11	38.79	1033†	400	633	158
8	MT X B	11	7.15	675†	400	275	69
9	MT X C	11	19.58	850	400	450	113
10	MT VII B	12	47.25	367	400	(33)	(8)
11	MT VIII A	12	24.26	608	400	208	52
12	MT VIII B	12	56.5	575	400	175	44
13	LR XXIV & LR XXVI	12	7.6	467	400	67	17
14	LR II	18	5.76	450	300	150	50
15	LR III	19	7.3	358	300	58	19
16	LR XXI i	38	34.56	208	300	(92)	(31)
17	LR XVII i & ii	40	29.63	383†	300	83	28
18	LR XIII i	45	22.56	150†	300	(150)	(50)
19	LR XIII ii & iii	45	31.19	242	300	(58)	(19)
20	LR XIII iv & v	45	21.31	167†	300	(133)	(44)
21	LR XIII vi	45	19	175†	300	(125)	(42)
22	LR XII i	46	15.67	250	300	(50)	(17)
23	LR XII ii & iii	46	18.43	117†	300	(183)	(61)

* Stocking deviations with figures in brackets indicate understocking and vice versa for unbracketed figures.

† Stocking is statistically significantly different from scheduled stocking.

Appendix 7: Timing of thinning operations at Mtibwa Forest Plantation

S/N	Compartment name	Planting year	Compartment age (years)	Actual first thinning year	Scheduled first thinning year	First thinning timing	Thinning delay (years)
				First thinning			
1	MT IV	2012	6	Not thinned	2017	Delayed first thinning	1
2	MT V A	2010	8	2017	2015	Delayed first thinning	2
3	MT V B	2010	8	2017	2015	Delayed first thinning	2
4	MT V C	2010	8	2017	2015	Delayed first thinning	2

5	MT V D	2010	8	2017	2015	Delayed first thinning	2
			Second thinning				
1	MT VII A	2008	10	2018	2018	Timely second thinning	0
2	MT X A	2007	11	2018	2017	Delayed second thinning	1
3	MT X A	2007	11	2018	2017	Delayed second thinning	1
4	MT X C	2007	11	2018	2017	Delayed second thinning	1
5	MT VII B	2006	12	2018	2016	Delayed second thinning	2
6	MT VIII A	2006	12	2018	2016	Delayed second thinning	2
7	MT VIII B	2006	12	2018	2016	Delayed second thinning	2
8	LR XXIV & LR XXVI	2006	12	2016	2016	Timely second thinning	0
			Third thinning				
1	LR II	2000	18	2016	2015	Delayed third thinning	1
2	LR III	1999	19	2016	2014	Delayed third thinning	2

Appendix 8: List of surveyed compartments showing blocks, ages, areas and site classes at Mtibwa Forest Plantation

SN	Comp name	Block name	Age (years)	Comp area (ha)	Site class
1	MT IV	Mtibwa	6	54.3	I
2	MT V A	Mtibwa	8	17.95	I
3	MT V B	Mtibwa	8	27.84	I
4	MT V C	Mtibwa	8	32.86	I
5	MT V D	Mtibwa	8	37.3	II
6	MT VII A	Mtibwa	10	41.83	I
7	MT X A	Mtibwa	11	38.79	II
8	MT X B	Mtibwa	11	7.15	I
9	MT X C	Mtibwa	11	19.58	II
10	MT VII B	Mtibwa	12	47.25	II
11	MT VIII A	Mtibwa	12	24.26	I
12	MT VIII B	Mtibwa	12	56.5	I
13	LR XXIV & LR XXVI	Lusunguru	12	7.6	I
14	LR II	Lusunguru	18	5.76	II
15	LR III	Lusunguru	19	7.3	III
16	LR XXI i	Lusunguru	38	34.56	II
17	LR XVII i & ii	Lusunguru	40	29.63	II
18	LR XIII i	Lusunguru	45	22.56	III
19	LR XIII ii & iii	Lusunguru	45	31.19	II
20	LR XIII iv & v	Lusunguru	45	21.31	II
21	LR XIII vi	Lusunguru	45	19	II
22	LR XII i	Lusunguru	46	15.67	II
23	LR XII ii & iii	Lusunguru	46	18.43	III

Appendix 9: Site class I compartments with measured dbh, Hdom, BA, Vol and VMAI with their deviations in percentage

SN	Comp name	Age (years)	Dbh (cm)	S*_dbh (cm)	Dbh deviation (%)	Hdom (m)	S*_Hdom (m)	Hdom deviation (%)	BA (m2/ha)	S*_BA (m2/ha)	BA deviation (%)	Vol (m3/ha)	S*_Vol (m3/ha)	Vol_deviation (%)	Vol MAI (m3/ha/yr)	S*_Vol MAI (m3/ha/yr)	Vol MAI deviation (%)
1	MT IV	6	12.2	9.8	25	13.0	10	30	13.3	6.1	118	129.7	52.1	149	21.6	12.4	74
2	MT V A	8	12.7	13.6	(6)	13.0	13.4	(3)	12.1	11.6	4	118.3	114.7	3	14.8	17.2	(14)
3	MT V B	8	13.5	13.6	(1)	13.7	13.4	2	13.1	11.6	13	130.7	114.7	14	16.3	17.2	(5)
4	MT V C	8	15.2	13.6	11	14.0	13.4	4	10.1	11.6	(13)	101.8	114.7	(11)	12.7	17.2	(26)
5	MT VII A	10	15.8	17	(7)	16.2	16.5	(2)	20.3	18.1	12	220.1	198.0	11	22.0	22	0
6	MT X B	11	19.1	21.1	(10)	17.9	17.9	(0)	19.3	14	38	219.6	159.0	38	20.0	25.2	(21)
7	MT VIII A	12	21.1	22.7	(7)	19.2	19.2	0	21.2	16.2	31	250.0	191.0	31	20.8	25.8	(19)
8	MT VIII B	12	20.8	22.7	(8)	18.8	19.2	(2)	19.6	16.2	21	228.3	191.0	20	19.0	25.8	(26)
9	LR XXIV & LR XXVI	12	24.6	22.7	8	21.1	19.2	10	22.1	16.2	37	273.1	191.0	43	22.8	25.8	(12)

S* stands for figures scheduled in the yield tables for *Tectona grandis*

Figures in brackets indicate negative deviation and vice versa for unbracketed figures

Appendix 10: Site class II compartments with measured dbh, Hdom, BA, Vol and VMAI with their deviations in percentage

SN	Comp name	Age (years)	Dbh (cm)	S*_dbh (cm)	Dbh deviation (%)	Hdom (m)	S*_Hdom (m)	Hdom deviation (%)	BA (m2/ha)	S*_BA (m2/ha)	BA deviation (%)	Vol (m3/ha)	S*_Vol (m3/ha)	Vol_ deviation (%)	Vol MAI (m3/ha/yr)	S*_Vol MAI (m3/ha/yr)	Vol MAI deviation (%)
1	MT V D	8	11.7	11.3	4	12.0	11.4	6	10.0	8.1	24	94.3	73.7	28	11.8	10.5	12
2	MT X A	11	14.6	17.6	(17)	15.0	15.1	(1)	17.2	9.7	78	180.0	102.2	76	16.4	14.3	14
3	MT X C	11	13.8	17.6	(21)	13.8	15.1	(9)	12.7	9.7	31	127.9	102.2	25	11.6	14.3	(19)
4	MT VII B	12	20.8	19	10	17.4	16.2	8	12.5	11.3	11	140.8	122.7	15	11.7	14.8	(21)
5	LR II	18	23.9	26.6	(10)	20.4	21.1	(3)	20.1	16.7	20	244.2	206.4	18	13.6	16.2	(16)
6	LR XXI i	38	38.6	34.3	13	27.9	26.6	5	24.4	27.6	(12)	345.3	381.8	(10)	9.1	12.3	(26)
7	LR XVII i & ii	40	32.4	34.5	(6)	26.4	26.8	(2)	31.5	28.0	13	432.8	387.9	12	10.8	11.8	(8)
8	LR XIII ii & iii	45	35.1	34.9	0	26.2	27.1	(3)	23.3	28.6	(18)	319.8	398.9	(20)	7.1	10.8	(34)
9	LR XIII iv & v	45	36.3	34.9	4	25.4	27.1	(6)	17.2	28.6	(40)	233.0	398.9	(42)	5.2	10.8	(52)
10	LR XIII vi	45	36.4	34.9	4	25.6	27.1	(5)	18.2	28.6	(37)	246.6	398.9	(38)	5.5	10.8	(49)
11	LR XII i	46	35.6	34.9	2	26.8	27.1	(1)	24.9	28.6	(13)	345.1	398.9	(13)	7.5	10.8	(31)

S* stands for figures scheduled in the yield tables for *Tectona grandis*

Figures in brackets indicate negative deviation and vice versa for unbracketed figures

Appendix 11: Site class III compartments with measured dbh, Hdom, BA, Vol and VMAI with their deviations in percentage

SN	Comp name	Age (years)	Dbh (cm)	S*_dbh (cm)	Dbh deviation (%)	Hdom (m)	S*_Hdom (m)	Hdom deviation (%)	BA (m2/ha)	S*_BA (m2/ha)	BA deviation (%)	Vol (m3/ha)	S*_Vol (m3/ha)	Vol_ deviation (%)	Vol MAI (m3/ha/yr)	S*_Vol MAI (m3/ha/yr)	Vol MAI deviation (%)
1	LR III	19	18.9	22.1	(14)	15.9	17.7	(10)	10.1	11.5	(13)	18.9	22.1	(17)	5.7	9.5	(40)
2	LR XIII i	45	35.8	28.1	27	24.6	22.1	11	15.1	18.5	(18)	35.8	28.1	(14)	4.5	6.3	(29)
3	LR XII ii & iii	46	33.8	28.1	20	22.4	22.1	1	10.5	18.5	(43)	33.8	28.1	(43)	2.9	6.3	(54)

S* stands for figures scheduled in the yield tables for *Tectona grandis*

Figures in brackets indicate negative deviation and vice versa for unbracketed figures

Appendix 12: Relative correction factors by compartments and site classes

SN	Comp name	Site class	Age (years)	Relative correction factor (f)
1	MT IV	I	6	2.18
2	MT V A		8	1.04
3	MT V B		8	1.13
4	MT V C		8	0.87
5	MT VII A		10	1.12
6	MT X B		11	1.38
7	MT VIII A		12	1.31
8	MT VIII B		12	1.21
9	LR XXIV & LR XXVI		12	1.37
	Average for site class I			**1.29**
1	MT V D	II	8	1.24
2	MT X A		11	1.78
3	MT X C		11	1.31
4	MT VII B		12	1.11
5	LR II		18	1.20
6	LR XXI i		38	0.88
7	LR XVII i & ii		40	1.13
8	LR XIII ii & iii		45	0.82
9	LR XIII iv & v		45	0.60
10	LR XIII vi		45	0.63
11	LR XII i		46	0.87
	Average for site class II			**1.05**
1	LR III	III	19	0.87
2	LR XIII i		45	0.82
3	LR XII ii & iii		46	0.57
	Average for site class III			**0.75**