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Optimal Rotation Age of *Pinus patula* in Government Forest Plantations in Tanzania

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ABSTRACT

A study to determine the optimal rotation age of *Pinus patula* was conducted in five forest plantations in Tanzania, i.e., Kawetire, Kiwira, North Kilimanjaro, West Kilimanjaro and Meru. Growth and yield, and mechanical properties data were collected from compartments representing age from 5 to 25 years. In addition, revenues and management costs data were collected for the purpose of determining the economic rotation age. For the purpose of determining the optimal rotation age based on growth and yield, the following basic models were developed: 1) site index curves model, 2) height-D model, 3) Single tree volume model, 4) Basal area growth model 5) stand volume model, 6) mortality model, and 7) simulation of thinning. Analysis of Variance (ANOVA) was carried out to ascertain whether the wood properties vary across age classes. Economic analysis of rotation age data involved computation of Net Present Value (NPV). Growth and yield data revealed irrespective of site class, *P. patula* can be harvested at age of 18 years while mechanical wood properties show that harvesting ages range between 16 and 21 years. Based on NPV, the optimal age was 16 years. Therefore, it is recommended *P. patula* be harvested at age of 18 years irrespective of site class.

Key words: Growth and Yield Models - Mechanical Properties - Net Present Value - Rotation Age.

INTRODUCTION

Plantation forestry in Tanzania (then Tanganyika) started during the German rule (1891-1914) with the establishment of nursery and field plantation trials. When the British took over the country after World War I, nursery, species/provenance trials and trial plantings using indigenous and exotic tree species were continued. It was also realised that the rate of growth of indigenous trees was slow, and it was therefore decided that fast growing exotic tree species be planted instead. Thus, in the early 1950s, large scale forest plantations based on exotic tree species commenced in various parts of the country. The objectives of establishing forest plantations were to ensure sustainable supply of forest products to the forest-based industries, communities, and for export. In addition, plantations near catchment areas were intended to buffer natural forests and thus increase their watershed protective capacity.

A total of 23 state-owned industrial plantations have been established covering about 117,000 ha (MNRT, 2015). In addition to the state-owned plantations, the private sector, including small scale tree growers, manages plantations and forest industries. These privately owned plantations are estimated to cover about 400,000 ha (Ngaga 2011).

The main species planted in plantations include *Pinus patula, P. elliottii, P. caribaea, Cupressus lusitanica, Eucalyptus maidenii,* *E. saligna*, *Tectona grandis*, *Grevillea robusta* and *Acacia mearnsii*. Pines are the dominant species in most of the government and private plantations occupying over 60% of the total area planted and the remaining area is shared among hardwoods and other softwood species (Ngaga 2011).

When plantation establishment started in the 1950s, there were no trials on plantation establishment and management (spacing, thinning and pruning) techniques and consequently these techniques were initially based on South African management practices (Nshubemuki *et al.* 2001). South Africa was a natural choice because of the long-term experience with forest plantations and some of the tree species were similar to those chosen for large scale planting in Tanzania. However, as research results became available, new Technical Orders were issued to revise the inherited management practices.

The Forest Department in 1956 issued the first Technical Order for thinning *P. patula*, *P. radiata*, *C. lusitanica* and C. *benthamii* with 6 thinnings and clearfelling at 40 years (Forest Department 1956). The Technical Order was revised in 1962 (Forest Division 1962) with 5 thinnings for *P. patula* and *C. lusitanica* and rotation ages of 25 (site class I), 30 (site class II), and 35 (site class III). The thinning schedule for *P. patula* was revised in 1970 by reducing thinnings from 5 to 4 (Forest Division 1970) and retaining the rotation ages. There are also thinning schedules for *T. grandis* and *Terminalia ivorensis*, but these appear in the forest plantation management plans and were thus not given as Technical Orders (Hyytiainen 1992). In 2003, a Technical Order was issued for Pines, Cypress and *T. grandis* with rotation age of 25-30 years for Pines and Cypress and 30-40 for Teak (FBD 2003).

To-date, Tanzania has large forest plantations with compartments covering broad range of age classes, sites and rotations. These plantations are able to provide useful information that can be utilized to update the management practices particularly rotation age. It is against this background, this study aims to review the rotation ages of *P. patula* in selected forest plantations by considering wood properties, growth, yield and economic aspects. These considerations have never been used simultaneously when establishing the Technical Orders in the past.

METHODOLOGY

Study sites

The study on determination of rotation age of *P. patula* was carried out at Kiwira and Kawetire forest plantations in the southern highlands; and Meru, North and West Kilimanjaro Forest plantations in northern Tanzania (Table 1).

Table 1: Study sites for determination of tree rotation age

Name of Forest Plantation	Plantation Area (ha)	Location and Altitude	Mean/Range in Rainfall (mm)	Mean Annual Temperature	Soil
Meru	5,530	Lat 3°15'- 3°18' S; Long 36°41'- 36°42' E; Alt 1,500 – 2,500 m.a.s.l.	844-1,040	20°C	Deep, dark brown or black volcanic soils and well-drained
Kiwira	2,784	Lat 9° 00'- 9° 03'; Long 33° 37' - 38° 42' Alt 2,225 – 2,440 m.a.s.l.	1,707	16.9-38.6°C	Thin fine dark volcanic ash with silt and OM
West Kilimanjaro	6,020	Lat 2° 59-3 10' Long 2° 30' – 37° 10'; Alt 1,562–3,125 m.a.s.l.	700	15 - 20°C	Volcanic, porous and free draining
North Kilimanjaro	6,754	Lat 3°05' 3°15' S; Long 37° 15' – 42° 00' E; Alt 1,800- 2,250 m.a.s.l.	800	16°C	Volcanic, well drained and fertile

Name of Forest Plantation	Plantation Area (ha)	Location and Altitude	Mean/Range in Rainfall (mm)	Mean Annual Temperature	Soil
Kawetire	1,956	Lat 8°30’- 8°49 S; Long 33°29’ –33°31’ E; Alt 2, 235 – 2,900 m.a.s.l.	1,099	17°C	Black loam soils rich in clay particles

Study design and data collection

Growth and yield data

The relevant collected data were guided by the different models that need to be developed before being integrated to a yield model. For pure even-aged plantations the following basic models are required: 1) Site index curves model, 2) Height (*H*) - diameter at breast height (*D*) model, 3) Single tree volume model, 4) Basal area growth model, 5) Stand volume model. To make this possible, suitable compartments in selected forest plantations were selected. Selection criteria were age (15-20 years), thinning status (both thinned and un-thinned compartment) and stocking level (understocked compartments were not selected such that a plot must contain 15 – 20 trees). The sampling design was systematic where the number of plots ranged from 60 to 100 depending of compartment size. The shape of the plots was circular with a radius of 15 m. In each plot, the following measurements were taken: *D* of all trees, five years radial growth, bark thickness, height of sample trees (intermediate *D*) and dominant height of 3 fattest trees in each plot. In addition, one dominant tree in each plot with age above 15 years old was felled for ring counting. Each tree was cross-cut at an interval of 4 m and annual growth rings were counted at the top end of each log. These data were used for site indexing. The reference age used for site indexing was 15 years.

Wood utilization properties data

Three defect-free trees of different sizes (small, medium and large) were selected and felled in each compartment. Each log was cut into three billets of 1.5 m representing the butt (1.3 m), middle (50% height) and the top (75% height). The billets were sent to Moshi Timber Utilisation Research Centre for the determination of wood properties. Physical and mechanical properties were determined using various methods as follows (British Standards 1957, ISO 1975):

i. Moisture content: Wood samples were weighed when green and oven dried at 103 ± 2^{0}C to constant weight. The weight of each wood sample was recorded for determination of moisture content.

ii. Basic density (BD): For each tree, 12 specimens were measured (5 butt, 4 middle and 3 top). The volume of each specimen was determined by water displacement method. The samples were dried at 103 ± 2°C to constant weight.

iii. Static bending: This was measured using Hounsfield Tensiometer machine. In this test, 30 specimens per tree (10 butt, 10 middle and 10 top) were measured. A specimen measuring 20 x 20 x 300 millimetre (mm) was supported over a span length of 280 mm. Load of the force plate and corresponding deflection were recorded from the dial gauge manually. Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) were determined.

iv. Impact bending (IB): IB was measured using Hatt Turner Machine. A total of 15 specimens per tree were measured (5 butt, 5 middle and 5 top). A hammer with a weight of 1.5 kilogrammes (kg) was released towards a stationary specimen (20 x 20 x 300 mm) at variable distances until breakage and the height of hammer drop was recorded in cm or m.

v. Compression parallel to the grain (CPG): 30 specimens per tree (10 butt, 10 middle and 10 top) were measured in this test. CPG was measured using Hounsfield Tensiometer machine. Each specimen with dimension of 20 x 20 x 60 mm was compressed in the direction of the length of a sample at a constant rate. Force that caused crushing of wood was recorded.

vi. Shear strength (SS): A total of 30 specimens per tree (10 butt, 10 middle and 10 top) were measured for SS. SS was measured using Hounsfield Tensiometer machine. Specimens with dimensions of 20 x 20 x 20 mm were each subjected to a force which tends to force one portion of it to move over the other in the direction parallel to grains using machine. This aimed to measure the ability of wood to resist the force. Maximum force used in this test was recorded.

vii. Hardness of wood (Hard): A total of 30 specimens per tree (10 butt, 10 middle and 10 top) were measured for hardness of wood using Hounsfield Tensiometer machine. Specimens with dimensions of 2 x 2 x 4.5 centimetre (cm) were used in which maximum load required to penetrate a steel ball of 1.128 cm to half of its diameter either radially, tangentially or end surfaces of the specimen was determined and recorded.

Economic rotation age data

To estimate Net Present Value (NPV) at the respective age of forest stands, the following data were collected: data of growing stock of each site class for each forest plantation as described in section 2.2.1 were used. Revenues in Tanzania Shillings per cubic meter (TZS/m^3), and management costs (TZS per ha) were estimated from data collected from each forest plantation. It was assumed that a single product was to be harvested from the forest stands i.e., timber to be harvested at the assumed rotation age between 15 -25 years and thinning at 10 and 15 years. Interest rates were obtained from literature and commercial bank data base.

Data Analysis

Growth and yield data

Site indexing

The ring count data from the dominant trees were first converted into dominant height-Age data to display the height growth trend of each tree over age. The Chapman-Richards model (eq. 1) was selected among other models in the literature and fitted to the data. It has been reported that the Chapman-Richards model provide good fit particularly site indexing model for *P. patula* (Malimbwi 1987, Malimbwi *et al.* 1998, Malimbwi 2016a).

$$Hdom = a \times site \times (1 - exp(-0.0923 \times Age))^c \quad (1)$$

Where:

Hdom = dominant height (m) *a*, *b*, and *c* are coefficients to be estimated,
Site = site index, which is the dominant height at the reference age of 15 years.

Height - diameter equation

Since forest inventory measured *H* of the representative sample trees, it was important to establish height-diameter relationship. The Naslund equation (eq. 2) was used to fit *H* - *D* equation to estimate the height of trees that were not measured for *H*. Since, the eq. 2 is non-linear, the models were fitted using maximum likelihood (ML) regression techniques which address the problem of heteroscedasticity (Henry *et al.* 2010, Mauya *et al.* 2014, Mugasha *et al.* 2013). The ML technique fits both model and variance parameters ($variance = a^2x^b$, where *a* and *b* are parameters to be estimated; and *x* is single or combination of variables). However, parameters for the variance were not presented.

$$H = 1.3 + \frac{D^2}{a + b \times D^2} \quad (2)$$

Where: H is total tree height; D is diameter at breast height; and a and b are parameters to be estimated.

Single tree volume and stand parameters models

Data used for site indexing was also used to develop volume equation after converting sectional logs parameters, i.e., log length and mid-diameter, to volume using Hubers formula. The tree volume was obtained by summing up volume of individual logs including cone. Stand volume and basal area models required stand volume and basal area computed from the plot data. Single tree volume was estimated using developed single tree volume model. All the three models were fitted using log-tranformed linear model (eq. 3) to take into account the heteroscedasticity of the data on the original scale (Chave *et al*. 2014, Djomo *et al.* 2016, Fayolle *et al*. 2013). However, this transformation introduces a systematic bias on the original scale that is corrected with a correction factor CF = exp($SE^2/2$), where RSE is the residual standard error. Therefore, for this study a correction factor CF = $SE^2/2$ was added to the exponent. The main predictors of the single tree volume and stand parameters (basal area and volume) were H and D; number of trees per ha (N), G, and *Hdom*, respectively. Different combinations of independent variables were fitted where the models with small Akaike information criterion (AIC) were selected. The models were fitted using *lm* function in R (R Core Team, 2020).

$$\log(Y) = \exp(a + b \times log(X_i) + c \times \log(X_{ii}) + \cdots \quad (3)$$

where:

Y are dependent variables (single tree volume, stand basal area and volume); a, b, and c are model coefficients.

Current annual increment, Mean annual increment and Rotation age

The mean annual increment (MAI) and current annual increment (CAI) follow the expected trends where MAI increases to a maximum where it equals CAI. The CAI, which is also the marginal increase, drops rapidly after faster increase in the early years. Optimal rotation age is the age when MAI is at its maximum. It is also the age when MAI=CAI. Using growth and yield data CAI and MAI were computed.

Wood utilisation properties data

Statistical Analysis Software (SAS) were used to whether MOE, MOR, Wm, Wt, HARD, IB, CPG and SS varies across age and site classes by carrying out Analysis of Variance (ANOVA) procedure. The Least Significant Difference (LSD) method was used for means separation at $p \leq 0.05$ (SAS Institute, 2000).

Economic analysis of rotation age

The average net value was calculated for the period between age 10 and age 25. The age volume (stand) and thinning volume was estimated by present cutting value method (as applied by Osavec *et al*. (2011) and CAI and MAI data from growth and yield data. Silvicultural, protection and administrative costs were estimated by using data collected from the plantations. Silvicultural, protection and administrative costs were assumed to decrease by 0.05% as age increases. That means early ages had higher costs than older ages. The net value was calculated by multiplying average revenue in TZS/m^3 by the attained volume due to standing trees and some thinning. Interest rate was one of variables used for determination of economic rotation age. Interest rate charged on commercial investments varies between financial institutions, nature of activities to be implemented and risk level. However, the overall interest rate of commercial banks in Tanzania is around 16% and 14%. Therefore, for determination of the NPV in this study, an interest of 15% was used.

RESULTS AND DISCUSSION

Spacing, pruning and thinning operations in the assessed compartment

Data for this study was collected from *P. patula* plantations planted at initial spacing of 2.5 x 2.5 m. Since 2003, spacing for *P. patula* has been changed to 3.0 x 3.0 m (FBD 2003). Pruning and thinning operations in the assessed compartments are shown in Tables 2 and 3. Table 2 shows that four compartments received two prunings while 13 received all three prunings. Four compartments had received one thinning, seven had received two thinnings and six had received three thinnings (Table 2). Thinning operations were fewer and lighter than specified in the respective schedules, resulting in many small diameter stems per ha (SPH) (Figures 1-2). All compartments have mean Dbh below 40 cm. The main reason given for the neglect of pruning and thinning operations is budgetary constraints. The neglect of both pruning and thinning operations in public sector plantations has been pointed out in previous studies (Nshubemuki *et al*. 2011, Chamshama and Nshubemuki 2011). Knotty and small diameters trees result in poor quality timber, low recovery and consequently lead to low financial returns.

Table 2: Pruning and thinning history for *Pinus patula*

Plantation	Compartment	Age (Years)	No of prunings	No of thinning
North Kilimanjaro	Kamwanga No.31	18	2	1 (combined)
	Endonet No. 97	19	2	1 (combined)
	Endonet No. 100	21	2	1 (combined)
	Rongai No. 236	20	2	1 (combined)
West Kilimanjaro	Wasendo No. 24	21	3	2
	Lemosho No. 141	18	3	2
	Lemosho No. 140	20	3	2
	Lemosho No. 146	21	3	2
	Wasendo No. 69	22	3	3
Meru	Olmotonyi No. 152	18	3	2
	Olmotonyi No. 156	17	3	2
	Nadingoro No. 91	22	3	3
	Nadingoro No. 92	20	3	3
	Narok No. 170	21	3	3
	Narok No. 177	23	3	3
Kiwira	11m/12F	14	3	2
	11J	20	3	3

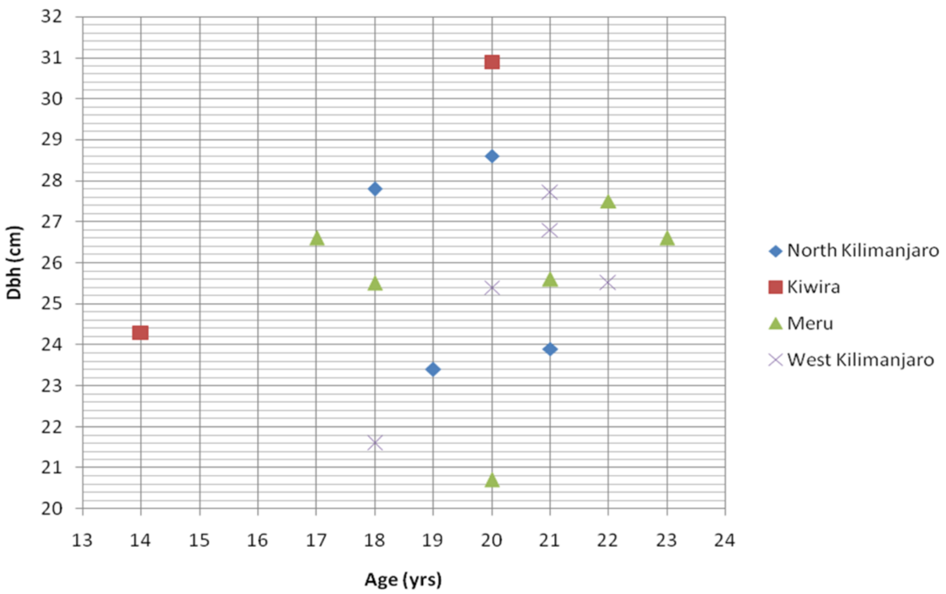

Figure 1: Mean Dbh against age for *P. patula* from different plantations in Tanzania

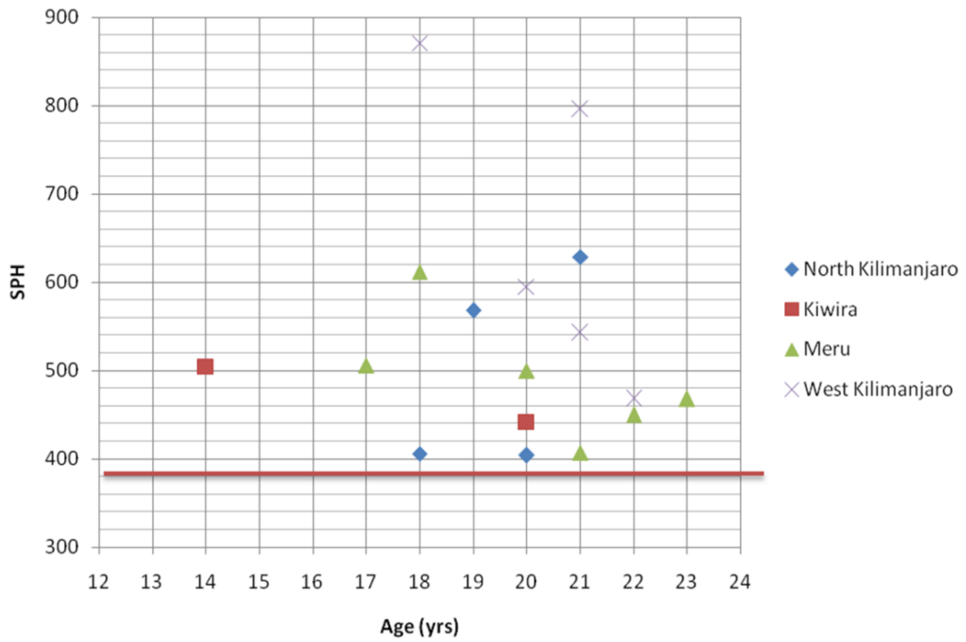

Figure 2: Mean SPH against age for *P. patula* from different plantations in Tanzania

Growth and yield

The composite models for developing yield tables for *P. patula* were developed as shown in Appendix 1. All the models had good fits with R^2 ranging from 0.77 (*H* - *D* model) to 0. 99 (stand volume model). The site index curves depict height growth driven by age for three site classes for each species (Figure 3). For a compartment of known age and dominant height, the site class is selected from the site index curves, which in turn indicates the appropriate yield class for forecasting yield from the yield table.

The stand basal area growth model is a function of the surviving number of stems and the dominant height at that age. The stand volume is explained by dominant height and stand basal area with almost a perfect fit of R^2 0.99 from the raw data. The integration of these models resulted into the yield tables for *P. patula*.

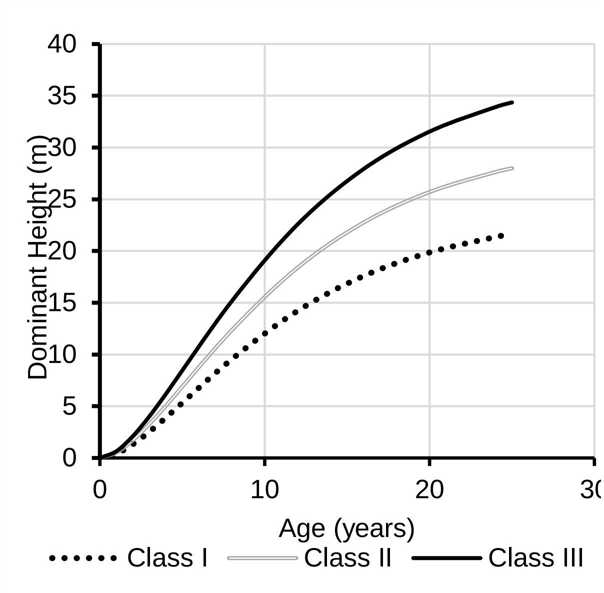

Figure 5: Site index curves for *P. patula* in Tanzania (black, grey, and dotted curves represent site classes I, II and III respectively)

Mortality model

Mortality assumes that below the age of 6 years there is no mortality since the trees are growing almost free of competition. Thereafter, mortality may set in. The model assumes that there is no mortality by competition after thinning has been carried out until such time when the stocking predicted by mortality model exceeds the stocking of the thinned stand. When this happens, mortality sets in. Several models were tested to predict N but none showed satisfactory performance. This is due to the uneven stocking in the plantations probably due to fire and the fact that some stands originated from natural regeneration which were unevenly singled. An existing model developed for Sao Hill *P. patula* plantations (Malimbwi *et al.* 1998), Eq. 4, was adopted and it appeared to perform well. The model was:

$$N_R = 1408 \times \exp\left(-0.0341 \times age\right) \qquad (4)$$

N_R is the remaining trees after mortlity has taken place.

Simulation of thinning

Just as it was observed with mortality, there were no suitable data and records for estimating removals by thinning. Therefore, an equation adopted for *Cupressus lusitanica* (Malimbwi 1984) was used (Eq. 5).

$$Y = \exp\left(4.143 \times K - 2.8\right) \qquad (5)$$

Where Y is the basal area fraction removed relative to basal area before thinning; and K is the fraction of number of trees removed.

Optimum rotation age based on growth and yield

The equity point of MAI and CAI was achieved at between 16 and 17 years with the maximum MAI being maintained until about 20 years when it starts falling irrespective of site classes (Figure 5). This could be attributed to improper management of the sites as the yield table assumed properly managed stands while the empirical data were from improperly managed stands. It is expected that data from properly managed stands could differentiate rotation age by site classes whereby better sites are expected to mature earlier than poor sites.

Taking into account all these observations, the yield studies recommend rotation ages for *P. patula* to be from 18 years of age irrespective of site class. Earlier rotation age for was 25. This study shows that the ages could be reduced substantially.

Wood utilisation properties

Basic density

The basic density (BD) of *P. patula* wood from different plantations ranged from 370 to 485 kg/m^3 and increased with age (Table 3). These values and trends have been reported in other studies (Bryce 1967, Chihongo, 2003, Felix *et al.* 2014). Based on FAO (2010) standards, wood from *P. patula* harvested below 17 years from all forest plantations are weak since they have BD which is less or equal to 400 kg/m^3 while wood of 17 to 25 years had BD ranging from 401 to 485 kg/m^3 which is fairly strong. According to FAO (2010), wood with BD $\geq$ 401and $\leq$ 500 are fairly strong hence *P. patula* can be harvested at age $\geq$ 17 years.

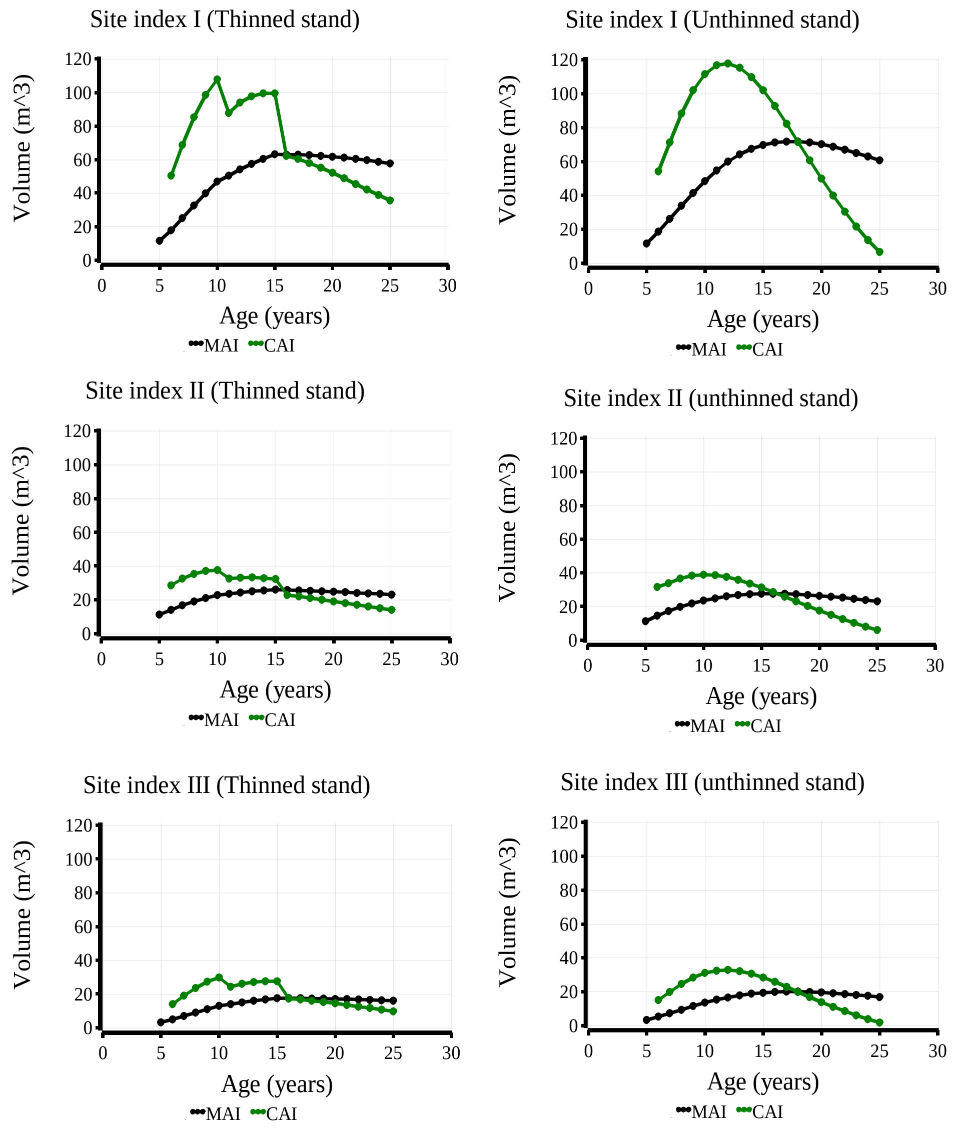

Figure 5: Development of MAI & CAI (m^3/ha) for thinned and un-thinned stands of *Pinus patula* in Tanzania

Table 3: Mean basic density of *P. patula* grown in different forest plantations

Plantation name	Age (yrs)											
	11	15	16	17	18	19	20	21	22	23	24	25
Kiwira	373.4	-	400.5	438.2	451.5	-	-	-	-	-	-	-
Kawetire	-	-	400.4	-	-	-	-	404.8	468.5	454.7	452.7	456.7
North Kilimanjaro	-	388	405	479	478	475	485	-	-	-	-	-
West Kilimanjaro	-	-	394	402	403	417	427	423	-	-	-	-
Meru	-	370	393	-	401	406	403	-	429	-	434	-

Mechanical properties

Mechanical properties of *P. patula* are shown in Figures 6 - 8. Generally, the mechanical properties increased with age as found in other studies (Bryce 1966, 1967, Saravanan *et al*. 2013, Makonda *et al*. 1998, Hamza *et al.* 1999, Ishengoma and Gillah 1992, Izekor *et al*. 2010). The results show that for the same age, sites have influence on mechanical properties. Mean MOE ranged from 5831 to 8734 N/mm^2, MOR from 19.7 to 56.9 N/mm^2 and CPG from 26 to 43 N/mm^2 for all *P. patula* plantations under study (Figures 6 - 8). There was no significant difference in utilization properties of *P. patula* between 16 and 25 years ($p > 0.05$). The MOE, MOR and CPG values for *P. patula* obtained in this study are similar to those reported in other studies (Bryce 1967).

FAO (2010) standards for mechanical properties are usually based on four strength properties such MOE, MOR, CPG and SS. The SS is based on beams and joints and therefore not considered in this study. According to FAO (2010) the minimum values of strength properties for wood to be considered strong are MOE $\geq$ 7500N/mm^2; MOR $\geq$ 20 N/mm^2 and CPG values $\geq$ 13 N/mm^2. Based on these standards, the minimum ages for *Pinus patula* are: Kiwira 17 years, Kawetire 21 years, North Kilimanjaro 17 years, West Kilimanjaro 21 years and Meru 16 years. While for Kawetire younger ages were not available for sampling, West Kilimanjaro seems to attain the required strength properties at a later age compared to other plantations.

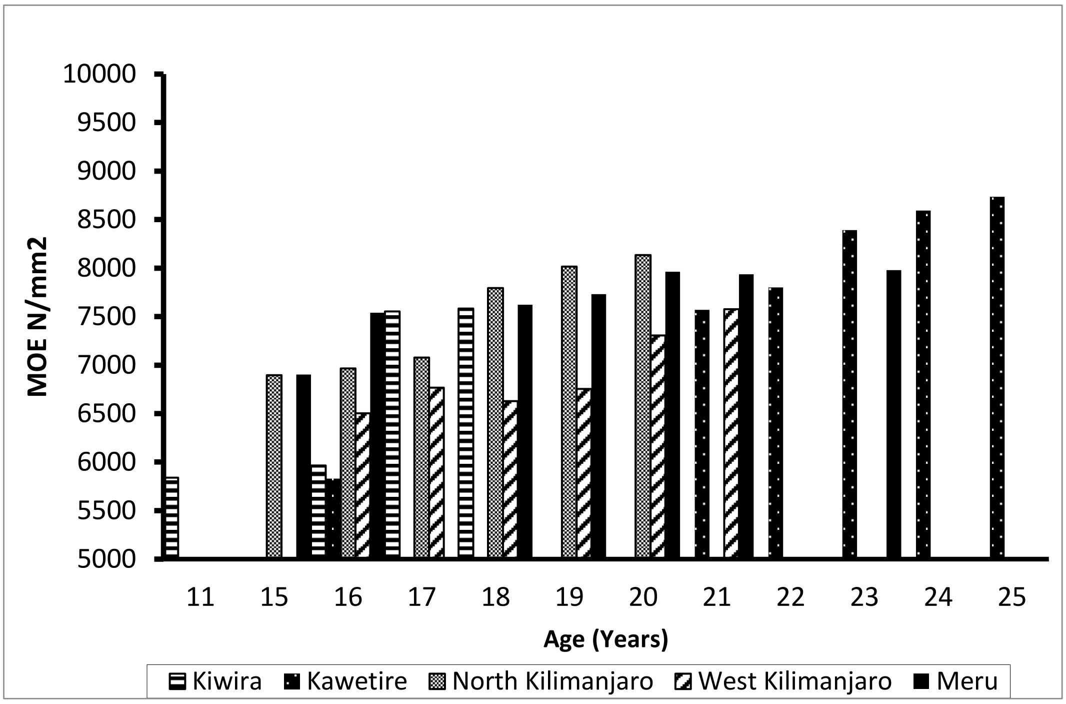

Figure 6: MOE values for *P. patula* wood from different plantations

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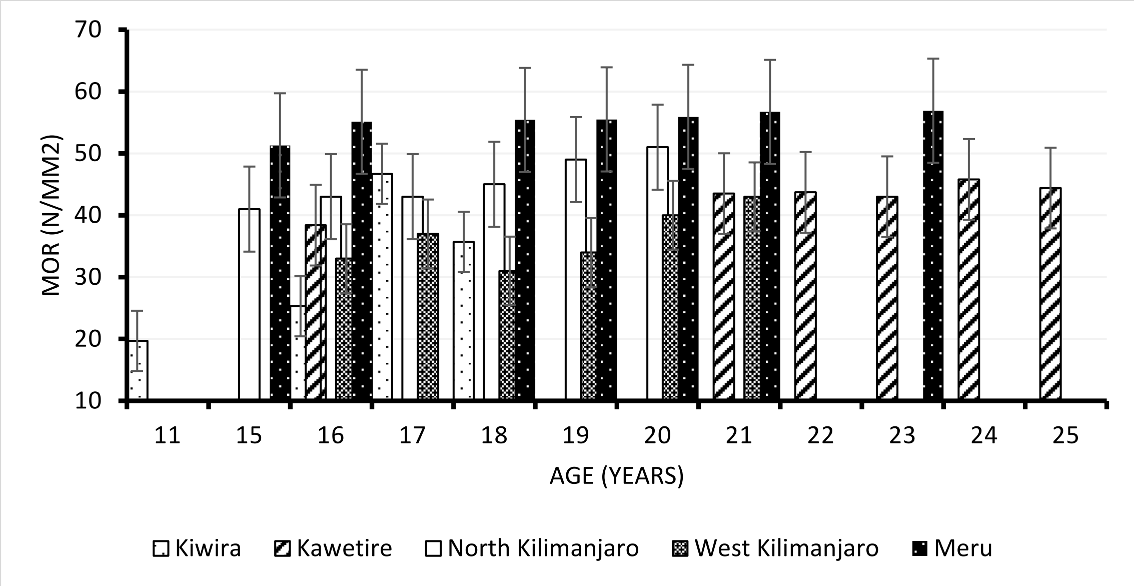

Figure 7: MOR for *P. patula* wood from different plantations.

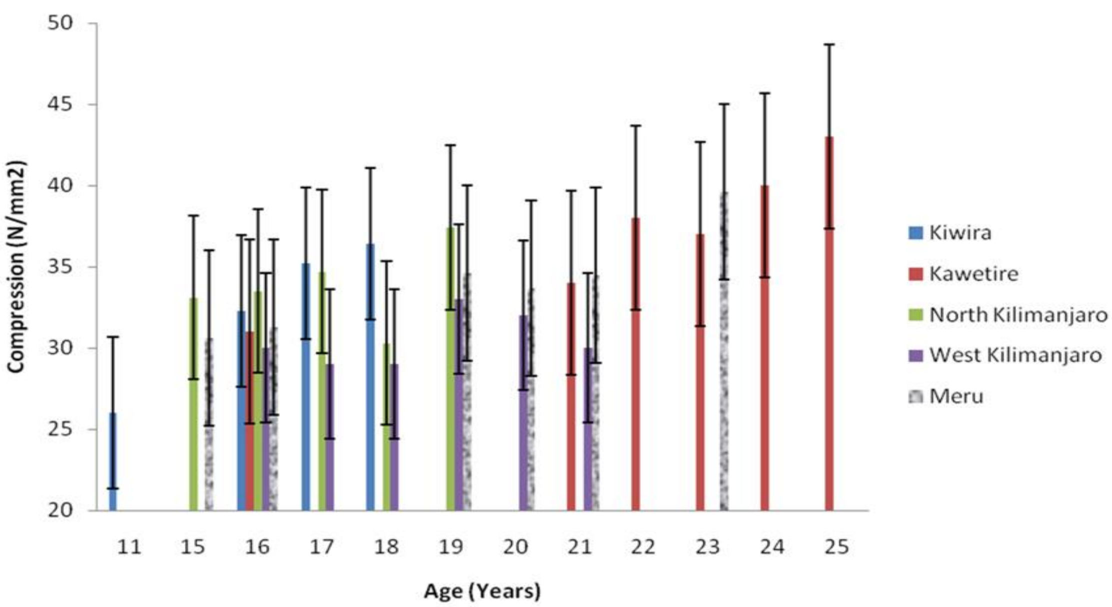

Figure 8: CPG values for *P. patula* wood from different plantations

Economic analysis of rotation age

Management costs

Tables 4 and 5 present direct and indirect management costs for *P. patula*. The direct costs captured were silviculture and protection. Silviculture included: land preparation, pitting, seedling transportation and planting, thinning and weeding and climber cutting. The indirect costs were maintenance and administrative costs. The administrative costs were various including office equipment, maintenance of buildings, vehicles, bridges and culverts. Other costs under this category were allowances for extra duty, medical, uniforms, furniture, telephone, postage, stationary, burial, fare, meeting/honoraria, training, electricity, refreshment/meals, security guards and newspapers. Costs for estimation of the rotation age were the average of the silviculture, protection, road maintenance, culverts, bridges, and administration costs of the plantations.

Table 4: Management costs estimates (TZS) for *P. patula* plantations.

Cost Items	Kiwira	Kawetire	West Kilimanjaro	North Kilimanjaro	Meru
Land preparation	12,000	113,335.38		23,367.99	
Planting	3,780,000	125,466.80		142,955.66	
Beating up	9,000	90,344.79		64,247.07	90,256.02
Weeding	54,000	69,333.33		81,620.87	
Pruning	15,000	78,298.70	227,905	69,357.16	38,654.22
Thinning	1,200,000		63,043		31,998.00
Protection (patrol, fire line, boundary clearing & fire campaign)	5,000	76,355.91	21,289	7,252.95	
Clear felling	24,000			428,794.51	
Rehabilitation of forest roads, running and maintenance of vehicles and motor cycles and administration				316,692,215.68	

Revenues

The obtainable revenue depended on Dbh and size of the merchantable height of the trees. For *P. patula*, the lowest revenue (22,015 TZS/m^3) was recorded in 2015/2016 in Kiwira and highest was 65,071.09 TZS/m^3 obtained in 2015/2016 in North Kilimanjaro (Table 5). On average *P. Patula* yield revenue of 41,348 TZS/m^3 that was calculated by averaging the revenue (TZS/m^3) from all plantations between 2012/2013 and 2015/2016 (Table 5). This revenue is within that received in other plantations Tanzania e.g., in Sao Hill, *P. Patula* is sold at between TZS 40,000 and 60,000 TZS/m^3.

Table 5: Revenues for *P. patula* plantations.

Financial year		2012/2013	2013/2014	2014/2015	2015/2016
West Kilimanjaro	**ha**	236	169	203	423
	m^3	14,000.05	15,043.21	6,526.30	10,716.00
	TZS/m^3	40,586	42,782	62,757	29,459
	Age	25	25	18	48
Meru	**ha**	41.5	25.84	124.03	52.4
	m^3	7,476	2,056	6,488	10,029
	TZS/m^3	20,611.87	27,442.67	20,612.00	52,303.24
	age	25	25	24	23
North Kilimanjaro	**ha**	81	87	81	41
	m^3	16,370	14,954	11,842	13,294
	TZS/m^3	32,115.10	42,141.56	58,111.38	65,071.09
	age	25	20	20	21
Kawetire	**ha**				
	m^3		17,637	17,500	9,841
	TZS/m^3		42,810	50,419	54,069
	age		25	25	18
Kiwira	**ha**			96.3	110.9
	m^3			24,632	22,015
	TZS/m^3			44,353	40,310
	Age			20	21

Economic rotation age estimation for P. patula

According to the calculation of the main parameters for *P. patula* stand value and forest management costs (silvicultural costs and administrative and infrastructure maintenance costs) from Figure 15, achieved economic rotation is highest at the age between 16 and 17 regardless of the site class. Therefore, it is economically feasible to start harvesting the *P. patula* stands at the age between 16 and 17.

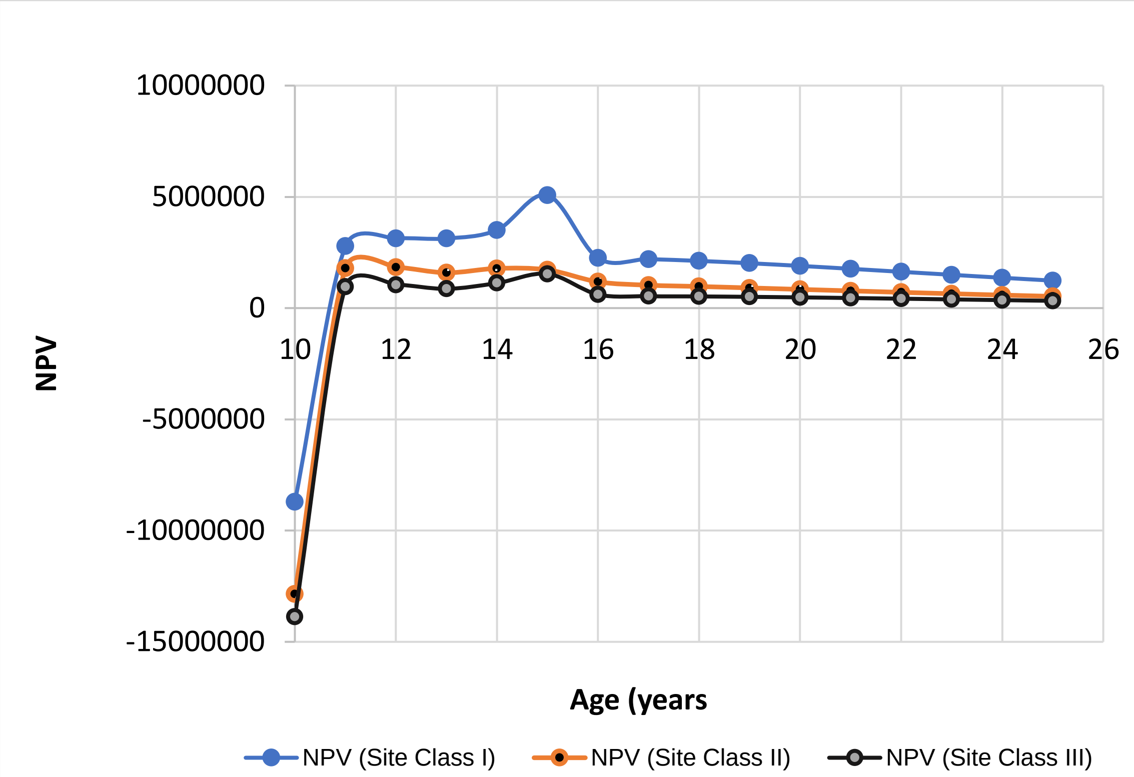

Figure 15: Economic rotation age estimation for *P. patula*.

CONCLUSION AND RECOMMENDATIONS

Results show that *P. patula* pruning and thinning operations were fewer and lighter than specified in the respective schedules, resulting in many small diameter stems. Results of growth and yield show that irrespective of site class, *P. patula* can be harvested at 18 years while based on mechanical wood properties, the harvesting ages for *P. patula* for the different plantations range between 16 and 21 years. Based on economic analysis, *P. patula* can be harvested at age above 16 years old because they revealed higher NPV. Based on considerations of growth and yield, wood properties and economics of rotation age, *P. patula* is recommended to be harvested at 18 years irrespective of site class. With proper thinning, trees will attain the recommended mean diameter and thus improve recovery.

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APPENDICES

Appendix 1: Composite models for yield table development of *P. patula* in Tanzania.

Model name	Model Expression	R^2	SE	n
Site index curves model	$Hdom = 1.4098 \times (1 - \exp(-0.116711 \times \text{Age}))^{1.844827}$	0.95	11.4	207
Height-Dbh model	$H = 1.3 + \frac{D^2}{13.63898 + 0.02648 \times D^2}$	0.77	6.98	1142
Single tree volume model	$V = \exp(-9.1040 + 2.1060 \times \ln(\text{N}) + 0.5211 \times \ln(H))$	0.82	0.16	209
Basal area growth model	$BA = \exp(-9.12628 + 0.9228 \times \ln(\text{N}) + 2.19596 \times \ln(Hdom))$	0.96	0.09	373
Stand volume model	$V = \exp(0.4403 + 0.6011 \times \ln(\text{Hdom}) + 1.01107 \times \ln(\text{BA}))$	0.99	0.09	373
Mortality model	$N_R = 1408 \times \exp(-0.0341 \times age)$	-	27	120
Simulation of Thinning	$Y = \exp(4.143 \times K - 2.8)$	-	-	-

Where:

Hdom= dominant height (m);
D = diameter at breast height (cm),
H = total tree height (m);
site=site index (m);
BA = stand basal area M^2/ha);
volume = single tree volume (m^3);
Volume = stand volume m^3/ha).

Note: for the linear equations, correction factor has been made to the intercept.