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Original Article

Forest Management Tool for Estimating Growth and Yield Stand Parameters in Pine Plantations. A Case of Sao Hill Forest Plantation

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ABSTRACT

This study presents the Forest Inventory Tool (FIT), designed for estimating and forecasting stand volume, growth, yield, and tree size distribution for Pinus patula plantations in Tanzania. The tool is designed to accommodate growth dynamics changes associated with the manipulation of management practices. Implementing management plans is often hindered by challenges such as budgetary constraints, weather state and market fluctuations often disrupt the implementation of management plans. These disruptions may lead to the omission of critical practices like thinning and harvesting, resulting in discrepancies between the analysed and forecasted metrics in the management plan and the actual stand state. The tool addresses these challenges by automating data processing, enabling real-time updates, and reducing reliance on manual analysis to update the stand structure that is prone to error. The FIT development followed the standard forest management prescriptions outlined in the forest management plan, which directs the five-year operations (e.g. thinning, pruning, planting and clear-felling). It was designed using Excel VBA to integrate inventory data with management prescriptions. Forest data were collected through stratified systematic sampling across 60 compartments. The FIT applies yield models to forest inventory data to inform forest structure and forecast its development under different management practices. The tool generates key stand parameters for forest management, including an overview of the plantation, stand summaries for a five-year management plan, and dynamic updates on plantation status. It provides an automated solution for managing plantations by supporting decision-making. It is recommended that the tool be expanded to support a broader range of species and be developed into an app or web-based platform to improve its applicability across different forest types and ensure remote access.

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INTRODUCTION

Tanzania is endowed with rich forests and woodlands that cover a total of 48.1 million hectares, which is equivalent to 55% of the land area of the mainland (MNRT, 2015). These forests offer critical resources to communities, including firewood, timber, medicinal plants, and food, while also delivering essential ecosystem services such as water regulation, climate change mitigation, and biodiversity conservation. However, these forests are significantly threatened by human-induced disturbances such as agricultural expansion and illegal logging resulting from population growth and the increase in wood material uses, leading to deforestation and degradation. In recent years, approximately 469,000 hectares of forest have been lost annually due to deforestation driven by the high demand for wood (FAO, 2020). This has resulted in an annual wood deficit of over 19 million m³ (MNRT, 2015).To reverse this trend would require a continuous planting of 185,000 hectares of trees each year(MNRT, 2015).

Tree planting efforts in Tanzania have so far covered approximately 583,691 hectares (MNRT, 2015; TFS, 2021). These comprise both softwood and hardwood species such as teak, cypress, eucalyptus, and pine. Among others, pines make up the majority of the tree species, accounting for roughly 78% of the planted area. Hardwoods and other softwood species share the remaining 22% of the planted area (Held et al., 2017; Ngaga, 2011). Pine species dominate due to their rapid growth rates, adaptability to various soil types, favourable climate conditions, and suitability for timber, resin and pulp production. According to Rodrigues et al. (2008), Forest plantations are a significant source of various beneficial goods, including timber and non-wood products that are widely used in the food, chemical, pharmaceutical industries, and biorefineries.

The productivity of forest plantations relies heavily on how well it is managed (Chamshama & Nshubemuki, 2011). The prescriptions of management practices are well described in the prescription section of the forest management plans (MNRT, 2021). Silviculture practices such as raising seedlings in the nursery, site preparation, planting, weeding, pruning, thinning and clear-felling, among others, have a significant effect on the health and growth of trees, thereby influencing the overall productivity of the stand-stock (Dangal & Das, 2015; Kuehne et al., 2022; Rubilar et al., 2018).

While all management practices are essential, the timing of thinning and clear-felling is particularly critical for maximizing the overall productivity of forest plantations (MNRT, 2021; Ngaga, 2011) For instance, delaying clear-felling beyond the designated rotation age is unlikely to improve the final yield and may even decrease timber quality due to natural decay or other degradative factors. Similarly, postponing thinning can result in overcrowded stands, heightened competition for resources, and stunted tree growth, ultimately diminishing both the quality and quantity of the final harvest (Crecente-Campo et al., 2009; Forrester et al., 2013; Kang et al., 2014).

Developing a forest management plan requires integrating tree-level models and whole-stand growth and yield tables (e.g., Malimbwi, 2016) to assess current stand parameters and predict future yields. A five-year forest management plan

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typically includes yield forecasts derived from forest inventory data. It outlines the annual harvest volumes, detailing quantities from thinning and clear-felling and specifying the management units (commonly known as compartments) targeted for harvesting. The plan assumes the timely execution of activities as scheduled.

However, challenges such as budgetary constraints and market fluctuations often disrupt implementation. These disruptions may lead to the omission of critical practices like thinning and harvesting. Delaying clear-felling beyond the designated rotation age is unlikely to enhance final yields and may even reduce timber quality due to natural decay and other degradative processes. Likewise, postponing thinning can result in overcrowded stands, increased resource competition, and reduced tree growth, ultimately lowering both the quality and quantity of the final harvest (Crecente-Campo et al., 2009; Forrester et al., 2013; Kang et al., 2014; Ngaga, 2011). Such delays can create discrepancies between the forecasted and actual stand-stock conditions. Such discrepancies need to be addressed, particularly if those stands will be required to be thinned and clear-felling within the planning period. This is not an easy task, particularly when there are multiple management units with similar issues.

This underscores the need for a tool to assist forest managers in monitoring and managing the backlog of thinning and clear-felling activities. Such a tool would also enable updates to the standing stock, as unmanaged units continue to grow and evolve over time. This study developed the *Forest Inventory Tool* (FIT), designed to provide quick estimations of stand stock parameters and forecast growth and yield for pine plantations based on the existing single and stand growth models. The tool is specifically adapted to accommodate yield changes resulting from management practices, and it allows for flexibility in forest management plans to account for delays or postpones of thinning or clear-felling activities. The approach is applied to a case study at the SAO Hill Forest Plantation in Iringa, Tanzania.

MATERIALS AND METHODS

Site Description

The study was conducted at Sao Hill Forest Plantation (SHFP), located in the Southern Highlands of Tanzania, within the Iringa Region. The plantation lies between latitudes 8°18′S and 8°33′S and longitudes 35°06′E and 35°20′E (Figure 1), at an elevation ranging from 1,700 to 2,000 meters above sea level (Petro & Madoffe, 2011). The soils are predominantly Dystric Nitisols in association with Orthic Acrisols (Nykvist, 1976). These sandy clay loam soils have a relatively uniform physical structure in their undisturbed state, with colours ranging from very dark brown (7.5 YR 2/2) to yellow-orange (7.5 YR 7/8). The clay minerals are primarily kaolinitic, characterised by low cation exchange capacity, low base saturation, and high acidity. The landscape is a rolling plateau marked by low hills and broad, flat-bottomed valleys (Silayo et al., 2010).

Established in 1939, SHFP was initially developed to supply raw materials for the wood industry, including pulpwood and timber and to support ecosystem services such as water catchment protection, soil erosion control, climate regulation, and acting as a buffer between local communities and the natural forest (Ngaga, 2011). The natural vegetation surrounding most compartments comprises poorly stocked Miombo woodlands, featuring grasslands with scattered trees and shrubs such as *Brachystegia spiciformis, Julbernardia globiflora, Dombeya rotundifolia, Erythrina caffra,* and *Albizia antunesiana* (Mhando et al., 1993).

SHFP covers a total area of 135,903 hectares, making it the largest forest plantation in Tanzania. Of this, 54,070 hectares are planted with pine species, 3,500 hectares with cypress and eucalyptus species, 48,200 hectares are managed as natural forest and river catchment areas, 31,933 hectares are designated for future expansion, and 1,700 hectares are allocated for other uses, including residential purposes (TFS, 2021).

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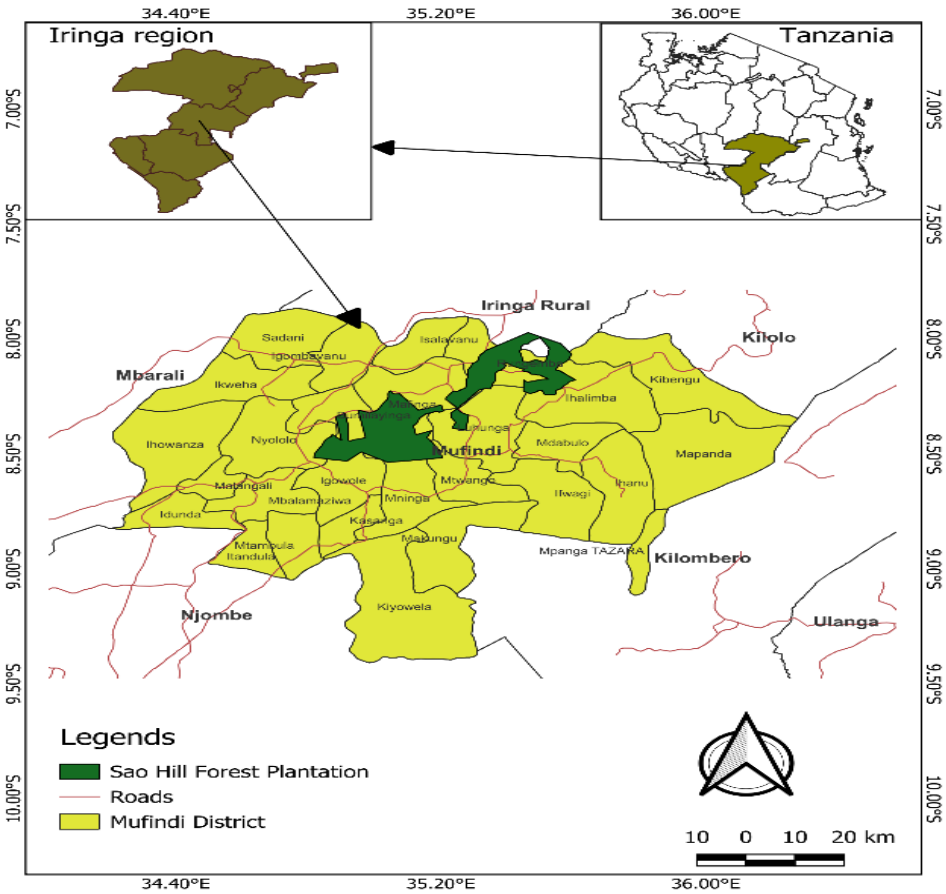
Figure 1: Location of Study Area in Mufindi District, Showing Study Site: Sao Hill Forest Plantation.



Study Design

The FIT was specifically designed to meet the forest management plan requirements outlined in the prescription chapter. By integrating stand parameters with management prescriptions, the tool empowers managers to make informed decisions about the "*how*," "*what*," and "*when*" to implement management practices (see Figure 2). The "how" provides details on the scope of management activities, such as the number of trees to remove during thinning; the "*what*" outlines the expected yield from these activities such as volume per ha from every management unit; and the "*when*" specifies the appropriate timing (e.g., at which year) for implementing specific practices. However, the operationalisation of the tool requires forest inventory data as an input to inform the tool on the current stand structure.

Collection of forest inventory data employed stratified and systematic sampling in two stages. In the first stage, 60 representative compartments were chosen, varying in age from 5 to 25 years, by ensuring that the compartments cover site quality and age variations. The second stage was the establishment and distribution of the sampling unit systematically in each of the selected compartments. Stratified sampling ensured that all age classes were adequately represented. The grids with dimensions of 150m by 100m and 100m by 60m for compartments aged 5 to 12 and above 12, respectively, were used. The intersection of the grids defined the location of the sampling units, i.e., plots. Circular plots with a radius of 9.78 m (0.03 ha). The number of plots varies with compartment size and age to ensure an accurate representation of stand conditions. Larger and older compartments, which exhibit greater variability, require more plots, while

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smaller or younger, more uniform stands need fewer plots for reliable assessment.

Data Collection

FIT

During the construction of the FIT, secondary data were collected through a literature review to inform its development and ensure its applicability. Key sources included yield models, forest inventory methods, and management plans documented in studies such as Malimbw (2016); Stankova et al. (2018). These references provided insights into growth modelling, stand density and volume estimation, and management prescriptions, which were essential in designing the tool's parameters and functionalities. This approach ensured that the tool was grounded in established methodologies while addressing practical forest management needs.

Forest Inventory Data

Forest inventory data were collected from pre-determined plot locations in each selected compartment. In each compartment, management history (e.g., pruning, age and thinning) and tree species were recorded. In each plot, the diameter at breast height (D, at 1.3 m from the ground) and tree height (H) were measured. Five sample trees were considered for H measurements, where two representative sample trees, i.e., the smallest and medium-sized trees, along with the three largest (fattest) trees in terms of D, were measured. The aim was to have three sample trees (small, medium and one largest) to establish H-D relationships and three largest trees for site class determination.

FIT Development and Structure

The FIT was developed using Visual Basic for Applications (VBA) programming in Microsoft Excel, leveraging built-in Excel functionalities like dynamic ranges, pivot tables, and formulas for data analysis and visualisation (e.g., Bovey, 2009; Chapke & Chandankhede, 2024). Various tools have been developed in forest management applications for estimating growth and yield projections (Alder et al., 2003; Bovey, 2009; Mugasha et al., 2017), demonstrating the effectiveness of Excel-based tools in forest stand modelling and management. The tool requires importing pre-prepared forest inventory data that has to be prepared in a specific format (see Appendix 1). The tool was designed to estimate various trees and stand parameters and forecast growth for five years as per a management plan requirement. The tool performs the computation of required trees and stand-level variables that are essential during the implementation of a management plan as prescribed using various equations and models, described in subsequent sections.

Stand Density

Stand density in this case included the number of trees and basal area per hectare. The average number of stems and basal area per hectare is calculated by applying the standard method for estimation of stem density and basal area as shown in Equations (3) and (4).

$$N = {}^{1}\!/_{m} \sum \left(\frac{ni}{ai} \right)$$

(3)

Where:

N – Number of stems per hectare;

m – number of sample plots;

ni – Individual trees per plot and

ai – plot area.

$$G = \frac{1}{m} \sum \left(\frac{g_i}{a_i} \right) \quad (4)$$

Where:

G – basal are per ha; (m^2/ha),

g_i – Basal area of individual tree; $g_i = \frac{\pi}{4} Dbh^2$ and

ai – plot area.

Tree Height (Ht)

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The height of trees that were measured for Dbh alone was estimated using the height equation by Malimbwi et al. (2016).

$$Ht = 1.3 + \frac{Dbh^2}{13.63898 + 0.026482 \times Dbh^2}$$

Where:

Ht = estimated tree height (m);

Dbh = Measured diameter at breast height (cm).

Stand Volume

Single tree volume was estimated using the single tree volume model for SHFP developed by Malimbwi et al. (2016).

$$V = \exp(-9.04925 + 1.14781 \times \ln(Ht) + 1.5496 \times \ln$$

Where:

V = tree volume (m3);

Ht = tree total height (m);

Dbh = tree diameter measured at breast height (cm).

Stand volume (m3/ha) was estimated in a similar way to the basal area per ha.

Site Class Determination

Site class was determined using the average dominant height, which represents the tallest trees from each plot. The equation developed by Malimbwi (2016) was applied to estimate the dominant height (Hdom) of the compartment based on age, as shown in equation (5):

$$Hdom = 1.564354 \times \text{site} \times (1 - \exp(-0.092288 \times \text{Age}))^{1.571869} \quad (5)$$

Where: Hdom – Dominant tree height and

Site – Site indices for site classes I, II, III, and IV correspond to dominant heights of 27, 22, 17, and 12 meters, respectively.

Current Annual Increment (CAI) and Adjusted CAI.

The CAI is a critical metric used to quantify the annual growth rate of trees within a management unit. It provides essential insights into the growth performance of the stand, helping to determine the volume increment over a specific period (Coops et al., 1999). In this study, the CAI values were obtained from the Yield Table developed by Malimbwi (2016) and were used to forecast the growth potential of each management unit. The Adjusted CAI, calculated using Equation 6, determines the growth of each management unit by comparing the CAI and yield table volume with the estimated volume per hectare of the management unit.

In the tool being developed, the CAI serves as a foundational input for simulating growth and yield projections. By incorporating CAI, the tool estimates future stand volume per hectare under different management scenarios, including thinning, clear-felling, or when these practices are not implemented.

$$Adjusted\ CAI(m^3/ha) = \frac{CAI\ (m^3/ha) \times Estimated\ volume\ (m^3/ha)}{Yield\ Table\ Volume\ (m^3/ha)}$$

(6)

These forest parameters outlined—such as stand density, basal area, tree height, volume, CAI, and site class determination using Hdom are essential for accurately estimating the stand condition, growth and yield, which is the primary objective of this management tool. These parameters provide crucial data for assessing the current condition of the plantation and projecting its future growth, enabling forest managers to make informed decisions and optimise plantation management. Stand density, which indicates the number of trees per hectare, helps assess the competition among trees and informs decisions on thinning and spacing to ensure optimal growth. Basal area and volume per hectare are key indicators for estimating timber yield and managing the plantation's output. Tree height, measured at diameter at breast height (Dbh), is used to estimate the volume of the stand, while Hdom (dominant height) is integral for determining the site class, a key factor in assessing the site quality and productivity potential. Volume estimation enables precise forecasting of timber

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production, guiding decisions on harvesting schedules and allowable cuts.

Description and Structure of the FIT

The FIT encompasses three subroutines. Subroutine1 allows users to import raw forest inventory data. The supported file formats are XLSX and CSV. Predefined templates (Appendix 1) guide the raw data required and formatting for importation. Subroutine 2 clears the stand data to allow the import of a fresh dataset. It includes a confirmation prompt ("*Confirm you want to clear the Dataset*?") to prevent accidental data removal. The third sub-routine performs initial analysis at tree level to tree/ha.

This software is organised into six integrated working sheets; a) The “compartment” sheet contains auto-updated pivot tables for initial analysis of stand parameters to plot level and compartment level. This sheet is designed to determine the site class of each compartment using dominant height. The sheet encompasses a yield table for CAI and Yield Table Volume, used to compute the adjusted volume increment of each stand. The sheet is designed to read the specific CAI and yield table volume based on the age, site class, and thinning status of each stand. b) The “DASHBOARD” serves as the main interface, offering visual summaries of stand parameters through graphs, charts, and tables, and interactive controls. This sheet provides hyperlinks to the other sheets. Additionally, the sheet connects a macro for data importation and cleaning when new raw data is about to be loaded. c) The “STAND DATA” sheet, designed using VBA in sub-rotune1, to process pre-processed forest inventory to stand parameters at tree/ha-level. d) “FORECASTING” sheet, designed to forecast the key stand parameters used in the forest management plan. This sheet has been linked with the “compartment” sheet to forecast casting stand parameters for a five-year duration. e) “FOREST PRACTICES” filters and lists the compartments in terms of trees per hectare, and volume per hectare, which are due to thinning and clear-felling from the “FORECASTING” sheet. f) “MANAGEMENT ACTION” This sheet requires the manager to specify the list of compartments which were due to thinning and clear-felled whether performed or not. This information is linked to the 'FORECASTING' sheet, where, if the action has been performed, it will reduce the respective compartment's thinned or harvested tree/ha and V/ha. If not, the forecasted volume growth and corresponding trees per hectare metric will continue to increase (See Figure 2).

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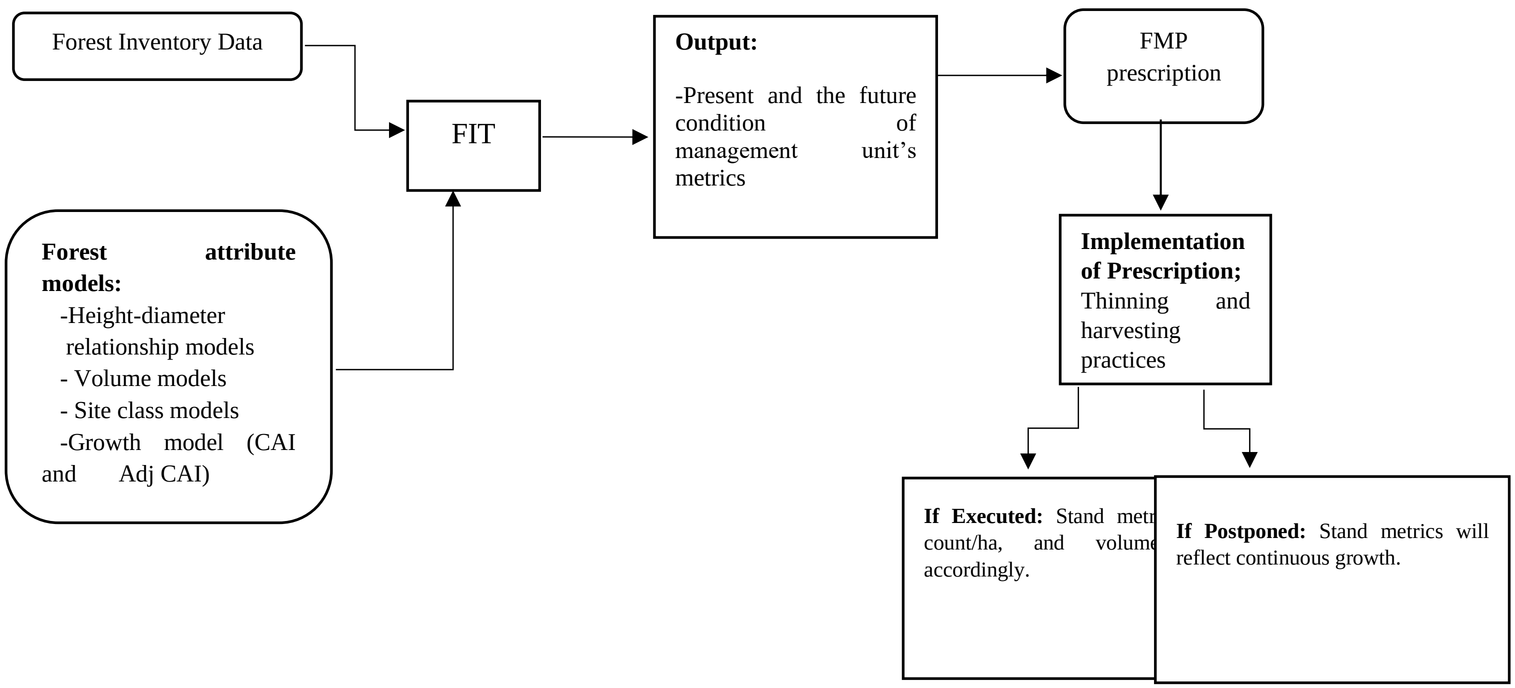
Figure 2: Shows the Working Flow of the FIT



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RESULTS

The present study FIT produces an automated and flexible management tool designed to generate stand parameters essential for forest managers in implementing management practices, particularly thinning and harvesting. The FIT produces outputs that are categorised into three main components. First, it provides general information about the plantation, including the total number of compartments, plantation area, and the site class distribution by area (see Figure 3a). Second, the FIT generates a stand summary tailored to the five-year management plan. This includes a detailed summary of the allowable cut (m³/ha) for the five years, the standing volume by age class, and the compartment-wise volume increment per hectare (see Figure 3a). These summaries enable managers to assess the current state and forecast future growth and yield.

Additionally, the FIT provides dynamic updates on the state of the plantation for each year within the five-year management plan. Key outputs include the total standing volume, annual allowable cut, and compartments due for thinning, specifying the number of trees to be removed and their corresponding volume per ha. For clear-felling, it also specifies the compartments, trees to be removed, and associated volumes for each year (See Figure 3b). This functionality allows for detailed planning and execution of management practices. Moreover, the FIT demonstrates flexibility by enabling managers to input data on compartments where thinning or clear-felling has been executed in a given year (see Figure 3c). This feature ensures that the FIT dynamically updates stand parameters by reducing volumes and areas for completed actions while continuing to forecast growth for postponed activities. This adaptability makes the FIT a practical and reliable resource for managing plantations efficiently (*Appendix 2 provides a detailed explanation of how to use it).*

Figure 3b: General Information in the Working Interface of the *FIT*.

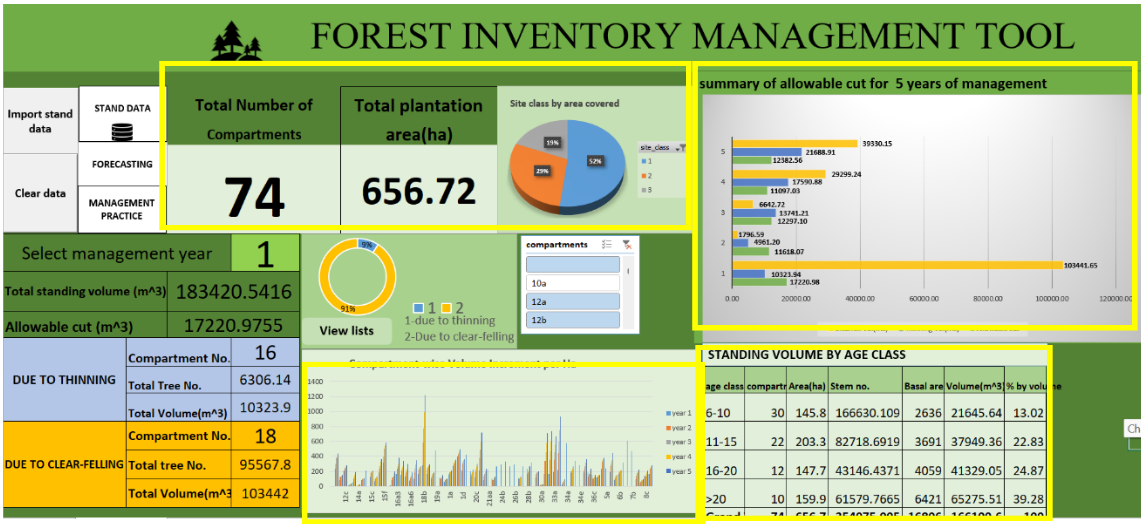

Figure 3b: The Management Unit Which are Due to Thinning and Pruning.

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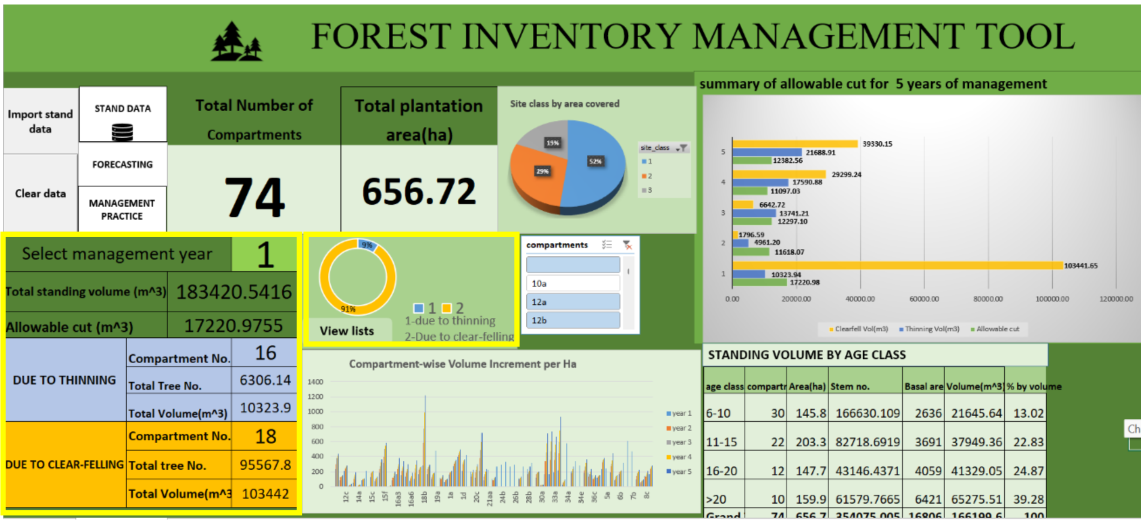
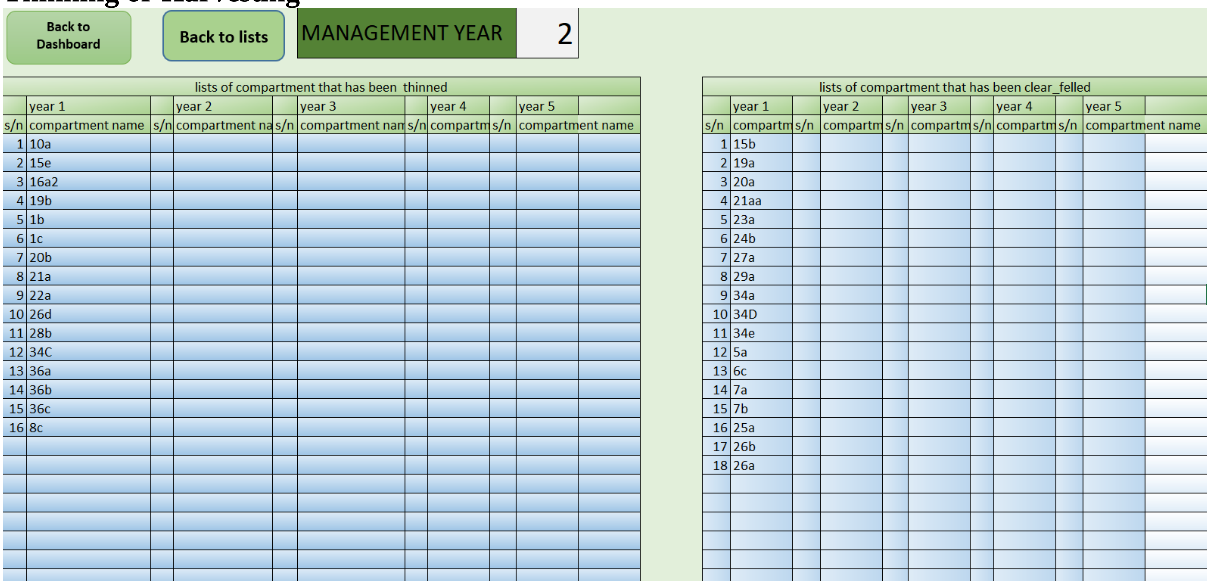


Figure 3c: Designates the Section for Managers to List Compartments that Have Undergone Thinning or Harvesting



DISCUSSION

Uncertainties such as financial crises, weather conditions and market fluctuations often result in backlogs in forest management. These backlogs lead to deviations from planned schedules and discrepancies between estimated and actual stand parameters. These discrepancies impact thinning and clear-felling practices, as the quantity of operations relies on stand metrics. Moreover, manual stand inventory analysis to obtain these stand metrics is time-consuming, requires specialised expertise, and may incur some costs. The present study addresses these issues by developing the FIT, a flexible and automated analysis tool that can generate stand parameters and dynamically update metrics based on implemented practices.

The results demonstrate that the FIT effectively produces essential outputs for forest management. The output includes general plantation information, stand summaries for a five-year management plan, and dynamic updates for each year of management. These outputs provide a comprehensive overview of the plantation.

A key innovation of the FIT is its ability to dynamically update plantation parameters based on completed or postponed management practices. This feature addresses the challenges posed by deviations from management plans. For instance, when a manager reports a compartment

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that has been thinned or clear-felled. The FIT automatically adjusts stand metrics, such as the total standing volume and volume removed, while leaving metrics unchanged for postponed practices. This flexibility minimises the risk of inaccurate projections. Unlike traditional manual analysis methods, where equations and models must be individually applied, this FIT simplifies the process through automation. With just data importation and the click of a "RUN" button, the FIT generates detailed outputs for planning and forecasting. This not only reduces the time and expertise required but also minimises human error. While the tool’s speed compared to manual methods was not quantitatively evaluated, its user-friendly interface and automated functionalities provide substantial efficiency gains.

The development of the FIT builds on prior research in forest management, drawing from studies like Stankova et al. (2018), which introduced the "PINEMANAGETOOL" for Scots pine plantations, focused on estimating growth, yield, tree size distribution, and simulating thinning alternatives for Scots pine plantations in Bulgaria. Additionally, the tool developed by Forne (2017) emphasises the use of Excel-VBA to automate and process forest operations.

However, certain limitations should be acknowledged. The Forest Inventory Tool (FIT) is currently tailored specifically to softwood species, particularly pine, due to the unavailability of relevant yield tables for other hardwood species. Additionally, regional variations in plantation conditions across Tanzania may affect the tool’s overall performance and applicability. Future developments should aim to incorporate yield tables for a broader range of species to enhance the tool’s versatility.

Despite its practical utility in forest management planning, several potential challenges may hinder the broader adoption of the FIT. First, effective utilisation requires adequate training for forest managers and field officers—particularly in tasks such as importing data, running simulations, interpreting stand metrics, and updating management actions. Without sufficient user capacity, the accuracy and reliability of the outputs may be compromised. Second, the tool relies heavily on clean, high-quality data formatted appropriately. Errors or inconsistencies in the input data can significantly affect results. Lastly, as forest operations scale up or as more compartments and species are added, the tool may encounter scalability limitations. For instance, managing datasets with more than 500 compartments may necessitate modifications to the tool’s current structure to ensure continued efficiency and responsiveness. Furthermore, expanding its functionality into a comprehensive application or web-based platform tailored to Tanzanian forest plantation management could further enhance its utility. Such advancements would solidify the FIT's role in bridging the gap between planned and actual management practices.

CONCLUSION

This study successfully developed a FIT that automates inventory data analysis, supports the preparation of a five-year forecasted management plan, and dynamically updates stand metrics when management practices, such as thinning and clear-felling, are either executed or postponed. The FIT’s automated analysis provides forest managers with the most updated data on critical metrics, such as the number of stems and volume per hectare, allowing for more accurate tracking and informed decision-making over time. The FIT has significant implications for forest management, particularly in improving the effectiveness of management plans by providing metrics based on whether management actions have occurred. However, limitations exist in the available yield tables for CAI and Mean Annual Increment (MAI) of species other than pine. Additionally, the available yield tables cover only up to 30 years, whereas some management units exceed this age range. Furthermore, the existing yield table does not comply with the current technical order, which specifies that the first thinning, second thinning, and rotation age should be carried out at 8, 13, and 18 years, respectively.

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Addressing these limitations in future work could expand the tool's applicability.

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APPENDICES

Appendix 1: Data Requirements for the Forest Inventory Tool

The Forest Inventory Tool requires input data in an Excel file with the following parameters and arrangement.

compartment	species	age	area	plot_number	tree_number	dbh	Hdom	thinning_status	plot_area	height

However, the header is not necessary when importing a dataset.

Appendix 2: User Guide for the Forest Inventory Tool (FIT)

Step-by-Step Instructions

1. Opening the Tool
    - Open the Excel file containing the Forest Inventory Tool (FIT).
2. Importing Data
    - Navigate to the "DASHBOARD" sheet.
    - Click the "Import Data" button.
    - Select the appropriate dataset from your computer and load it into the tool.

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3. Viewing Stand Data
    - Click the "Stand Data" button to navigate to the sheet displaying the stand-level parameters.
4. Running the Simulation
    - Click the "Run" button to initiate the simulation process.
    - The tool will process the data and update stand metrics based on management practices and growth simulations.
5. Reviewing the Results
    - Return to the "DASHBOARD" sheet.
    - The updated summary of various parameters, including stand metrics, thinning, and clear-felling volumes, will be displayed.