Sustainable Forest Management in Uasin-Gishu-Kenya: Design of Yield Estimation Modelling Tool on Cupressus Lusitanica and Pinus Patula

Wanyonyi Mungau Michael [*], zhuo Li [*], Mwangi Kinyanjui [**]

[*] Tongji University, UN Environment Tongji Institute of Environment for sustainable Development (IESD)
College of Environmental Science and Engineering, 1239 Sipping Road, Yangpu district, Shanghai China)
[**] Mountain Studies and Climate Change, Karatina University, P.O box1957-10101, Karatina Kenya

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Abstract- The conservation and sustainable management of forests are vital for climate change mitigation, biodiversity preservation and ensuring the socio-economic well-being of communities. This is specifically important to Kenya where the general projection shows that the demand for timber and its products is set to increase steadily by the year 2032 while the forest cover is decreasing. This thesis focuses on developing a yield estimation modelling tool for *Cupressus Lusitanica* and *Pinus Patula* in the Uasin-Gishu region of Kenya.This will enable forest managers and stakeholders to make informed decisions regarding sustainable forest management practices

This study was carried out in Kenya-Eastern part of the continent of Africa and was restricted to the area of Uasin- Gishu County. The County spans a total area of 3,345.2 km2 and covers the area between latitudes 00 03' South and 00 55' North and longitudes 340 50' East and 350 37' West.The main areas of interest are Timboroa and Nabkoi forest stations which form part of the former Northern Tinderet forests.

This study applied the concept of comparative experimental research using random sampling. The intervention and control groups were subjected to randomized post hoc tests at each forest station where field surveys were conducted to collect data. This involved comparing the control tree species, which were harvested at the designated ages of 6, 11, 16, 21, and 30 years, with the experimental tree species to be harvested a year earlier, at 5, 10, 15, 20, and 29 years. Multiple linear regression modelling was employed to establish relationships between the measured variables and volumes.

The results from study comparing the two forests were found to be statistically insignificant, suggesting that there would be no real difference in yields if the revised harvesting schedule was implemented. This study developed a set of yield models based on Volume, Height and Diameter as the harvesting ages increased. The Models developed were presented in the form of multiple linear regression equations;

1) $Volume_{c.lusitanica=} 0.058508A_{ave} + 2.843382D_{ave} +(-0.05776)H_{ave}$
2) $Volume_{P.patula}= 0.042432A_{ave}+0.023043181H_{ave} +(-2.387094599)D_{ave.}$

Where; A_{ave}-age of tree, D_{ave}-average, H_{ave}-Total height of tree

The proposed modelling tool provides a user-friendly interface and incorporates dynamic variables to ensure flexibility and adaptability to changing forest conditions. The tool can assist in optimizing forest planning, including timber harvesting schedules, rotation periods, and silvicultural interventions.

The findings of this research contribute to the advancement of sustainable forest management practices in Uasin-Gishu, Kenya.The study recommends more research to be conducted in different Counties and come up with a modern standard Model for application and the continuation of use of previous harvesting schedule.

Index Terms- Uasin-Gishu-Kenya Area, Sustainable Forest Management, Modelling tool, Yield Estimation

I. INTRODUCTION

Sustainable development of forests refers to the responsible management and conservation of forest resources to meet the present and future needs of society while maintaining the ecological integrity of the forest ecosystem. According to the article by [1], despite the progress made in gathering information on forest resources and evaluating forest sustainability remains challenging. Practicing sustainable forest management is made difficult by unfavorable market conditions and the ensuing lack of funding, challenges in developing and implementing forest management plans, and uncertainties including potential impacts of climate change, population growth, and changing market [2,3]. The preservation of a sustainable forest is essential for maintaining a delicate equilibrium between environmental preservation and fulfilling the growing need for forest resources.

Kenya reached 10% forest cover, falling short of the aim of 20% by 2030. That percentage, according to Kenya Forest Services (KFS), was reached after more than 1.8 billion trees were planted during a three-year period (2019-2022). Kenya has lost 368,000 hectares of tree cover, which equates to an 11% decline in tree cover between 2001 and 2021. In Kenya, *Pinus patula* and *Cupressus lusitanica* are the two widely cultivated tree species known for their commercial value and are primarily utilized for timber and board production, as well as the manufacturing of paper and pulp. With the global concerns regarding climate change, it is crucial for the country to expedite the development of reliable techniques and approaches for accurately evaluating and predicting the potential output of forest areas [4]. This is particularly significant for commercially valuable tree species like *Cupressus lusitanica* and *Pinus patula*, which are extensively grown for their timber and non-timber forest products.

Cupressus lusitanica, commonly known as Mexican cypress, is a foreign tree species cultivated for commercial purposes such as the production of saw timber, plywood, and poles for construction [5]. It is also valued for its various services, including live fences, shade, and ornamental purposes. Originally introduced from different regions of Mexico, *Cupressus lusitanica* has been widely planted in various parts of the world. Several yield estimation models have been developed specifically for *Pinus patula* and Cupressus lusitanica to assist in predicting their growth and timber production [6,7].According to the Kenya Forest Research Institute's (KEFRI) Guide to Tree Planting in Kenya, *Pinus Patula* thrives in ecological zones situated between 1,600 to 3,000 meters above sea level. It also demonstrates moderate tolerance to drought conditions. In its original habitat, this species typically experiences an average annual rainfall ranging from 750mm to 2,000mm [8]. These species have gained prominence due to their commercial value and adaptability to the region's climatic conditions. However, the absence of precise yield estimation tools and models poses significant challenges for sustainable forest management in the region [9]. Accurate estimations of forest yields are crucial for decision-making processes related to harvesting, rotation periods, and timber supply planning.

Forests cover over four billion hectares of the Earth's landmass, around 31 percent of total land area. As of 2020, worldwide forest area measured some 4.06 billion hectares, down from approximately 4.24 billion hectares in by 2020. Between 2015 and 2020, the rate of deforestation was estimated at 10 million hectares per year, down from 16 million hectares per year in the 1990s. The area of primary forest worldwide has decreased by over 80 million hectares since 1990 [10]. The United Nations General Assembly (UNGA) developed the Sustainable Development Goals (SDGs) in 2015 as a component of the Post-2015 Development Agenda. This agenda aimed to establish a new global development framework to replace the Millennium Development Goals, which concluded in that same year. SDG 15 specifically focused on the objective of ceasing deforestation and rehabilitating degraded forests. Its targets included the promotion of sustainable management practices across all forest types, halting deforestation, restoring damaged forests, and significantly increasing global afforestation and reforestation efforts by the year 2020 [11]. Africa has approximately 26% of its land designated as forested areas, with nearly 43 billion trees residing on the continent. The majority of these trees can be found in South Africa, Ethiopia, and Nigeria. According to the [12]. African forests are experiencing an annual deforestation rate of nearly 4 million hectares, which is nearly double the global average for deforestation speed. The major causes of deforestation in Africa, its effects on the environment, as well as current policies and potential solutions to combat it have been discussed at length.

Yield estimation model is the predictive tool developed to gauge the potential yield of trees or forests by considering various factors. This model takes into account data such as tree species, age, size, site conditions, and historical growth patterns to generate precise estimations of future tree yields. By examining these variables, the model offers valuable insights into the expected amount of timber volume, biomass, or other forest products that can be obtained from a specific area or stand of trees. This information holds immense importance in forest management planning, sustainable harvesting practices, and optimizing resource allocation. Tree yield estimation models assist forest managers in making well-informed decisions that ensure the long-term health and productivity of forest ecosystems. Estimating the yield of these species is essential for effective forest management and planning

In Kenya, we currently do not have a known tree yield modelling tool for purposes of forecasting, planning and policy decision making [18]. According to [19], the yield from a field-level crop simulation model and adjustments to the simulated potential yield will help to assess the impact of varying levels of model complexity on the accuracy of regional yield. The outcomes of this study will contribute to advancing sustainable forest management practices by enhancing the accuracy and precision of yield estimations for *Cupressus lusitanica and Pinus Patula* stands. Forest managers will be able to optimize their decision-making processes, ensuring a balance between economic viability and environmental conservation. Furthermore, policymakers can rely on these yield estimation models to guide the development of evidence-based policies aimed at promoting sustainable forest practices and fostering long-term ecological resilience.

This research was conducted in Uasin Gishu county, one of the 47 counties in Kenya which is located within the former Rift Valley Province. Eldoret serves as the administrative and commercial center of the county, where is the most of its residents reside. The county comprises six sub-counties: Turbo, Kesses, Ainabkoi, Kapsaret, Soi, and Moiben. KNBS 2019 estimates that 1,163,186 people live in the Uasin Gishu county. It is a rural county with an agricultural economy, thriving biodiversity, transportation, industry, and urbanization. Due to the large population, there is a significant need for wood products for economic services like construction and fuel. The county's main problems include poor farming practices, poor housing conditions, excessive environmental exploitation in the form of deforestation, and potential climate change effects [20]. For the study mentioned above, two forest stations named Nabkoi and Timboroa were selected which initially formed part of the Former Northern Tinderet forest block. Timboroa is situated at an elevation of 2,743 meters above sea level (masl) and positioned at a latitude of 0°04' north and a longitude of 35°33' east. Nabkoi, located at a latitude of 0°8' north and a longitude of 35°28' east, lies at an altitude of 2,591 meters above sea level. Both locations experience relatively low temperatures, with Timboroa ranging from 12 to 14°C and Nabkoi ranging from 14 to 16°C. The forest coverage in the county is estimated to be 7.6%, which falls significantly below the recommended minimum of 10%.

In conclusion, this thesis seeks to contribute to the sustainable management of forest resources in Uasin-Gishu County, Kenya, by developing a yield estimation modelling tool specific to Cupressus Lusitanica and Pinus Patula. The integration of accurate yield estimations into forest management practices will promote informed decision-making, ensuring the long-term viability of forests while meeting the economic and environmental needs of the region [21].

II. RESEARCH METHODOLOGY

2.1 Location of study

This research was conducted in Kenya, specifically in the eastern region of Africa, within the locations situated in Kenya's Rift Valley. Uasin Gishu County, one of Kenya's 47 counties, is located in the former Rift Valley Province. The largest town in this area is Eldoret, which serves as the administrative and commercial center of the county and houses the majority of its residents. Eldoret consists of six sub-counties: Turbo, Kesses, Ainabkoi, Kapsaret, Soi, and Moiben [72].Within the County, there are six government forests known as Kapsaret, Timboroa, Nabkoi, Kipkurere, Cengalo, and Lorenge Forest Stations. For the study mentioned earlier, two forest stations, namely Nabkoi and Timboroa, were selected. Both of these stations belong to the Former Northern Tinderet block. Timboroa is situated at an altitude of 2,743 meters above sea level (masl), with coordinates at latitude 0°04' North and longitude 35°33' East while Nabkoi is located at latitude 0°8' North and longitude 35°28' East, at an elevation of 2,591 meters above sea level.

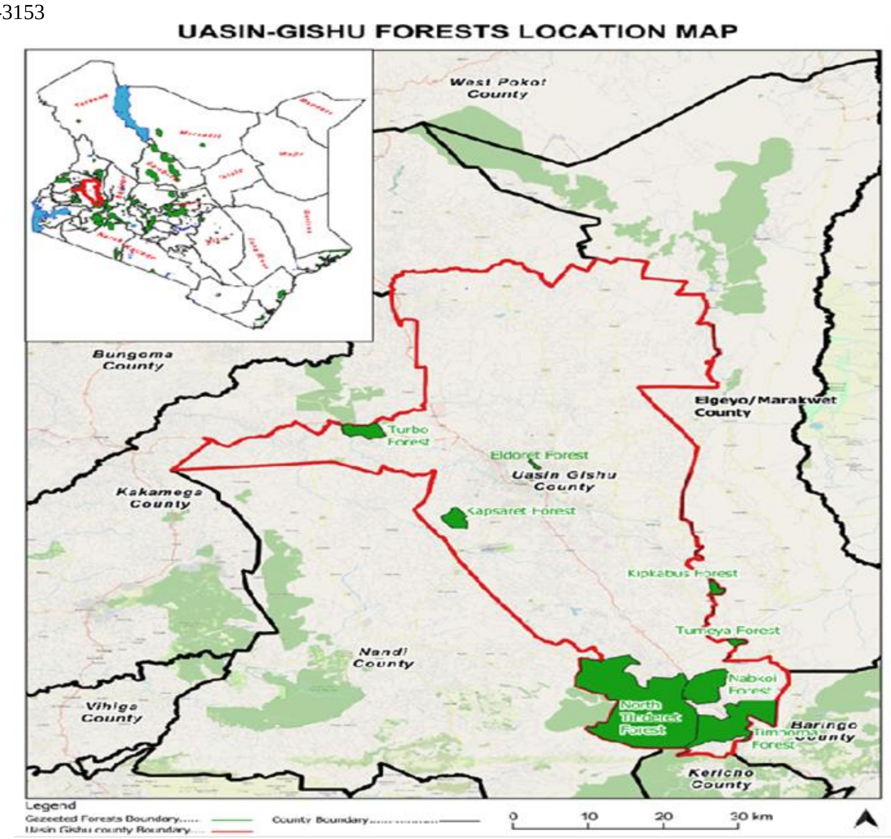

Figure 2. 1 Location map of Uasin-Gishu County Forests-Kenya

2.1.1 Population

According to the 2019 estimates by KNBS, the population of Uasin Gishu County population stands at 1,163,186 individuals. This County is predominantly rural, with an economy centered around agriculture, vibrant biodiversity, transportation, industry, and urban development. Given its sizable population, there is a notable demand for wood products, which are crucial for economic activities such as construction and fuel.

2.1.2 Forest cover

The forest coverage in the county is only 7.6%, which falls well below the recommended minimum of 10%. Within the Nabkoi forest, there are 90 plantations of the *Cupressus lusitanica* species and 53 plantations of *Pinus patula.* In the Timboroa forest, *Pinus patula* species occupy 70 plantations, while *Cupressus lusitanica* covers 89 plantations [73].The Nabkoi Forest consists of two distinct habitats: forest and grassland. The grassland habitat has a higher species count compared to the forest habitat. This is likely due to the predominance of herbaceous species in the grassland, which have shorter life cycles compared to the predominantly tree species found in the forest ecosystem [74].

2.1.3 Weather and climate

Uasin Gishu County experiences a warm and moderate climate with a significant amount of rainfall even during its driest month. Based on the Köppen-Geiger classification, this region is categorized as Cfb. The average temperature in Uasin Gishu is 17.3 °C (63.2 °F), and it receives an annual rainfall of 2027 mm or 79.8 inches. The summer season in this area spans from June to September. From October to March, both sites undergo periods of low precipitation. The average annual rainfall in Nabkoi ranges from 1000 to 1600 mm, while in Timboroa it ranges from 1100 to 1700 mm [75]. Additionally, both locations experience cool temperatures, with Timboroa ranging from 12 to 14°C and Nabkoi's temperatures falling within a similar range of 14–16°C.

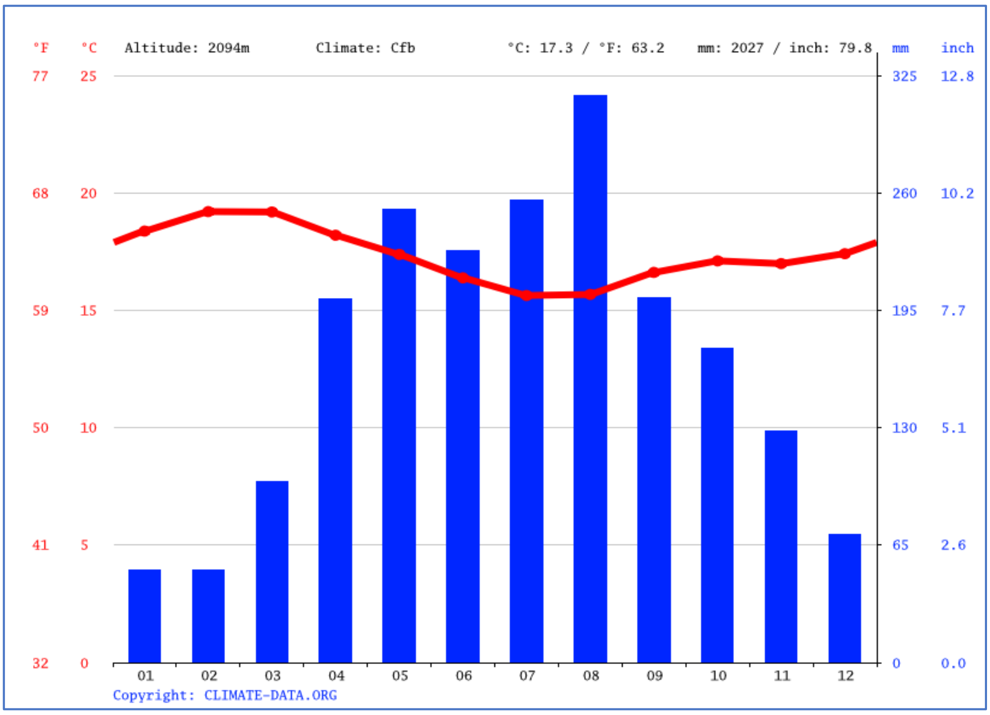

Figure 2. 2 Climatic conditions in Uasin-Gishu County

2.1.4 Soils, relief and drainage

The region contains HI2 and FUC soil units, which developed on underlying igneous rocks, basement System rocks, and river terraces. On acidic igneous rocks and other parent materials, there exist soils with different levels of fertility [76]. The upland area exhibits varying elevation levels. The lower-level soils, including UmG3, UmU2, UlU3, and UmN2, have relatively low natural fertility. However, these soil types seem to create a favorable environment for tree growth in the selected study areas (Farm Management Handbook of Kenya Vol. II, 2011).

2.2 Research design

The idea of comparative experimental studies was used in this study. The type of random experiments was used. In each forest station, randomized tests with intervention and control groups were applied. This study's design involved two groups, one of which received the intervention (varied harvesting schedule) and was compared to the other, which did not receive the intervention (a normal harvesting schedule). The results from Timboroa forest and Nabkoi forest were later compared to assess similarity and differences in order to improve the study's quality.

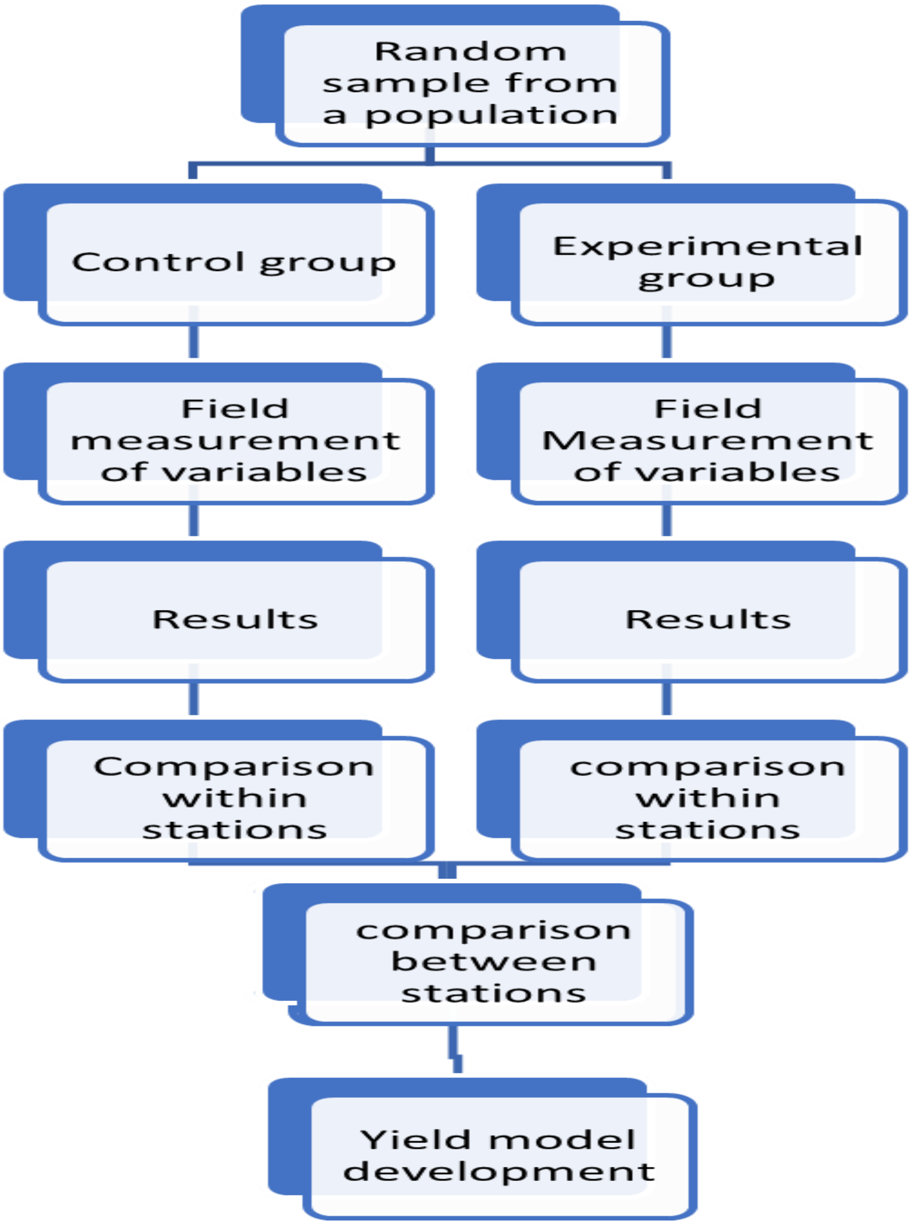

Figure 2.3 Experimental design for the research

2.2.1 Sampling procedures

A precise and closely spaced grid measuring 150m in the North-South direction and 125m in the East-West direction was superimposed on a Universal Transverse Mercator (UTM) map of the sub-compartment, which had a scale of 1:10,000. This grid served as a reference for creating the point samples. Each sample point was accurately marked on the map by aligning it with the intersections of the grid lines. The coordinates of each sampling point were determined on the map and later confirmed on-site. The starting point (PC) was identified on the map and its corresponding UTM coordinates were recorded. Using a GPS device, the starting point was then located on the ground and marked with a peg. In order to determine the distance from the PC to the first sample, a measuring tape and compass were employed, resulting in a measurement of 30 meters. Subsequently, the remaining sample points were identified relative to the initial one using the compass and measuring tape. At each sampling point, a

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painted wooden peg was driven into the ground at its center, and GPS coordinates were recorded to verify the locations. In line with the concept that circular plots are more straightforward to establish [77], the radius of each sample point varied based on the tree density within the respective sub-compartment. If multiple thinning operations were conducted on the plantation and recorded in the compartment register, or when there were fewer than 500 trees per hectare, a circular plot with a radius of 11.28 m was initially employed. For sub-compartments under 10 years old, irrespective of thinning evidence, a smaller diameter of 7.98 m was used, and the number of trees in each plot was counted. In cases where only one thinning was documented in the compartment register or the density exceeded 500 trees per hectare, a circular plot with a radius of 7.98 m was utilized.

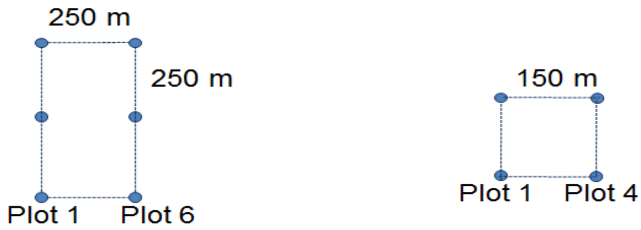

Figure 2.4 Sample plots design for the research

2.2.2 Determination of the required number of samples

The National Forest monitoring system (NFMS 2021) guidelines for acceptable confidence intervals and target error rates were used to determine the necessary number of samples for each forest stratum. For the NFI survey in Kenya, the target error rate was10% and the confidence interval at 95% are set for the calculation.

Table 2. 1 Standard procedures for sample plots allocation

S/No	Area of compartment in Ha	No of sample plots	Distance between sample plots
1	0.5-1.8	1	150m -N, 125m -E
2	1.9-4.0	2	
3	4.1-5.9	3	
4	6.1-9.8	4	
5	9.9-13	7	
6	13.1-15	8	
7	15 above	10	150m in all directions

The targeted sample plots were established using the QGIS and coordinates identified before ground truthing and location in the field. The description of variables to be collected within the plot radius is shown in (Table 3.2);

Table 2. 2. Data contents of a sample plot

Subject	Number	Units
Number of trees	All	Numbers
Species identification	All	Botanical names
Tree heights	10 Best trees	Meters
GPS coordinates	One	Degrees, minutes seconds
Tree diameters	All	Centimeters

The data collected was later put in topographic map with clear boundaries, contents and scale for effective representation of the research areas. The (Figure 3.6) below shows the developed map of

Timboroa 1(M) which is located in North Tinderet forest block with all the sample points and respective GPS coordinates.

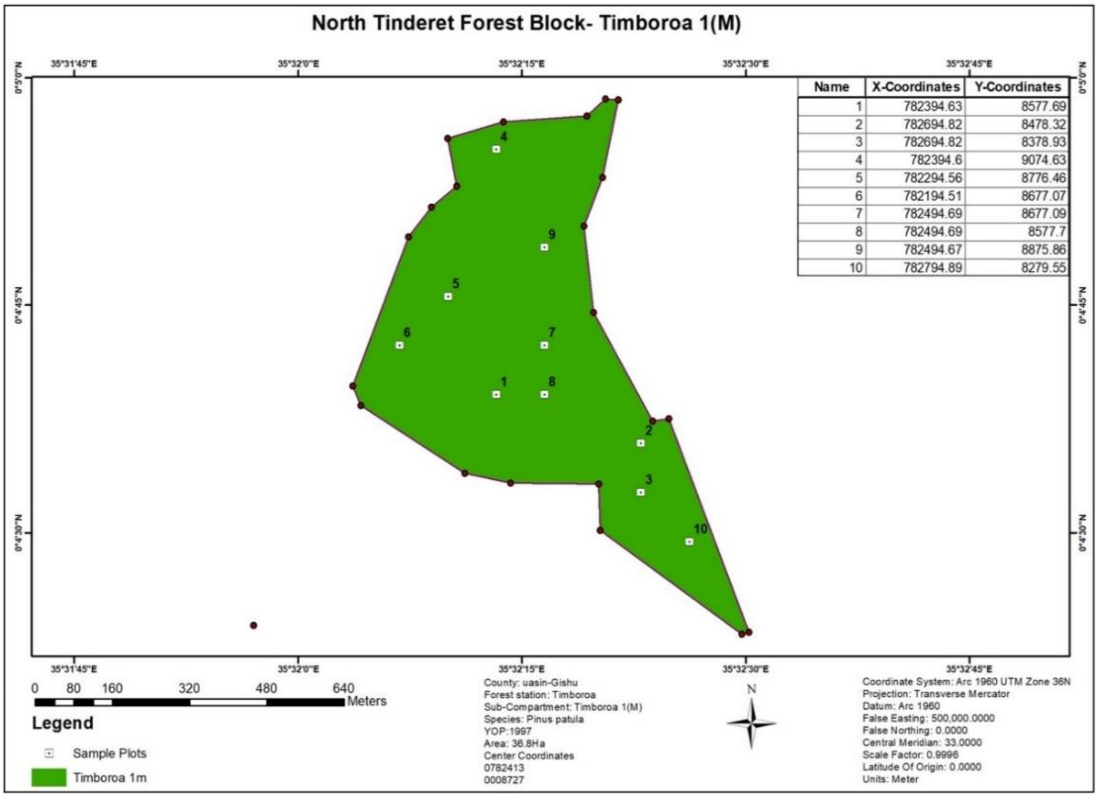

Figure 2.5 Map of plotted samples in Timboroa 1M

2.3 Measurements for data collection

For this study, it is preferable to utilize unprocessed or initial data obtained directly from the fields or forests. Trees with a height of less than 15 meters were assessed using a height pole, while trees taller than this were measured using a Suunto Clinometer. The heights of trees measured with a height pole were directly recorded, whereas the heights obtained with a Suunto Clinometer needed to be calculated. To calculate these heights, a diameter tape was utilized to measure the diameter of a tree at a height of 1.3 meters above the ground.

2.3.1 Data sources and recordings

The essential data, their format, and their source are provided in the (Table 3.3) below.

Table 2. 3 Data sources and recordings

Data	Format	Source
Tree Species	Table	Compartment Registers
Plantation Areas	Table	Compartment Registers
Plantation Density	Numbers	Field Measurements
Tree Heights	Numbers	Field Measurements
Tree Diameters	Numbers	Field Measurements
Plantation Ages	Table	Sub-Compartment Registers

Plantation Boundaries	Gps Coordinates	Survey Department
Tree Volumes	Numbers	Calculations

2.3.2 Field measurements criteria

The measurement of tree variables in the field were done in line with the forest inventory procedure and the National Forest management and information systems guidelines as outlined below;

Table 2. 4 Field Measurements conducted

Measurement	Specification	Units	Equipment
Tree heights	Top height Bottom heights Horizontal distances	meters	Suunto Clinometer
Tree diameters	Diameter at Breast height (At 1.3 m)	Centimeters	Diameter tapes
Sample plots	Systematic sampling	Numbers	Q-GIS
GPS coordinates	Eastings &Northings	UTM, UPS	GPS gadget

2.3.3 Materials and equipment

The multi-purpose field-based forest inventories collect primary data on tree species, diameter and height, land use, Slope and Gps coordinates. Some of the materials required for the exercise are shown in (Table 3.5) below.

Table 2. 5 Tools and Equipment used for inventory

Tools	Number	Remarks
Measuring tools		
Compass (360°)	1	In degrees, Water proof model
GPS receiver (precision ca. 5 m) + extra batteries + charger + downloading cables	1	GPS points recording
Measuring tape, 30 m	2	Metric, 1 cm units (fibre glass)
Measuring tape, 50 m	2	Metric, 1 cm units (fibre glass)
Calliper for big trees	1	Metric, 1 cm units
Calliper for small trees (<30 cm)	1	Metric, 1 cm units
Diameter tape	1	mm scale
1.3 m stick	1	To measure breast height level
Tree height and land slope measuring equipment	1	Suunto hypsometer with 15m, 20m and % scales to measure ratio and percent.
Colored flagging ribbon	5 rolls	For marking plots
Waterproof bags	5	To protect from rain
Digital camera, memory card, batteries.	1	For taking photographs of plots
Machete / Bush-knife	4	For bush clearing

Pocket knife	1	For general use
Color spray	1	marking of fixed points
Plastic sticks	10	For marking of fixed points
40 cm long metallic pin	4	Marking of plot center on PSPs
Clothing		
Boots and waterproof outfits	12	For team members
Helmet	6	Prevent risk from falling branches
Rain coats	6	Optional
Documents, papers, recording tool		
Field forms	400	Plastic ones for rainy days
Code check list	4	-
Field manual		
Flora and species check list	2	-
Topographic maps, field maps and printed aerial photo/satellite image	5	-
Laptop PC	1	To enter/transfer field data
Pencils and markers	8	Data recording
Supporting board / writing tablet	1	To take notes
Hand calculator	1	calculations
Clipboard	2	To take notes
A4/A3 size flipchart	1	For photo identification
Other equipment (camping, security, communication…)		
Mobile phone	At least 1	
Radio phones	1+1	Communication
Chain saw	1	When necessary
Field car	2	-
First aid kit	1	With emergency numbers
Flashlight and batteries	As required	-
Camping equipment and cooking utensils	1	-
Rucksack	As required	-

2.3.4 Primary data collection

Tree variables were collected from designed sample plots within the selected sub-compartments within Nabkoi and Timboroa forest. This involved the cooperation of personnel, equipment and materials towards achieving the target. All the measurements were conducted in line with the national forest management systems standards and forest inventory procedures. The important variables collected are listed below;

2.3.4.1 Diameter

The diameter at breast height (Diameter) was taken for each tree in the plot for all sub-compartments sampled using the diameter tape and recorded in respective data sheets. Special considerations were followed based on the ground slope, tree characteristics and measuring equipment. They were recorded in cm.

2.3.4.2 Height

Total heights of ten (10) dominant trees (usually largest diameter) for larger plots with radius of 11.28m, and four dominant trees in smaller plots of 7.98m radius were taken using Suunto Clinometer. In all the measurements, the top height, bottom heights and a horizontal distance were taken.

2.3.4.3 Density

Density is normally captured as the number of tree species per ha of forest land. The density was calculated based on the number of trees per given size of sample plot. The total number of stems were counted and recorded in data sheets for the above purpose.

2.3.5 Secondary data collection

The secondary source of this data was obtained through a comprehensive review of relevant literature, including sub-compartment registers, management plans, KFS strategic plans, forest journals, and articles. The research in Kenya was authorized by the National Commission for Science, Technology, and Innovation (NACOSTI), leading to the issuance of Certificate No. License No: NACOSTI/P/22/22280 in December 2013.

2.4 Data analysis process

The descriptive analysis encompassed calculating the mean, standard deviation, and volumes of the samples. To assess the statistical significance of the comparisons, the non-parametric alternative test employed was the Mann-Whitney U test. Furthermore, the Shapiro-Wilk test was conducted to determine if the sample data collected by the researcher was drawn from a normally distributed population.

For the regression analysis, the development of the final models in the study involved utilizing one-way ANOVA.

2.4.1 Spatial analysis

Spatial analysis was employed to establish the boundaries of forests, species distribution, and sub compartment boundaries [78] highlighted that the arrangement of trees can vary from relatively even to highly clustered patterns, making it necessary to employ spatial modeling techniques. Furthermore, this approach aided in determining the GPS coordinates for selected sample plots for data collection. The NFIMS guidelines dictated the number of sample plots per plantation, which depended on the size of the plantation.

2.4.2 Empirical evaluation model

The applied empirical model is based on a statistical analysis of data that was observed and gathered from a forest or a plantation. Regression analysis was used in this model to establish the relationship between yield and independent variables. These models can predict tree growth more accurately than simple distribution models, and they can be used to explain growth variation brought on by changes in forest structure [79]. Models aid researchers to understand the process of tree growth [80] in response to environmental influences. They provide reliable method for forecasting future yields and for exploring impacts of various management and silvicultural options [81].

III. RESULTS AND FINDINGS

3.1 Data analysis

This chapter presents the results of the analysis conducted on the data collected. The analysis is divided into two main parts, descriptive analysis and inferential analysis. The sample was drawn from 376 sub compartments of the two forest stations in Uasin-Gishu County.

3.1.2 Demographics

The descriptive analysis for this study focused on the experimental and control groups of the two tree species and compared the mean volumes between the Nabkoi and Timboroa forest stations. The control *Cupressus lusitanica* trees at Timboroa station had the highest mean volume (0.718), as shown in (Figure 4.1). The Timboroa station recorded the lowest mean volume as well (0.397), which came from the experimental *Pinus patula* trees.

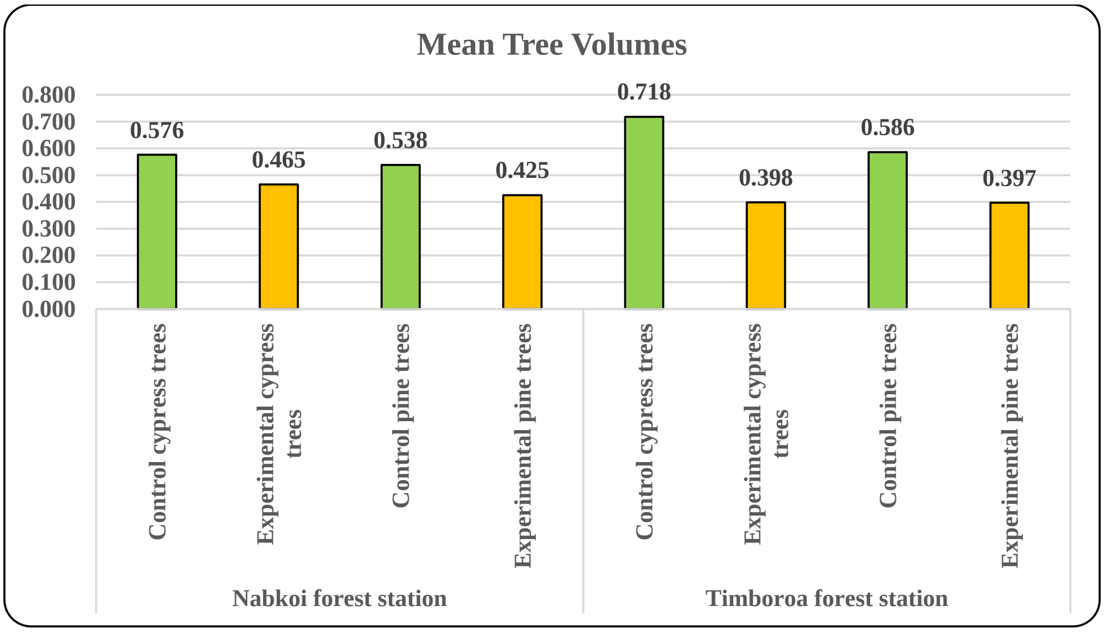

Figure 3. 1 Results of the research mean tree volumes

There is less variation in the standard deviation (SD) between the two tree species in the Nabkoi forest station compared to the Timboroa forest station. For the cypress species in Nabkoi station, the control sample has a slightly higher SD than the experimental sample, with a difference of 0.062. Same is the case for the pine tree species, which has a difference in SD of 0.035. The case is however different for the Timboroa station, where the difference in the SD of the volumes of the *Cupressus lusitanica* tree species between the control and experimental samples is 0.398 and that for the pine tree species is 0.1. In both cases, the control group has a higher SD

Table 3. 1 Summary statistics of key variables

Species		Variables	Nabkoi Forest				Timboroa Forest			
			Min	Max	Mean	SD	Min	Max	Mean	SD
Cupressus lusitanica	Control	Age	6	30	16.8	8.6	6	30	16.8	8.6
		Area (Ha)	17	23	20.1	2.1	3.5	24.4	14.5	9.1
		Density	13	38	23.1	5.9	9	48	28.5	11.6
		M diameter	194	380	281.8	62.7	190	494	296.1	111.3
		Mht	9	28.2	19.5	5.6	10	26.5	19.9	4.7
		Volume	0.114	1.243	0.576	0.389	0.116	2.083	0.718	0.673
	Experimental	Age	5	29	15.8	8.6	5	25	15	7.3
		Area (Ha)	16.6	27.5	20.3	3.9	4.1	26	15.9	8.6
		Density	13	31	21.7	5.7	14	38	28.7	7.9
		M.diameter	124	338	257.9	73.4	117	358	242.1	76.6
		Mht	6	28	17.2	7.3	9	24	17.9	4.1
		Volume	0.03	1.03	0.465	0.327	0.04	0.991	0.398	0.275
Pinius patula	Control	Age	6	30	16.8	8.6	6	30	16.8	8.6
		Area (Ha)	6.6	35	15.8	10.3	6.2	25.1	15.7	8.3
		Density	14	53	31.1	14.3	12	41	26.5	9.3
		M.diameter	153	368	256.9	64.7	155	360	255.4	67
		Mht	13	28	19.8	5	12.5	28.2	21.4	5.8
		Volume	0.108	1.292	0.538	0.365	0.106	1.292	0.586	0.388
	Experimental	Age	5	29	15.8	8.6	5	29	15.8	8.6
		Area (HA)	6.4	15	10	3.3	2	21	10.6	6.6
		Density	17	41	25.7	6.7	11	43	27.9	11.6
		M.diameter	135	360	228.1	66.6	131	323	219.8	60.9
		Mht	12	25.7	19.4	4.4	10	26.8	19.5	5
		Volume	0.084	1.113	0.425	0.33	0.061	0.988	0.397	0.288

3.1.3 Inferential analysis

The non-parametric alternative test utilized in this analysis was the Mann-Whitney U test. It served the purpose of comparing the results of the collected data by examining two sample means originating from the same population. The objective was to determine whether these means were equivalent or different. This choice was made due to the failure of the data to pass the normality test. The formula employed for this test is presented in equation 1

$$U_1 = R_1 - \frac{n_1(n_1+1)}{2}$$

or

$$U_2 = R_2 - \frac{n_2(n_2+1)}{2}$$ (Equation 1)

Where: U=Mann-Whitney U-test
N1 =samplesize1
N2=Samplesize2
Ri = Rank of the sample size

3.2 Comparison within the forests

In order to address the initial objective of the study, an analysis was conducted within each station to examine the forest yields. This analysis involved comparing the control tree species, which were harvested at the designated ages of 6, 11, 16, 21, and 30 years, with the experimental tree species that were harvested a year earlier, at 5, 10, 15, 20, and 29 years. The purpose of this comparison was to determine if there were any variations in yields between the two species and whether these differences were statistically significant. The study results are presented based on the variables determined; Average height (H_{ave}), average diameter (D_{ave}), age of tree (Age) and average volume (Vol_{ave}). The average volumes were calculated using the Hubers formula $V=\pi d^2 h/4xFF$……. Equation 2. The coefficient used was a form factor (FF) of 0.41 for *Cupressus lusitanica* and 0.45 for *Pinus patula* to cater for the tapering characteristics of the trees.

3.2.1 Comparison for *Cupressus lusitanica* species in Nabkoi forest.

This task involved comparing results gotten from *Cupressus lusitanica* variables in the varied harvesting schedules with the normal harvesting schedules in Nabkoi. The diagrammatic representation is shown in Figure 4.1.

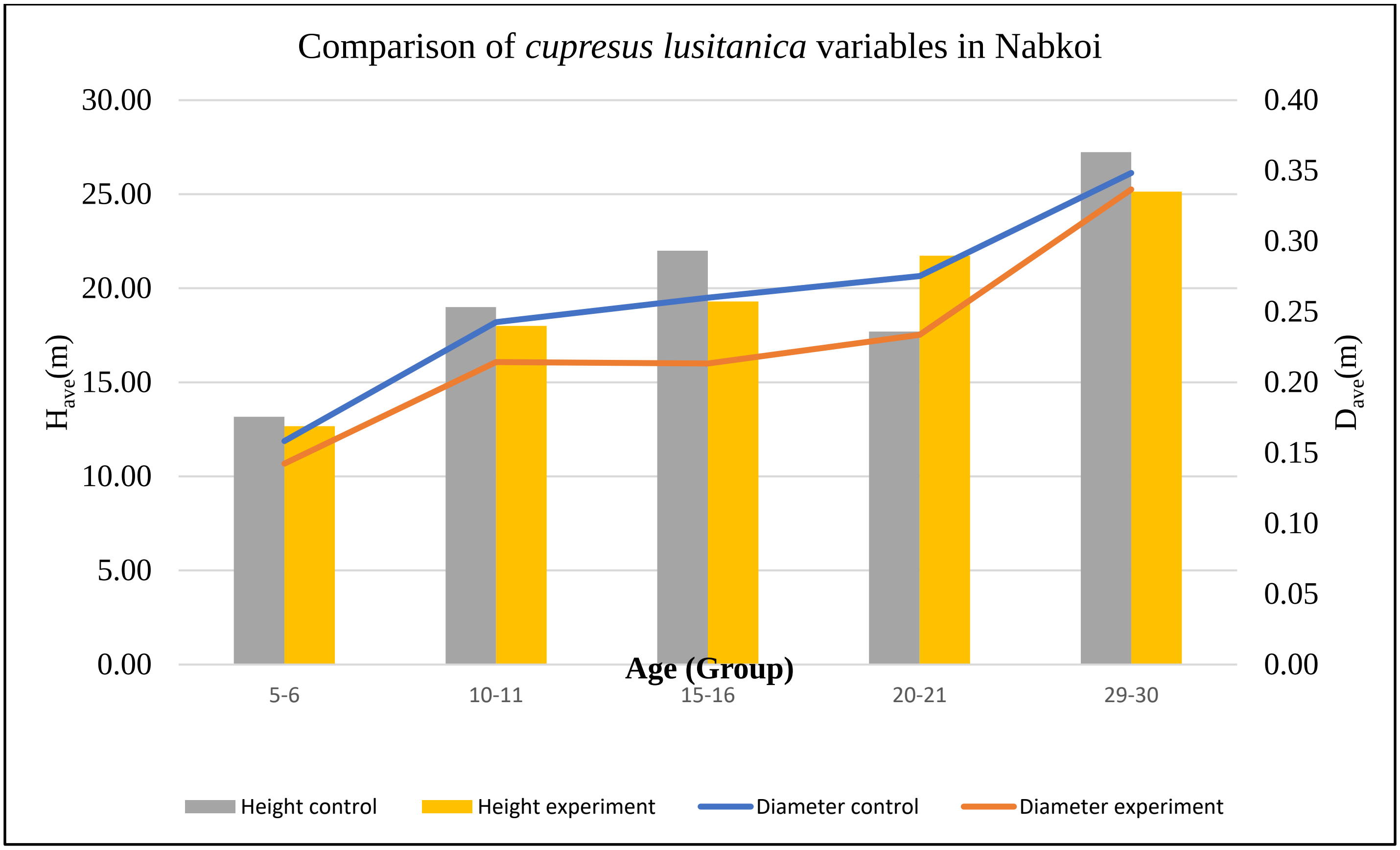

Figure 3. 2 Graph for comparison of *Cupressus lusitanica* variables in Nabkoi forest

The Mann Whitney U test results showed that the control cypress had a higher mean rank (16.27) than the experimental cypress (14.73). The Mann Whitney U test however found the 1.53 points difference in mean rank not statistically significant (U = 101, p = 0.633), implying that the difference in tree volumes between the control and experimental cypress species was just by chance.

3.2.2 Comparison for *Pinus patula* species in Nabkoi Forest

Similarly, comparing of results gotten from *Pinus patula* variables has the diagrammatic representation is shown in (Figure 4.2).

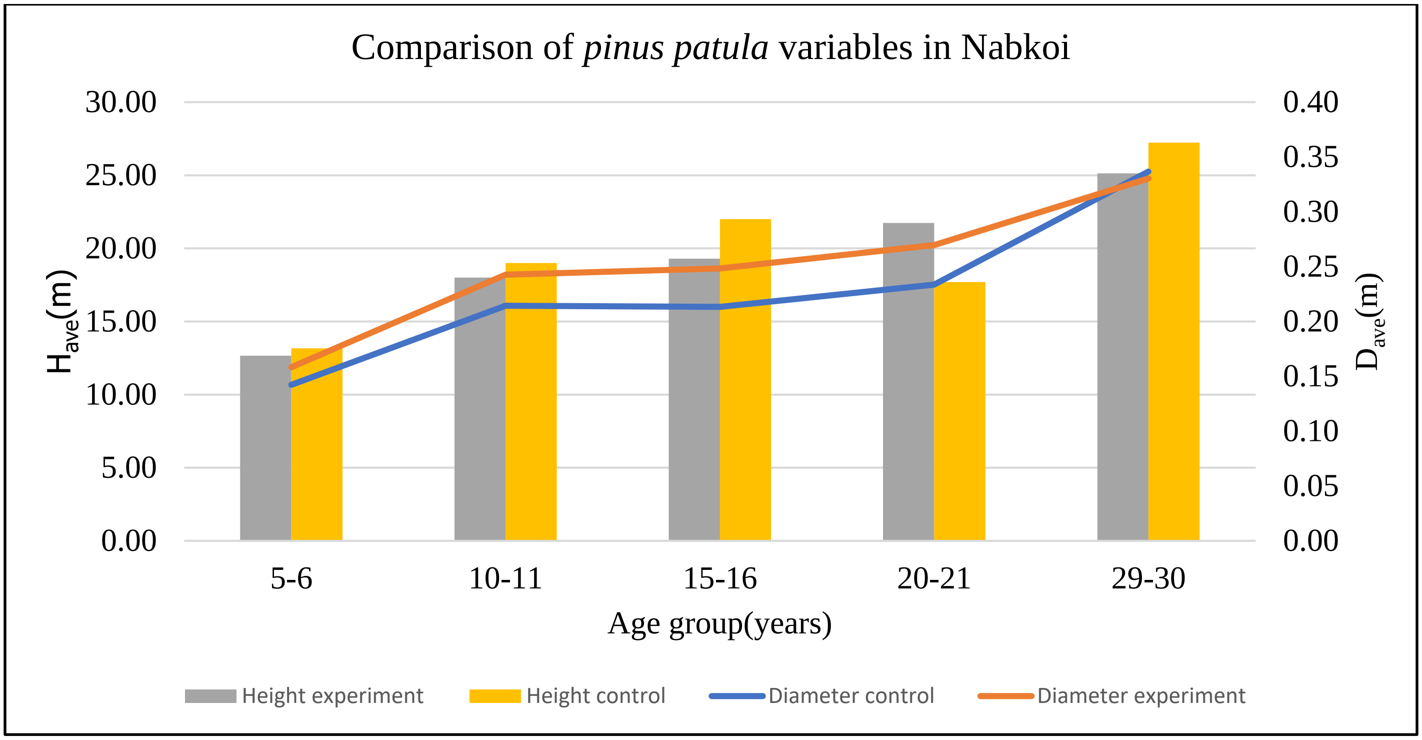

Figure 3. 3 Graph for comparison of *Pinus patula* Variables in Nabkoi forest

A similar comparison between control pine trees and experimental pine trees at the Nabkoi forest station also found the control pine having a higher mean rank (17.93) compared to the experimental pine (13.07). Despite the difference being considerable (4.86 points), the Mann Whitney U test found it not statistically significant ($U = 76$, $p = 0.130$). The implication of this was also that the noted difference in mean ranks, and by extension the tree volumes was not just by chance and consequently in tree volumes, was not merely a result of chance.

3.2.3 Comparison for *Cupressus lusitanica* species in Timboroa forest.

The same task involved comparing results gotten from *Cupressus lusitanica* variable had a diagrammatic representation is shown in (Figure 4.3)

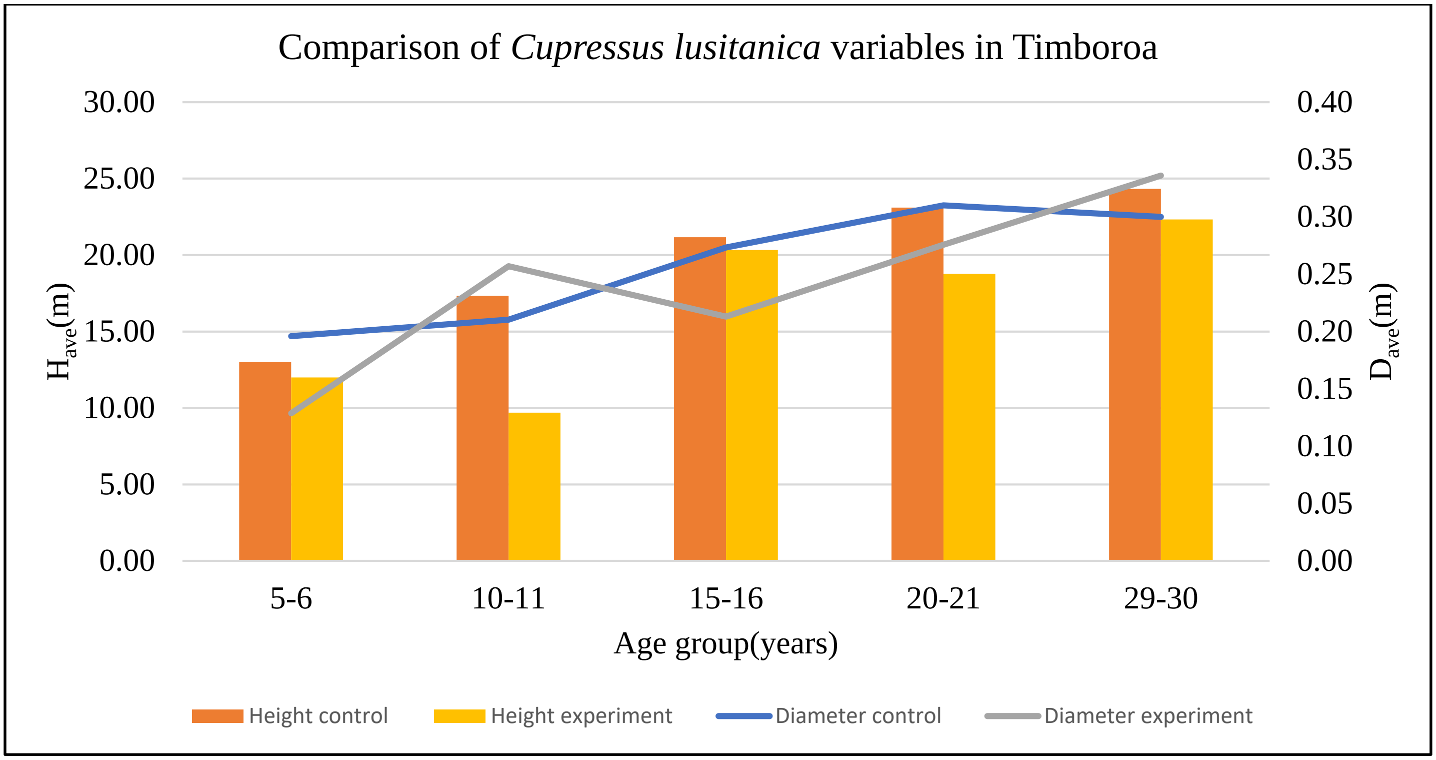

Figure 3. 4 Graph for comparison of *Cupressus lusitanica* variables in Timboroa Forest

It was observed that the control *Cupressus lusitanica* trees had a higher mean rank of 16.93 compared to the altered age regime cypress trees which had a mean rank of 14.07, giving a difference of 2.87 mean points. This difference was however found not to be statistically significant upon running the Mann Whitney U test ($U = 91$, $p = 0.373$)

3.2.4 Comparison for *Pinus patula* species in Timboroa forest

The diagrammatic representation is shown in (Figure 4.4) shows the results of the tests.

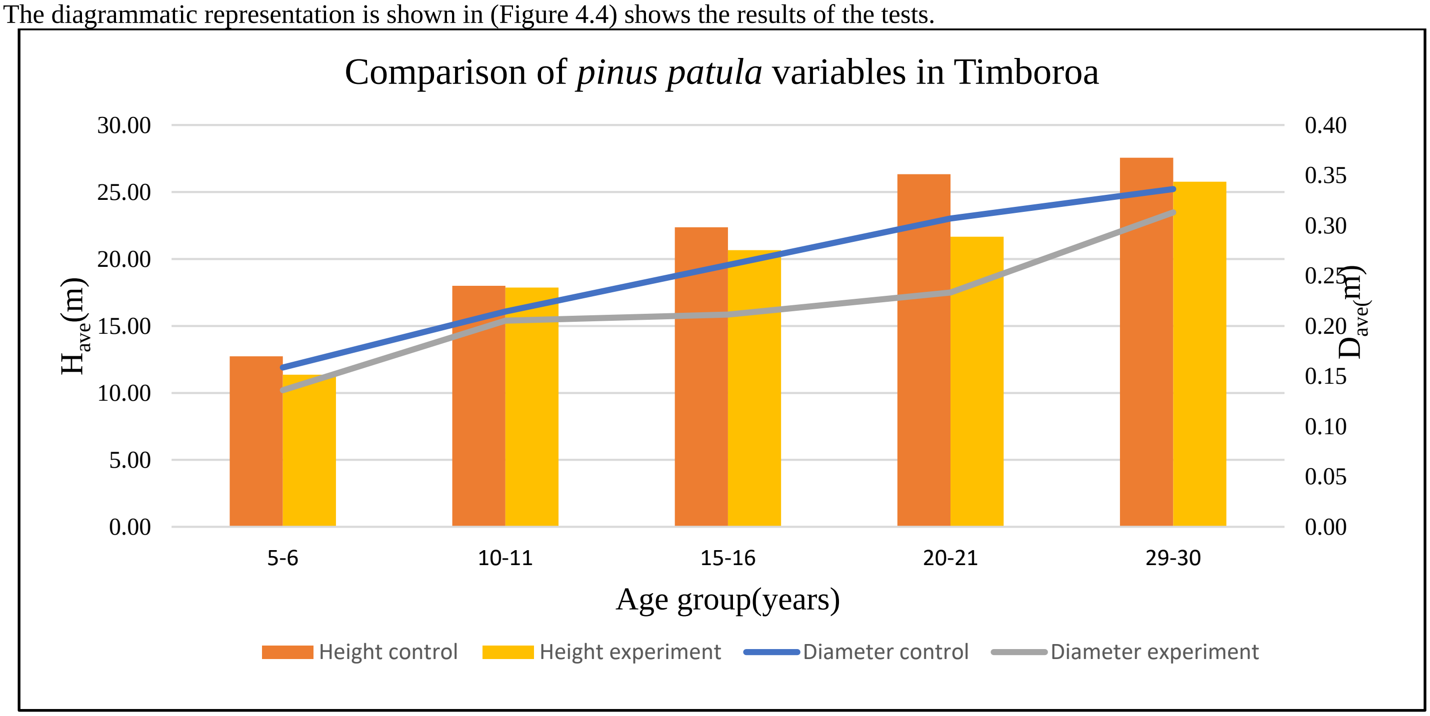

Figure 3. 5 Graph for comparison of *Pinus patula* variables in Timboroa

Findings of the analysis for the pine species also revealed a higher mean rank for the normal age regime pine trees (17.87) compared to the altered age regime's (13.13), a difference of 4.73 points. The Mann Whitney U test established the difference to be non-significant (*U* = 77, *p* = 0.141).

3.3 Comparison between the two forests

In order to gain a deeper understanding of variations in forest yields between different stations, a comparison was conducted between the sampled forest stations of Nabkoi and Timboroa. This comparison specifically examined the yields of the same tree species under both normal age and altered age regimes. To analyze the data, a Mann Whitney U test was performed to compare the yields of *Cupressus* lusitanica and *Pinus patula* between the Nabkoi and Timboroa stations

The study focused on determining the minimum variables (age, diameter, height) that would be ultimately utilized in developing a standard model for predicting yields for *Cupressus lusitanica* and *Pinus patula* trees species within Uasin-Gishu County. The graphical representation of the results is shown in radar diagrams from (Figure 4.9) and (figure 4.10).

4.4.1 Comparison of *Cupressus lusitanica* volumes in the two forests

The researcher combined all the volumes results calculated from *Cupressus lusitanica* species in both forest stations and represented the in Figure 4.9.

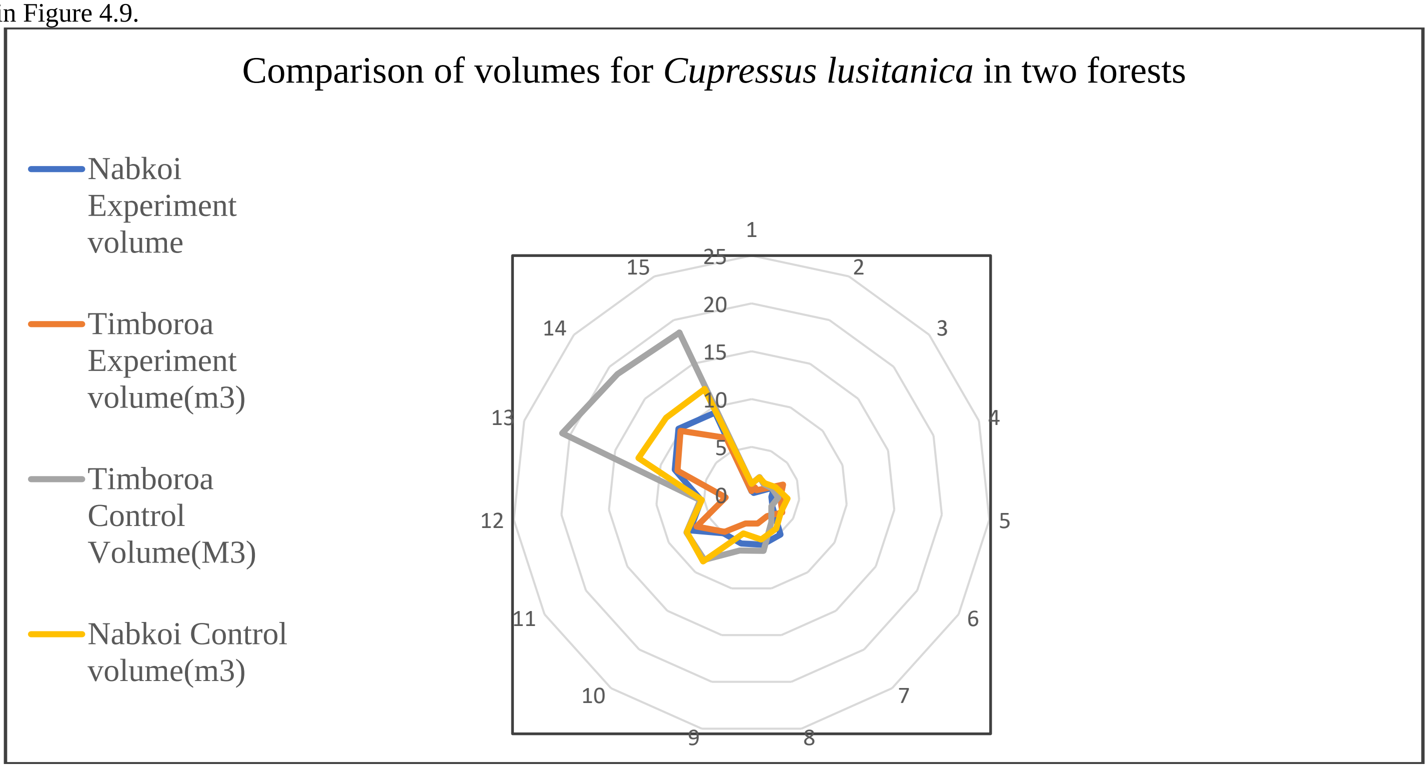

Figure 3.6 Radar diagram for comparing *Cupressus lusitanica* volumes between two stations

3.4.2 Comparison of *Pinus patula* volumes in the two forests

The researcher also combined all the volumes results calculated from *Pinus patula* species in both forests and represented the in Figure 4.10.

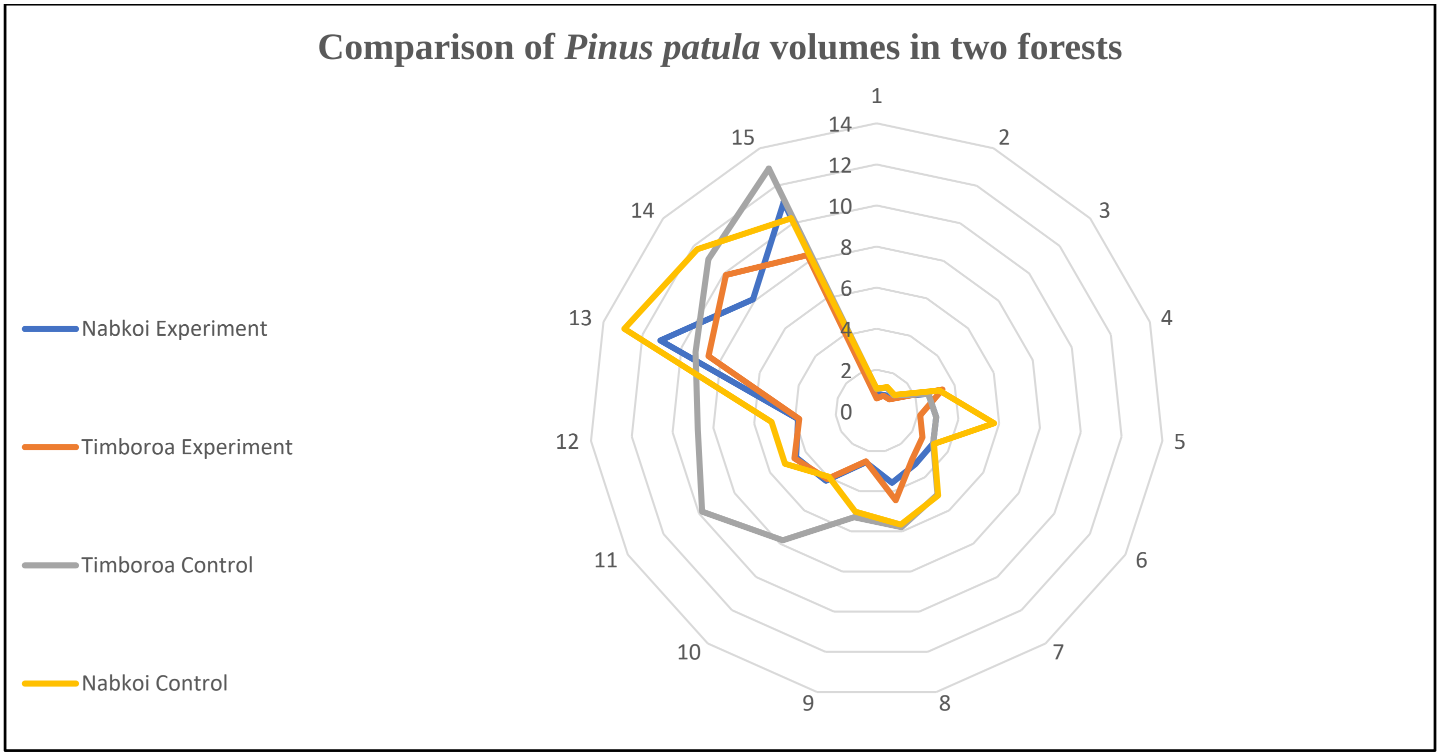

Figure 3.7 Radar diagram for comparing *Pinus patula* volumes between two forests

The difference in average rankings was found not to be statistically significant after the Mann Whitney U test was run within and between the forests. This suggests that, despite the variation in mean rankings, no important factor significantly affects the difference, indicating that similar yields can be anticipated from both harvesting procedures. Because there was no compelling reason to change, the researcher decided to keep using the data from the original harvesting regime (control). However, the researcher attempted to create a predictive model for predicting future yields based on age, mean diameter, and mean height using the information gathered from the control samples.

3.5 Model development

In this study, Regression Analysis was used to develop Yield Models of *Pinus Patula* and *Cupressus lusitanica*. The researcher ran regression analysis on the gathered data to comprehend the causal relationship between the variables of interest, which aided in creating a model construct for forecasting tree volumes. The relationship between a single dependent variable (volume) and several independent variables (age, height, and diameter) was examined using the statistical technique known as multiple regression. The purpose of this multiple regression analysis was to forecast future volumes (yields) of forest exploitation for sustainable development using the independent variables.

3.5.1 Volume model for *Cupressus lusitanica* species

For this analysis, volume was used as the dependent variable while the age, mean diameter and mean height were used as independent variables. The analysis returned the following results. The relationship between all variables established for model development is displayed in (Figure 4.20).

3.5.1.1 Relationship of variables in *Cupressus lusitanica* model

The scatter diagram describes the relationship between the two variables of height and diameter and their corresponding effect with increase in tree ages. They relationship between diameter and volume show an upward trend with no signs of outliers in a linear relationship.

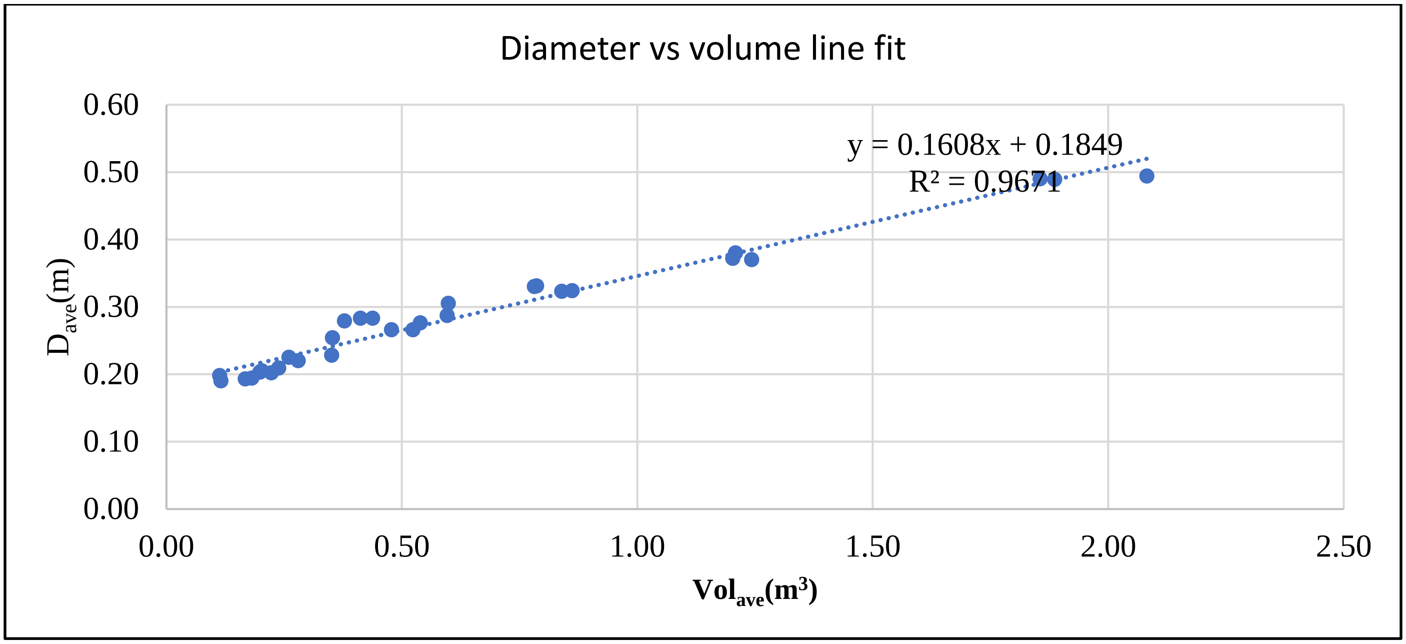

Figure 3.8 Relationship between diameter and volume for *Cupressus lusitanica* model

The volume was calculated using the Hubers formula ($v=\pi d^2 h/4xFF$).) using the coefficient (FF) of 0.41 for *Cupressus lusitanica* to cater for the tapering characteristics of the trees. The heights and volume values show a logarithmic trend with a high rise in volume between heights 10-25m.This is followed by a leveling up of the graph indicating a slow increase in higher heights.

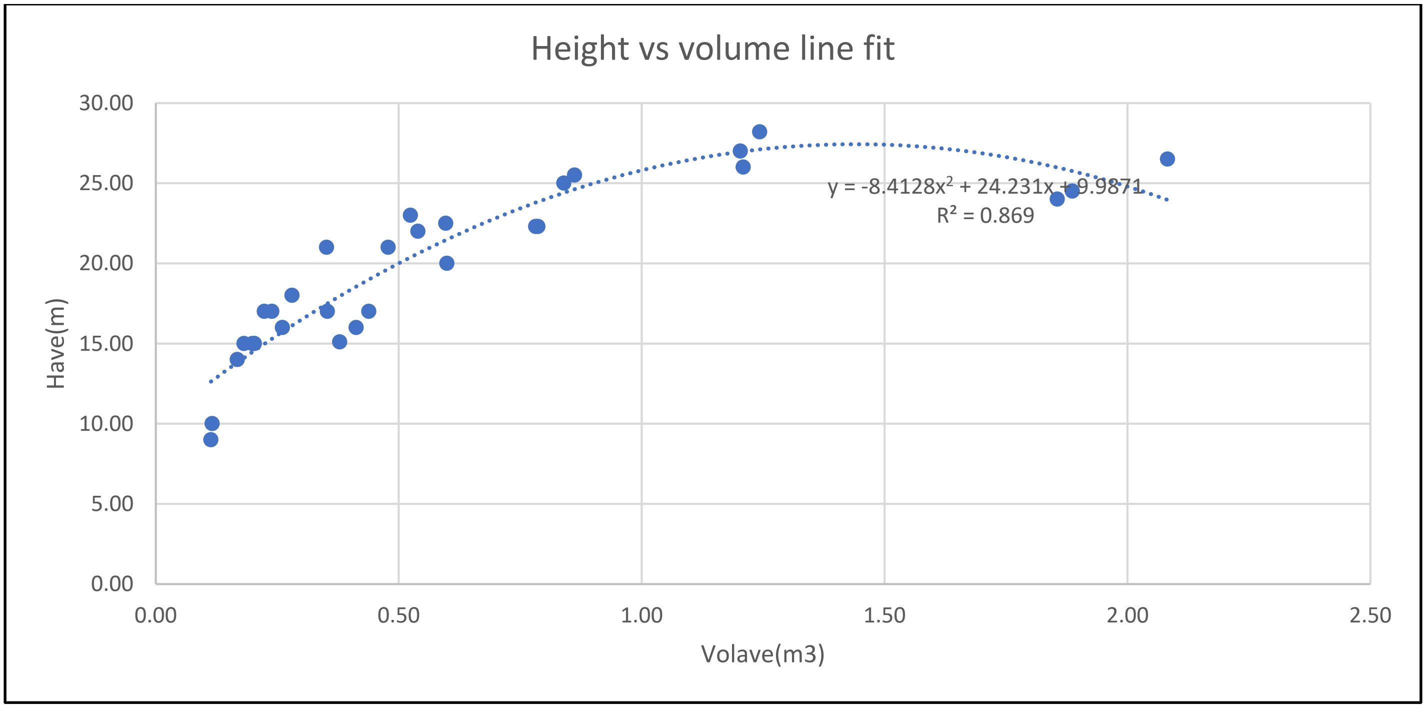

Figure 3.9 Relation of height and volume for *Cupressus lusitanica* model

3.5.1.2 The *Cupressus lusitanica* developed model

From the model summary table (Appendix 1), the finding was that the overall correlation coefficient between the dependent and all the independent variables was 0.978, meaning there was a very strong positive association between them. The R Square value, which is the coefficient of determination was 0.957, meaning 95.7 per cent of the variations in the dependent variable (volume) was explained by the independent variables. Generally, a higher r-squared indicates more variability is explained by the model.

The ANOVA table, which tests the overall goodness of fit of the regression model returned a statistically significant p value ($p<0.05$). This means that the regression equation predicts the dependent variable well.

From the SPSS output, age and mean height were found not to be statistically significant in predicting the volumes of the *Cupressus lusitanica* species because they had coefficients whose p values were above 0.05. Only the mean diameter had a significant coefficient. The Model for *Cupressus lusitanica* was presented using a multiple linear regression equation;

Volume $_{c.lusitanica=}$ $0.058508A_{ave} + 2.843382D_{ave} + (-0.05776)H_{ave}$ ………Equation 3

This means that a unit increase in the age of a *Cupressus lusitanica* will lead to increase in the mean volume by 0.058508 m^3; a unit increase in the mean diameter will lead to an increase in the volume by 2.843382m^3; and a unit increase in the mean height while holding ag and mean diameter constant will lead to a decrease in the mean volume by (-0.05776m^3.

3.5.2 Volume model for *Pinus patula* species

The relationship between all variables established for *Pinus patula* model development is displayed in (Figure 4.30).

3.5.2.1 Relationship of variables in *Pinus patula* model

The scatter diagram describes the relationship between the two variables of height and diameter and their corresponding effect with increase in tree ages. They all show an upward trend although height values show signs more signs of outliers. This may be caused by trees competition for light and soil nutrients.

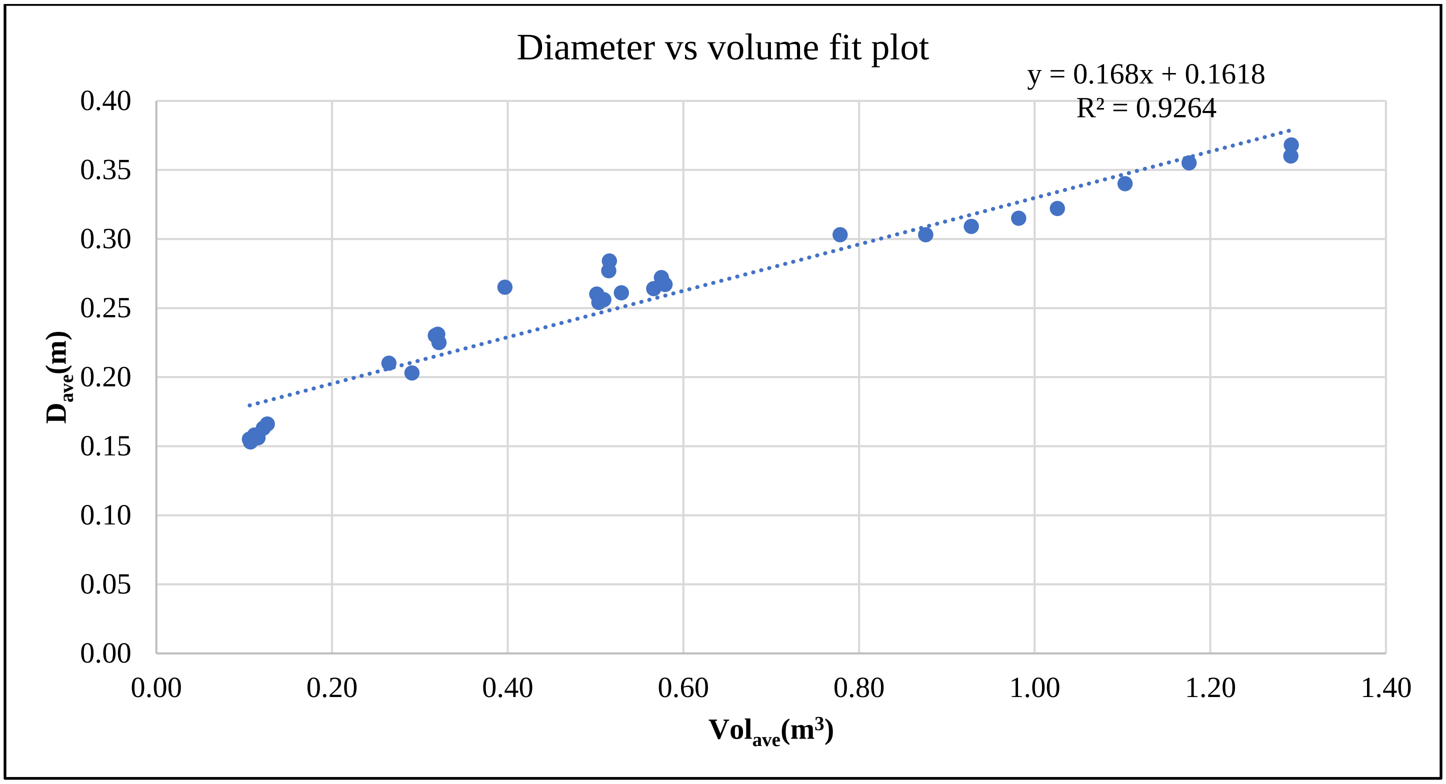

Figure 3.10 Relationship between diameter and volume for *Pinus patula* model

The volume was calculated using the Hubers formula ($v=\pi d^2 h/4xFF$).) using the coefficient (FF) of 0.45 for *Pinus patula* to cater for the tapering characteristics of the trees. The height and volume show a logarithmic relationship with the highest increase in volume between 10-20m followed by a leveling up.

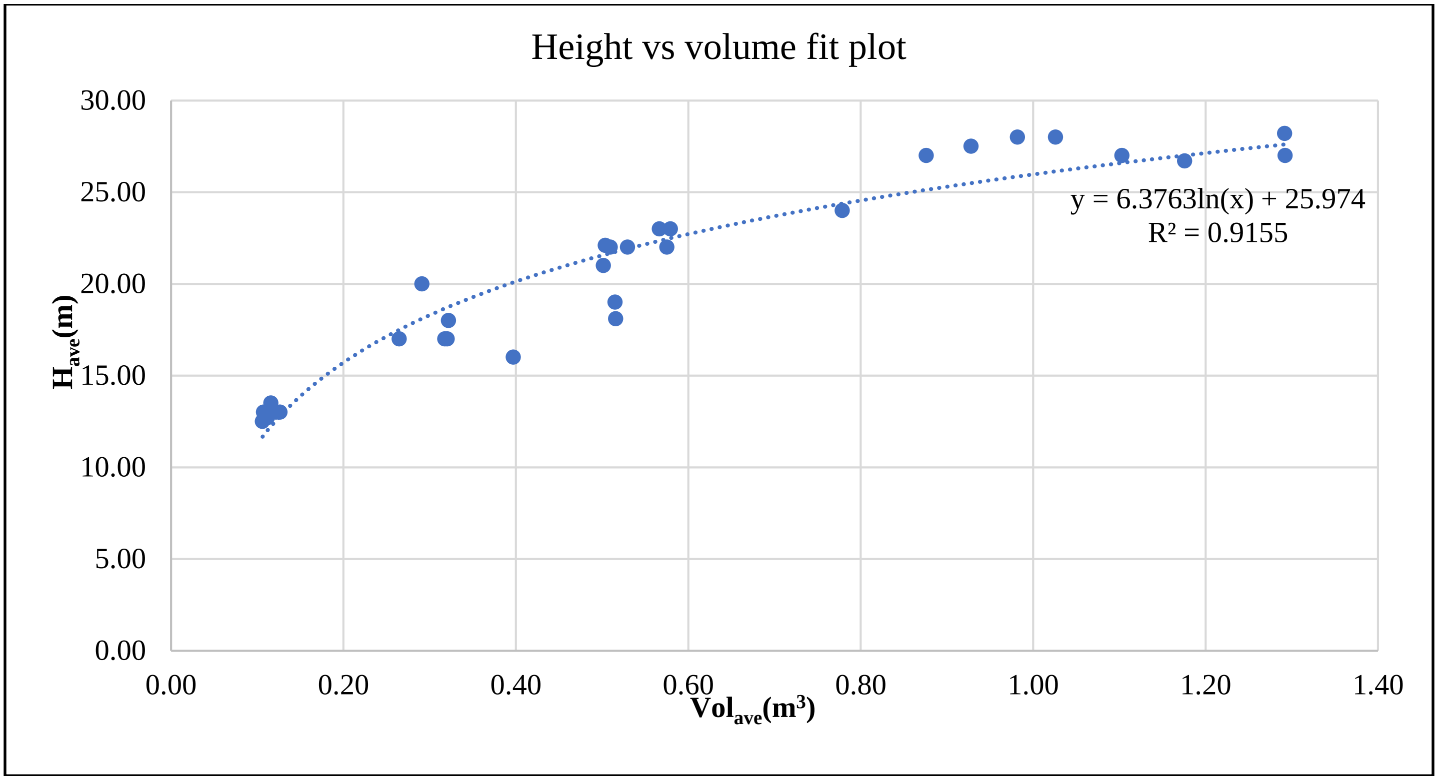

Figure 3.11 Relationship between height and volume for *Pinus patula* model

3.5.2.2 The *Pinus patula* developed model

The model summary table had a correlation coefficient (R=0.981), pointing to a very strong positive association between the dependent variable and the independent variables. The coefficients of determination (R Square = 0.964) were also high, implying that 96.4 per cent of the variations in the dependent variables could be explained by the independent variables (Appendix 2).

The ANOVA table showed a p value equal to 0.000, pointing to the overall regression model being statistically significant in predicting the relationship between the dependent and independent variables.

The final coefficients table showed that the coefficient for age and mean diameter were not statistically significant in predicting the volume of the *Pinus patula* trees as it had a p value > 0.05. On the other hand, mean height were found to have statistically significant coefficients.

The Models for *Pinus patula* was presented using the multiple linear regression equation;

$Volume_{P.patula} = 0.042432A_{ave} + 0.023043181H_{ave} + (-2.387094599)D_{ave}$ … Equation 4

Interpretation of this equation shows that a unit increase in the age of *a Pinus patula* tree while holding mean diameter and mean height constant will lead to an increase in the mean volume by 0.04243 m^3; a unit increase in the mean diameter while holding the age and mean height constant will lead to an decrease in the mean volume -2.387094599m^3; and, a unit increase in the mean height while holding the age and mean diameter constant will lead to an increase in the mean volume by 0.023043181 m^3.

IV. CONCLUSION AND RECOMMENDATIONS

The findings of this study show that as plantation ages increase, tree volumes also tend to increase. It demonstrates a positive association between the volumes and the diameter, Heights sampled variables. The relationship between measured volume and heights depicted an exponential trend showing that volume of *Pinus patula* and *Cupressus lusitanica* rises at an increasing rate with an increase of height with age. The increase between heights 10-20m is slow as compared to the higher rate between 20 and 30m. The relationship between measured volume and diameter showed an increase in a linear manner and showed no signs of deviating from the line. This indicates that diameter steadily increases with age and consequently increasing the volume The measured volume and diameter increased in a linear manner and showed no signs of deviating from the trend line. This indicates that diameter steadily increases with age and consequently increasing the volume. The relationship between volume, height, diameter and age indicated a linear relationship and thus the developed models were presented using a Linear Regression Equations; Y = b0 + b1X1 + b2X2 + b3X3.

Although the usual harvesting schedule of 6, 11, 16, 21, and 30 years produced larger harvestable volumes than the variable schedule of 5, 10, 15, 20, and 30, there was no statistically significant difference that could have justified a change in policy. Although this was caused by differing forestry practices in separate sampling zones between two stations, the Mann Whitney U test determined that, despite the considerable variation, it was not statistically significant. This implied that the observed discrepancy in average ranks, and by extension the tree volumes was not just by chance. It caused modest variations in the height and diameter figures. Despite different mean ranks created by the comparison of the species both within a forest station and between two stations, the Mann Whitney U test determined that the difference was not statistically significant. This implied that the observed discrepancy in mean ranks, and hence the tree volumes, was not simply due to chance.

Recommendations

The optimal model for yield estimation must be developed through ongoing study and monitoring of tree variables for the country's plantation forestry to be managed effectively. Although a lot of efforts has been put in developing this model, the ongoing ban on harvesting of trees in public forest has limited the research to no destructive sampling. It is encouraged to undertake more research based on destructive sampling to compare results and deduce a more accurate and reliable model. It is also advised that periodic forest inventory activities be combined with tree yield estimation models in order to track trends and changes that would affect the number of trees in forest plantations. Last but not least, it is encouraged to conduct more research on additional variables including rainfall, soil type, and temperatures that may affect tree yields and eventual models. Furthermore, a computer-based yield estimation model was developed using advanced algorithms and software tools.

Appendices

Appendix 1. Summary results for *Cupressus lusitanica* regression model

Regression Statistics	
Multiple R	0.978242
R Square	0.956957
Adjusted R Square	0.916731
Standard Error	0.183683
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	20.25291	6.750969	200.0916	4.46E-18
Residual	27	0.910964	0.033739		
Total	30	21.16387			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.058508	0.008392	6.971779	1.71E-07	0.041289	0.075727	0.041289	0.075727
X Variable 2	2.843382	0.705167	4.032213	0.000406	1.396499	4.290264	1.396499	4.290264
X Variable 3	-0.05776	0.00929	-6.21785	1.19E-06	-0.07682	-0.0387	-0.07682	-0.0387

Appendix 2. Summary results for *Pinus patula* regression model

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.981595
R Square	0.963528
Adjusted R Square	0.92379

Standard Error	0.134835
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	12.96824	4.322747	237.7671	5.18E-19
Residual	27	0.490876	0.018181		
Total	30	13.45912			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.042432	0.005592	7.588408	3.66E-08	0.030959	0.053906	0.030959	0.053906
X Variable 2	0.023043	0.011974	1.924478	0.064893	-0.00152	0.047611	-0.00152	0.047611
X Variable 3	-2.38709	1.083289	-2.20356	0.036268	-4.60982	-0.16437	-4.60982	-0.16437

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AUTHORS

First Author – Wanyonyi Mungau Michael, Mobile Phone: (+254) 725284653, (+86) 17269690523 Email: mikewanyonyi@gmail.com , *(Tongji University, UN Environment Tongji Institute of Environment for sustainable Development (IESD) College of Environmental Science and Engineering, 1239 Sipping Road, Yangpu district, Shanghai China)
Email: unep_tongji@tongji.edu.cn
Second Author – zhuo Li, Mobile Phone: (+86) 021-65980329 Email: zhuoli2013@tongji.edu.cn ,*(Tongji University, UN Environment Tongji Institute of Environment for sustainable Development (IESD) College of Environmental Science and Engineering, 1239 Sipping Road, Yangpu district, Shanghai China), Email: unep_tongji@tongji.edu.cn
Third Author – Mwangi Kinyanjui , Mobile Phone: (+254) 722623972, Email: jmkinyanjui@karu.ac.ke , *(Mountain Studies and Climate Change, Karatina University, P.O box1957-10101, Karatina Kenya