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

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Abstract

Globally, multiple ecosystem services are increasingly becoming an important agenda in sustainable forest management. However, it is still unclear which forest management practices would lead to an optimal bundle of ecosystem services promoting sustainability. This study aimed to determine whether implementing thinning schedule and 30 years rotation age has implications on the provision of ecosystem services and economic benefits of Teak stands in Tanzania. Carbon quantification and cost-benefit analysis methods were used to study the climatic and economic benefits of wood production and carbon sequestration under five scenarios where three thinning schedules and 30 years rotation age were the baseline. Data were collected from 168 purposively selected circular plots of radius 9.78 m distributed systematically in 9 thinned stands. Thinned stands were implemented with intensities of 50%, 50%, and 25% in first, second, and third thinning respectively. Results showed that decreasing 33.4% rotation age from baseline while maintaining three thinning schedules maximized climatic and economic benefits of combined wood production and carbon storage goal by 181.5%. Preferred thinning schedules and rotation age had wood production and carbon sequestration of 821 m^3/ha and 41.3 t/ha respectively. Managing Teak Forest plantation for the combined goal of wood production and carbon sequestration is recommended.

Keywords: Carbon sequestration; Ecosystem services; Net present value; Thinning schedule

Introduction

Teak (*Tectona grandis* L.f.) forest plantations are crucial for restoring tropical forest cover, carbon sequestration, and providing woody materials to industries and residents (Chayaporn et al. 2021, Rahmawati et al. 2022, Zagade et al. 2022, Nesha et al. 2021). With a growing demand for Teak wood materials and high-quality timber, these plantations attract private and public sectors. With a global area of 7 million hectares, Teak forests account for 3.2 Gt CO_2 year^{-1} of carbon sink (Nesha et al. 2021). The production of Teak wood and its carbon sink depends on factors like age, volume, and stem number (Behera and Mohapatra, 2015). Recommended silvicultural management practices are essential to optimize production and mitigate climate change. Thinning schedules in Teak plantations reduce tree density, increase tree volume, and manage timber yield and income. Tanzania Technical

Order of 2003 recommends three thinning schedules with intensities of 50%, 50%, and 25% in first, second, and third thinning treatments at the age of 5, 10 and 15 years, respectively, at the spacing of 2.5 m x 2.5 m with optimal rotation length at 30 years Ministry of Natural Resources and Tourism (MNRT 2003).

Until now, forest management practices have focused on either timber yield or carbon stock, in spite of that the research is geared to determine which forest management practices would optimize both climatic and economic benefits aiming to explore the balance between maximizing carbon sequestration (climatic benefits) and optimizing the economic returns (timber yield) of Teak plantation. However, little research exists on assessing thinning intensity and optimal rotation age that could provide the basis for understanding the importance of Teak Forest plantation for carbon stock and wood production (Chayaporn et al. 2021). Inadequate implementation of thinning intensity and delayed thinning schedules could impair tree wood volume and hamper carbon sequestration in Teak Forest plantations. According to Bauhus and Schmerbeck (2010), and Dobner and Quadros (2019) thinning intensity in Forest Plantation promotes higher economic values through the production of quality wood and carbon sequestration. However, knowledge is rare about the efficiency of different forest management practices (thinning intensity and optimal rotation age) in influencing the provision of ecosystem services needed to maximize profits on carbon sequestration and round wood production in Teak Forest Plantation in Tanzania. Therefore, this study addressed this gap for *Tectona grandis* stands grown in the Longuza forest plantation. The results are expected to provide the basic knowledge on thinning intensity and optimal rotation age regarding the profitability of Teak wood production and carbon sequestration, promoting the economy of the private and public sectors involved in forest management.

Materials and Methods

Study area

The study was conducted in the Longuza forest plantation in Muheza District, Tanga region, Tanzania (Figure 1) in October, 2021. For easy management, the plantation was divided into three reserves of Longuza (LG), Kihuhwi Sigi (KS), and Kihuhwi (KH) with an estimated area of 1,541.97 ha, 921.43 ha, and 605.91 ha, respectively (MNRT 2018). The plantation total area is 3,496.31 ha, whereby 2,025.82 ha are planted with *Tectona grandis*, 24.36 ha are planted with *Milicia excelsa*, *Terminalia* sp and *Cederella odorata*, 1032.05 is the natural forest, and 430.81 ha is the extension area. Native species dominated in natural forests are *Khaya anthotheca, Newtonia paucijuga, Albizia gummifera, Combretum schumannii, Brachystegia s*p*, Isoberlinia* sp*, Pterocarpus angolensis*, *Milicia excelsa*, *Antiaris* sp, *Zanha* sp, *Sterculia* sp and *Acacia* sp. The plantation borders the Eastern Arc Mountains in the west. The plantation lies between Latitudes 4º55’ and 5º10’ South and Longitudes 38º 40’ and 390 00’ East. The altitude ranges from 160 m to 560 m above sea level. The maximum temperature ranges between 26 °C and 32 °C and the minimum temperature ranges from 15 °C to 20 °C (Van Zyl 2005, Ngaga 2011). The study area experienced two major seasons: the dry and wet seasons. The area received short and long periods of rainfall. Short rains begin from October to December, while long rains begin from March to June. The amount of annual rainfall the study site received is 1,500 mm. The dry season is between June and September (Van Zyl 2005, Ngaga 2011). The study site has moderately deep soils ranging from 40 to 80 cm. The soil depth ranges from shallow (<20 m) to intense (>120 m). The soil type is dominated by sandy clay loamy. The soil colour ranges from darkish brown to red (Ngaga 2011).

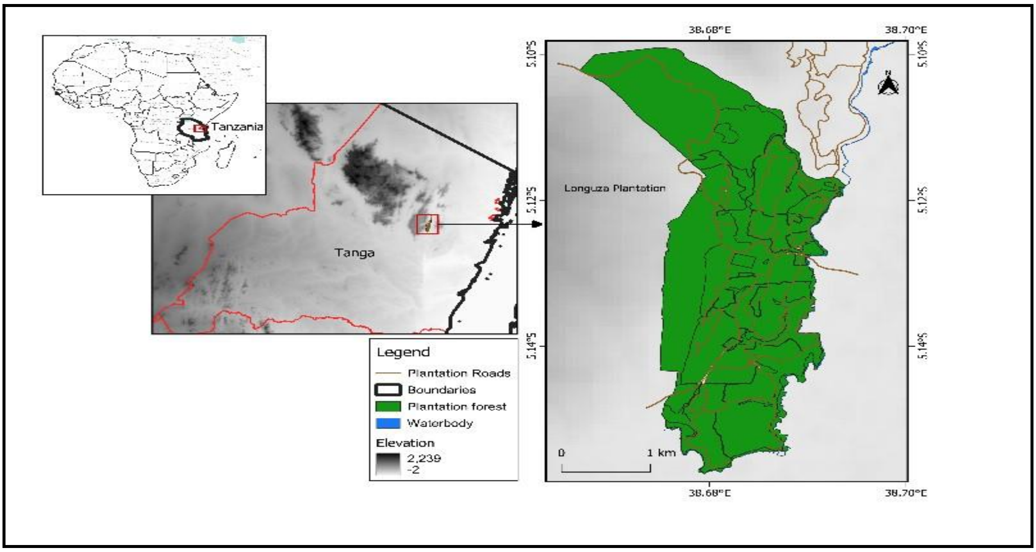

Figure 1: Map of Longuza Forest Plantation showing the location of the study area in Tanzania

Study design

Thinning scenarios were developed to assess the role of forest management practices (thinning intensity, thinning schedules and optimal rotation age). A quasi-experimental research design assessed the effects of thinning intensity and optimal rotation age. In order to assess the effects of thinning, two categories of ecosystem services were involved: provisioning services (wood production) and regulatory services (CO_2 sequestration). Provisioning services were assessed by quantifying stand volume, and CO_2 sequestration was estimated by determining the capacity of a stand to transform atmospheric CO_2 into biomass by considering two carbon pools (the above and below-ground biomass). The above and below ground biomass of Teak trees was estimated using the allometric models developed for *Tectona grandis* species. The biophysical assessment of carbon sequestration in above-ground biomass and below-ground biomass was estimated as tons of CO_2 sequestered per ha using the variable tree volume increment (m^3 ha^{-1}) measured in stands after receiving thinning treatments.

Thinned stands were stratified into age groups of 6-9, 10-14 and >15 years, representing the first, second, and third thinning respectively. Heavy thinning treatments were implemented in the first and second thinning schedules, while moderate thinning was implemented in the third. The initial density of the measured stands was 1600 trees/ha. The treatments were (1) First heavy thinning; removal of 50% of the initial density of 1600 trees/ha at age five years, remaining 800 trees/ha density. (2) Second heavy thinning: Remove 50% of the remaining trees after the first thinning at age ten years, with a remaining density of 400 trees/ha. (3) Third moderate thinning; removal of 25% of the remaining trees after the first and second thinning, with a remaining density of 300 trees/ha at age 15 years.

Sampling design

A systematic sampling design was used to lay out plots and transects. A reconnaissance survey was conducted to determine the number of plots per stand. Stands were surveyed using the Global Positioning System to secure the actual stand area, eliminating natural forests and wetlands. GPS and stand maps were used to position plots and transects. Four transects were laid whereby the distance between transects within a stand was determined by dividing the distance of the width of the stand by the number of transects, which ranged from 100 m to 140 m. The first plot was laid half from the compartment border to avoid edge effects. Malimbwi (2016) dictated that sampling intensity be as low as 0.01% due to financial constraints, time limitations, the purpose of forest stocking and sampled area. The distance between plots was determined by dividing the total length of four transects by the total number of plots. Then, 194 temporary circular plots of a 9.78 m radius with 300.33 m2, equivalent to 0.0300 ha (Malimbwi 2016), were laid systematically in nine purposively selected stands (Table 1).

Table 1: Sampling intensity applied in surveyed areas at Longuza, Tanzania

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

Forest management scenarios

Forest management scenarios were developed to connect timber production and carbon sequestration. Assumptions were made based on rotation age and thinning intensity, and five scenarios were defined and assessed. The objective was to evaluate the efficiency of forest management practices in influencing ecosystem services by maximizing net present value from timber production and carbon sequestration. The developed scenarios were noted and described, as shown in Table 2.

Table 2: Description of forest management Scenarios at Longuza, Tanzania

S/no.	Scenario type/name	Description
1	Business as usual ($BAU/T_{5/10/15}$).	Under this scenario, the management consider a tree rotation age of 30 years and three thinning schedules performed at age 5, 10, and 15 years.
2	Increasing rotation age by 10 years ($IR10/T_{5/10/15}$).	Under this scenario, the management consider a tree rotation age of 40 years and three thinning schedules performed at age 5, 10, and 15 years.
3	Decreasing rotation age by 10 years ($DR10/T_{5/10/15}$).	Under this scenario, the management consider a tree rotation age of 20 years and three thinning schedules performed at age 5, 10 and 15 years.
4	Increasing rotation age by 10 years and adopting two thinning schedules ($IR10/T_{5/15}$).	Under this scenario, the management consider a tree rotation age of 40 years and adopts two thinning schedules at age 5 and 15 years only.
5	Decreasing rotation age by 10 years and adopting two thinning schedules ($DR10/T_{5/15}$).	Under this scenario, the management consider a tree rotation age of 20 years and adopts two thinning schedules at age 5 and 15 years only.

Data collection

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

Data analysis

Teak plantation average management expenses in Tanzania shillings (TZS) per ha were estimated to obtain the actual costs incurred to establish and manage stands. The estimation of expenditure per ha was done by summing the costs of the stand surveyed divided by area. The average price of volume of the final harvests (clear-felling) was estimated by summing prices divided by years. Yield and biomass values were estimated by using models presented in Table 3. The height of trees measured for Dbh was estimated by Equation number 1. Mean volume (MV) per ha was obtained by summing volume in plots divided by total plots and was done by Equation 2. Mean annual volume increment (MAVI) was done by dividing MV by the tree's age. The volume of the third commercial thinning schedule was calculated as a product of MV, and stems were removed. Estimating tree biomass in kg for above-ground (AGTB) and below-ground (BGTB) was done by Equations 3 and 4, respectively. Total biomass was obtained by summing AGTB and BGTB. Mean biomass (MB) was obtained as a ratio of total biomass and the total number of measured trees. Mean annual biomass increment (MABI) was calculated as MB divided by tree age. Kg carbon stock was determined to be 49% of the total biomass (Temu et al. 2015). Mean carbon (MC) was obtained by dividing the individual tree carbon by the total number of measured trees. Mean annual carbon increment (MACI) was done by dividing MC by the tree's age (Pokhrel and Mandal, 2019). The values were estimated based on individual tree values divided by the area of the sample plot.

Table 3: Models used to estimate yield, tree height and biomass at Longuza, Tanzania

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

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

The estimated information on prices and quantities of volume per ha, tons of carbon per m^3 and removed stems per ha was used to determine the benefits of the surveyed stands. The estimated information on costs and benefits was used to calculate the net benefit for round wood production and carbon sequestered for total amounts estimated from AGB and BGB using data from forest inventory. Carbon revenue was estimated by converting carbon stock into tCO2e per ha by multiplying it by 44/12 molecular weight over carbon (Temu et al. 2015, Chayaporn et al. 2021). The obtained volume in m^3 per ha of commercial thinning and clear-felling and carbon in tCO2e per ha quantities were converted into revenues by multiplying it with an average price of each quantity of TZS 67,500/-, 743,129.20 and 12,500/- respectively. Net present value (NPV) was used to assess the profitability of wood production and carbon sequestration. The discount rate of 9% was used to discount net benefit for NPVs of carbon sequestration and wood production estimation because it is the lending rate used in agriculture and forest projects in Tanzania (NMB 2023). According to this criterion, an investment is economically efficient if the NPV exceeds zero. Equation 5 was adapted to estimate NPVs for Carbon storage and round wood production (Temu et al. 2015, Dobner and Quadros 2019).

$$NPV = \sum((Benefits - Costs)_t) \div ((1 + r)^n)$$

---------Equation 5

Where NPV = Net Present Value, r = Discount rate, t = Time (Year) of running project, $(Benefits\text{-}Costs)_t$ = Net Benefits at Year t, n = Number of years in the project.

Sensitivity analysis was done by increasing the costs of establishment and management by 20% and different values of NPV were obtained in the forest management scenarios. Comparison of NPVs without sensitivity method and with sensitivity method was done by performing paired T-test. The aim of the analyses was to determine which scenario is sensitive to costs due to diseases, fire eruption, heavy rain or drought conditions since forest management are susceptible to these calamites.

Results

Operating costs and selling prices

The results revealed that average establishment expenditure per ha of implemented land preparation had greater cost in contrast with seedling production and seedling planting. However, the results observed that average management expenditure per ha of weeding had greater expenditure in contrast with pruning and thinning. Also, the result revealed that rotation of 40 years of scenario S2 had greater expenditure compared to rotations of scenarios S1, S3, S4 and S5 (Table 4). The selling prices of poles in the first and second thinning schedules were TZS 1,000/- and TZS 2,000/-, respectively. However, the observed average commercial thinning volume selling price in the third thinning schedule and final harvests (clear-felling) is TZS 67,500/- and TZS 743,129.20, respectively. Moreover, the global carbon average price was US$ 5 per tCO_2e, equivalent to TZS 12,700/- (1US$ = TZS 2,540/- exchange rate of July 2023).

Table 4: Average establishment and management costs in TZS per ha at Longuza Tanzania

Cost item	TZS ha^{-1}	Rotation age (years)				
		30	40	20	40	20
			3rd thinning schedule		2nd thinning schedule	
Seedling Production	239,906	239,906	239,906	239,906	239,906	239,906
Land preparation	178,325	178,325	178,325	178,325	178,325	178,325
Planting	686,730	686,729	686,730	686,730	686,730	686,730
Weeding	1,374,186	13,741,863	13,741,863	13,741,863	13,741,863	13,741,863
Pruning	177,831	355,661	355,661	355,661	355,661	355,661
Thinning	123,539	370,616	370,616	370,616	247,078	247,078
Protection	264,435	7,933,058	10,577,412	5,288,705	10,577,412	5,288,705
Total costs TZS	**3,044,952**	**23,506160**	**26,150,514**	**20,861,807**	**26,026,975**	**20,738268**

Yield, biomass and carbon sequestration

Forest management practices had a distinctive effect on wood volume, biomass and carbon sequestration. Among the management scenario, the highest value of wood production was found in scenario S2, which was 821 m3/ha, while the lowest value of 249 m3/ha was observed in scenario S5. The highest values of above-ground biomass, below-ground biomass and carbon sequestration were 18.7 m^3/ha, 4.3 t/ha and 41.3 t/ha, respectively, in the S2 and S4 scenarios. The lowest values, 9.1 t/ha, 2.2 t/ha, and 20.3 t/ha, were observed in the S3 and S5 scenarios in both implemented thinning schedules (Figure 2).

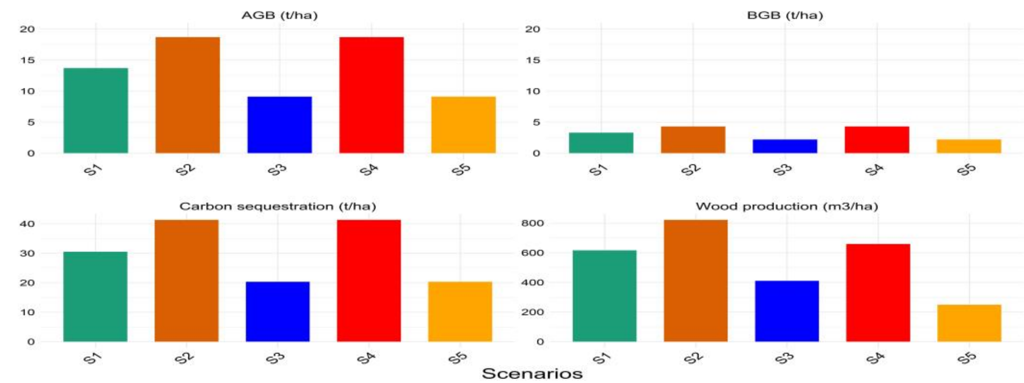

Figure 2: Wood volume, biomass and carbon sequestration under forest management scenarios at Longuza, Tanzania. S stand for the scenario

Economic benefits

The revenue and cost treatment results of the implemented three thinning schedules in scenario S2 revealed that wood production, carbon sequestration, wood production plus carbon sequestration had higher values than scenarios S1, S3, S4 and S5. However, the results revealed that two treatments of the thinning schedule in scenario S5 influenced lower revenues and expenses for wood production, carbon sequestration and wood production plus carbon sequestration (Table 5).

Table 5: Revenue and costs under forest management scenarios in TZS per rotation age at Longuza, Tanzania

Scenarios	Rotation age (years)	Revenue (TZS)			Actual costs (TZS)	Management costs increase by 20% (TZS)
		Wood production	Carbon sequestration	Wood+Carbon		
S1	30	461,713,587	6,238,750	467,952,337	23,506,160	28,207,392
S2	40	613,651,073	10,738,750	624,793,823	26,150,514	31,380,617
S3	20	308,628,972	2,995,000	311,623,972	20,861,807	25,034,168
S4	40	492,626,143	10,738,750	503,364,893	26,026,975	31,232,370
S5	20	188,185,171	2,995,000	191,180,171	20,738,268	24,885,922

The results revealed that the NPV value of wood production in three implemented thinning schedules in the S1, S2, and S3 scenarios was TZS 22,917,213.8, TZS 7,714,474.7and TZS 43,088,012.5 per ha respectively. In two implemented thinning schedules, the NPV values of wood production were TZS 3,627,693.8 and TZS 21,505,332.2 per ha in the S4 and S5 scenarios, respectively. The highest NPV value for wood production was found in scenario S3, while the lowest NPV value was observed in scenario S4. However, the NPV values of the combined wood with carbon in the three implemented thinning schedules were TZS 24,300,963, TZS 9,317,621.6 and TZS 44,104,826.5 per ha in S1, S2, and S3 scenarios respectively. The NPV values of the combined wood and carbon in the two-thinning schedules were TZS 5,179,901.1 and TZS 22,471,206.5 per ha in the S4 and S5 scenarios respectively. Values of NPV for wood production, combined wood production, and carbon sequestration were higher in the three implemented scenarios, S3 than in the S4 and S5 scenarios of the two thinning schedules. The NPV for carbon sequestration was negative for all scenarios (Figure 3).

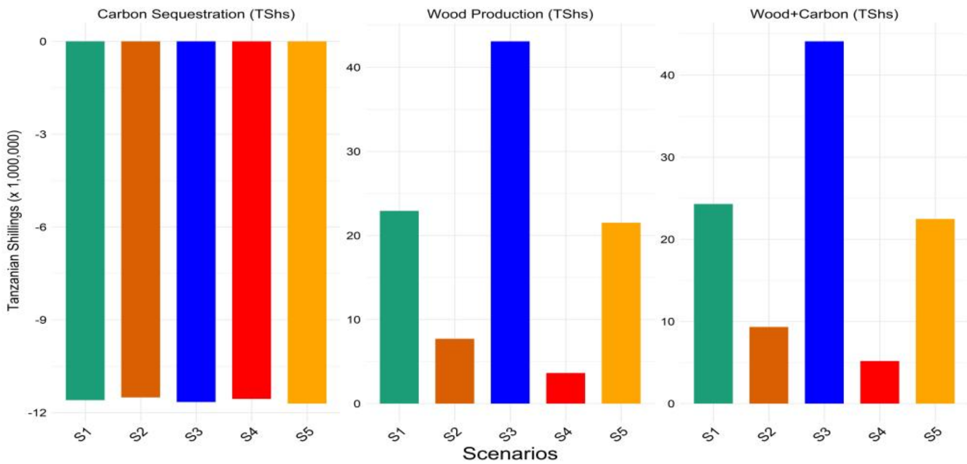

Figure 3: Net Present Values (in TZS/ha) under forest management scenarios at Longuza Tanzania. S stand for the scenario

The results of the NPV of wood production with sensitivity analysis for S1, S2, S3, S4, and S5 were TZS 20,471,726, 5,240,181, 40,697,440, 3,1,107,356, and 19,100,208 respectively. The results of the NPV of carbon sequestration with sensitivity analysis were negative for all scenarios. The results of the NPV of wood production plus carbon sequestration with sensitivity analysis for S1, S2, S3, S4, and S5 were TZS 21,832,192, 6,814,070, 41,696,666, 2,681,244 and 20,099,433 respectively. The highest NPV value for wood production and wood production plus carbon sequestration was found in scenario S3, while the lowest NPV value was observed in scenario S4 (Table 6).

Table 6: Net Present Values (in TZS/ha) with sensitivity analysis under forest management scenarios at Longuza Tanzania

Economic Management Scenarios	Rotation age (years)	Net Present Value (TZS)		
		Wood production	Carbon sequestration	Wood production + Carbon sequestration
S1	30	20,471,726	-14,130,535	21,832,192
S2	40	5,240,181	-14,070,592	6,814,070
S3	20	40,697,440	-12,182,523	41,696,666
S4	40	1,107,356	-13,485,707	2,681,244
S5	20	19,100,208	-14,076,268	20,099,433

Results of paired T-test showed that the mean of the actual NPV and sensitivity analysis values was statistically significant ($P<0.05$) from both scenarios. NPV from actual values and sensitivity analysis of wood production demonstrated substantial ($P<0.05$) results in S1, S2, S4, and S5 and negligible results in S3 for carbon sequestration. The NPV values of carbon sequestration and wood production was significant ($P<0.05$) in both scenarios (Table 7).

Table 7: A statistical result between Net Present Values of the actual values and sensitivity analysis (in TZS/ha) under forest management scenarios at Longuza, Tanzania

Forest Management Scenarios	Statistical items	Economic benefits + ecosystem services					
		Wood production		Carbon sequestration		Wood production + Carbon sequestration	
		ANPV	SANPV	ANPV	SANPV	ANPV	SANPV
S1	n	30	30	30	30	30	30
	Mean	766053.9	682390.9	-387355	-471918	811402.8	727739.7
	df		29		29		29
	P-value	0.000712		0.000712		0.000712	
S2	n	40	40	40	40	40	40
	Mean	194391.3	131004.5	-288378	-351765	233738.6	170351.7
	df		39		39		39
	P-value	0.000799		0.000799		0.000799	
S3	n	20	20	20	20	20	20
	Mean	2157330	2034872	-583956	-609126	2207300	2084833
	df	19		19		19	
	P-value	0.000571		0.329877		0.000571	
S4	n	40	40	40	40	40	40
	Mean	91070.06	27683.91	-287070	-337143	130417.3	67031.11
	df	39		39		39	
	P-value	0.000798		0.032566		0.000798	
S5	n	20	20	20	20	20	20
	Mean	1077477	955010.4	-581346	-703813	1127439	1004972
	df	19		19		19	
	P-value	0.000571		0.000571		0.000571	

ANPV refer to Actual Net Present Value, SANPV refer to Sensitivity Analysis Net Present Value, df refer to Degree of freedom, and n refer to Number of observations

Discussion

Forest management practices apparently affected the provision of ecosystem services and economic benefits in the study area. This study revealed that scenario S3 is more reliable in Teak Forest management for combined wood production and carbon sequestration in the study area. In general, increased wood production and carbon sequestration of Teak forests lead to higher climatic and economic benefits influenced by forest management practices. Temu et al. (2024), Hiltunen et al. (2021) and Kolo et al. (2020) reported that forest management practices maximized the economic benefits and climatic amelioration. However, Forest management practices in S2 and S4 scenarios improved the ability of Teak forests to produce wood biomass and consequently sequester carbon compared to business as usual in scenario S1. However, both scenarios showed that wood production and carbon stock increased as the thinning schedule increased regardless of rotation age, which positively affected wood biomass and carbon sequestration due to implementing heavy thinning intensity. The observed results of this study could be compared with the findings of the study conducted by Mendez and Rico (2019), and Rahmawati et al. (2022), who observed heavy thinning intensity practices enhance the highest wood production and carbon sequestration. Moreover, it has been found in scenario three that implementing heavy thinning intensity and three thinning schedules with 20 years optimal rotation age improved the NPV value of combined wood production and carbon sequestration positively. The results of this study are supported by the findings of Mendez and Rico (2019), Mgoo et al. (2022) and Zagade et al. (2022) who reported that for Teak wood production and carbon storage objectives, heavy thinning intensity in the first and second thinning schedules offer more significant advantage than moderate thinning intensity. On the other hand, investing in wood production only has more significant returns than investing in carbon sequestration. However, the study showed that carbon sequestration can be achieved with management goals to maximize wood production. The study conducted by Häyhä et al. (2015), and Pohjanmies et al. (2017) explained that maximizing wood production also increases carbon storage, and they found that wood production is positively correlated with carbon storage.

Sensitivity analysis undertaken indicates robustness of the economic benefit and ecosystem services of the forest management scenario S3. The NPV of the wood production and wood production plus carbon sequestration had higher positive values indicating conducive condition for the investment even at a cost higher by 20%. On the other hand, NPV of carbon sequestration under all scenarios are not economically plausible. The implication is that giving more resources to manage a forest plantation solely for carbon sequestration may not be financially viable (Temu et al. 2015).

Conclusion and recommendations

Generally, decreased clear-felling age with three thinning schedules was the most suitable management for *Tectona grandis* stands when climatic and economic benefits were managed together. The climatic benefit gained from forest management decreased the NPV when carbon stock was prioritized. However, high NPV could be simultaneously achieved by targeting the combined goal of wood production and carbon stock. The study revealed that adopting the S2 scenario had a high-value increment in wood production, AGB, BGB, and carbon sequestration with low NPV, in contrast to the S3 scenario. The study found that S3 and S5 scenarios had similar values of AGB, BGB and carbon sequestration but high values of wood production and NPV in the S3 scenario. The study revealed that forest management practices improved both climatic and economic benefits. To ensure better provision of ecosystem services and climatic benefits, it is recommended that plantation managers should consider a tree rotation age of 20 years and three thinning schedules at 5, 10 and 15 years. However, to ensure better returns from a thinned commercial Teak forest plantation, it is recommended that heavy thinning in the first and second schedules be carried out to encourage large-diameter trees, which promises high profitability. Furthermore, it is recommended that the current Technical Order No. 1 of 2021, the recommended two thinning regimes for spacing of 2.5 x 2.5 m, be reviewed to 3 to ensure better gain in volume and to store carbon to a great extent. It is also recommended that Teak Forest plantation owners could engage in the carbon business as it gives higher net revenue and NPV when considering a combined goal of timber production and carbon stock compared to a plantation managed solely for timber production.

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Declaration of competing interests

We declare that there is no competing financial and non-financial interest to disclose.

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