BASIC DENSITY AND SOME STRENGTH PROPERTIES OF *PINUS CARIBAEA, PINUS KESIYA AND PINUS OOCARPA* GROWN IN KATUGO, UGANDA

BY

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Abstract

Basic density and six strength properties and their variations in 25-y-old three *Pinus* species grown in Katugo, Uganda were investigated.

Six trees in each of *Pinus caribaea* and *Pinus oocarpa* and three in *Pinus kesiya* were selected, felled, billeted and test samples prepared according to standard methods. In each of the three species, 3 diameter classes, 3 axial positions and 4 radial positions (3 for basic density) were sampled. Basic density was determined by water displacement method. Tests of various strength properties were done in accordance with standard procedures. The data were analyzed using Statistical Analysis System (SAS) software. Results showed:

- The overall mean wood properties values were as follows:

Basic density was 424.33, 431.37 and 444.37 kg/m^3; Modulus of rupture was 54.51, 56.31 and 60.69 N/mm^2; Modulus of elasticity was 8590.51, 8752.24 and 8825.37 N/mm^2; Work to maximum load was 0.088, 0.099 and 0.101 mmN/mm^3; Maximum compression strength was 33.38, 33.83 and 34.66 N/mm^2; Maximum shear strength was 9.43, 9.80 and 10.37 N/mm^2 and Cleavage was 11.78, 12.15 and 12.48 N/mm in *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* respectively.

- Wood strength properties values determined were within range with properties of Pines grown in Kenya and Tanzania. Research findings suggest the possibilities for expanding the use of the three species investigated. The inner wood can be used for non-structural applications and the outer for structural purposes.

- There were no significant differences in all wood properties between the three species.

- Between trees variation in wood properties were statistically significant in all the species, indicating the potential of improving wood quality through selection.

- Growth rate had no significant difference on wood properties.

- Wood properties studied decreased significantly from stump upwards the stem and increased from pith outwards in the three species studied.

- Strength properties of the three Pinus species were strongly correlated to basic density.

Declaration

I Geoffrey Odokonyero, do hereby declare to the Senate of the Sokoine University of Agriculture, that this is my original work and that it has neither been submitted nor being concurrently submitted in any other institution.

Candidate:..............

Date: 30.03.1998

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ABBREVIATIONS AND SYMBOLS

BD = Basic density in kg/m^3.

MOR = Modulus of rupture in N/mm^2.

MOE = Modulus of elasticity in N/mm^2.

Wmax = Work to maximum load in mmN/mm^3.

MCS = Maximum compression strength parallel to grain in N/mm^2.

MSS = Maximum shear strength parallel to grain in N/mm^2.

CLR = Cleavage, resistance to splitting in radial plane in N/mm.

Species = c: *Pinus caribaea*, k:*Pinus kesiya*, c:*Pinus oocarpa*.

Dclass = Diameter classes of s = small (10-14 cm), m = medium (15-19 cm) and l = large (20-24+ cm).

Vposi = Vertical or axial position from butt upwards in percentage of the total tree height:- A = 7.5% , B = 45 % and C = 75 %.

Rposi = Radial position levels from pith to bark:- levels 1, 2, 3 and 4. and 17%, 50% and 83% radius from pith to bark, representing mid-point of the inner, middle and outer wood respectively.

AAC = Annual Allowable Cut
FAO = Food and Agricultural Organisation
FD = Forest Department
FRP = Forestry Rehabilitation Project
FORI = Forestry Research Institute
GRW = Growth ring width
MPED = Ministry of Planning and Economic Development
NARO = National Agricultural Research Organization
NORAD = Norwegian Agency for Development Cooperation
THF = Tropical High Forests
USDA = United States Department of Agriculture

CHAPTER 1. INTRODUCTION

Uganda has an area of 240 000 km^2 and a population estimated at 19.8 million people (MPED, 1996). About 47 % of the total area is covered by forests (FRP, 1995).

The government owned forest estate is 1.5 million hectares and consists of three forest types: Tropical High Forests (THF), Savanna Woodlands and Plantations. Currently, however, 320 000 hectares of THF have been converted into National Parks under the Uganda Wildlife Authority where timber harvesting is not permitted. Thus the 1 176 397 ha of the Forest Reserves left with the Forest Department (FD) is distributed as in Table 1 and their geographic locations are shown in Fig.1.

Pinus caribaea, *Pinus oocarpa* and *Pinus kesiya* are exotic softwood tree species planted widely on lower altitude sites in Uganda since 1950s. Currently more than 70% of the about 14,000 hectares of total softwood plantations are mainly under the three *Pinus* species (FD Inventory Report, 1990). These species predominate the lower altitude sites and planting continues (FD Inventory Report, 1990; FRP, 1995). According to the Inventory Report (1990), the gross Annual Allowable Cut (AAC) from the softwood plantations is 208 000 m^3.

Table 1. Status of Forest Reserves in Uganda.

Class	Description	Area (ha)	%
1	Deciduous plantations	6 878	0.58
2	Coniferous plantations	14 761	1.25
3	THF - fully stocked	252 485	21.46
4	THF - depleted/encroached	50 221	4.27
5	Woodland	434 197	36.91
6	Bush	110 233	9.37
7	Grassland	195 661	16.63
8	Wetlands (papyrus, reeds)	5 380	0.46
9	Small - scale farmland	103 756	8.82
10	Uniform, large-scale farmland	1 221	0.10
11	Built - up areas	312	0.03
12	Open water	939	0.08
13	Impediments (bare rock, etc)	353	0.03
	Total Forest Estate	1 176 397	100.00

source: Forest Department, Uganda (1995)

Forest management has focused on high production of well known timber species and environmental protection. However, from 1975 to the 1980s systematic forest management, utilization and protection virtually collapsed due to breakdown of law and order and lack of funds (Aluma and Ndimukulaga, 1996). For example tree planting in the plantations stopped in 1974 when the Norwegian Agency for Development Cooperation (NORAD) funding was withdrawn and resumed during Forestry Rehabilitation Project from 1986 to 1995 (FRP, 1995). During this period, neither pruning nor thinning were done giving rise to small logs of poor form. The net utilizable volume was therefore estimated to be 70 % of the gross volume, which is equivalent to 146 000 m3 (Aluma and Ndimukulaga, 1996).

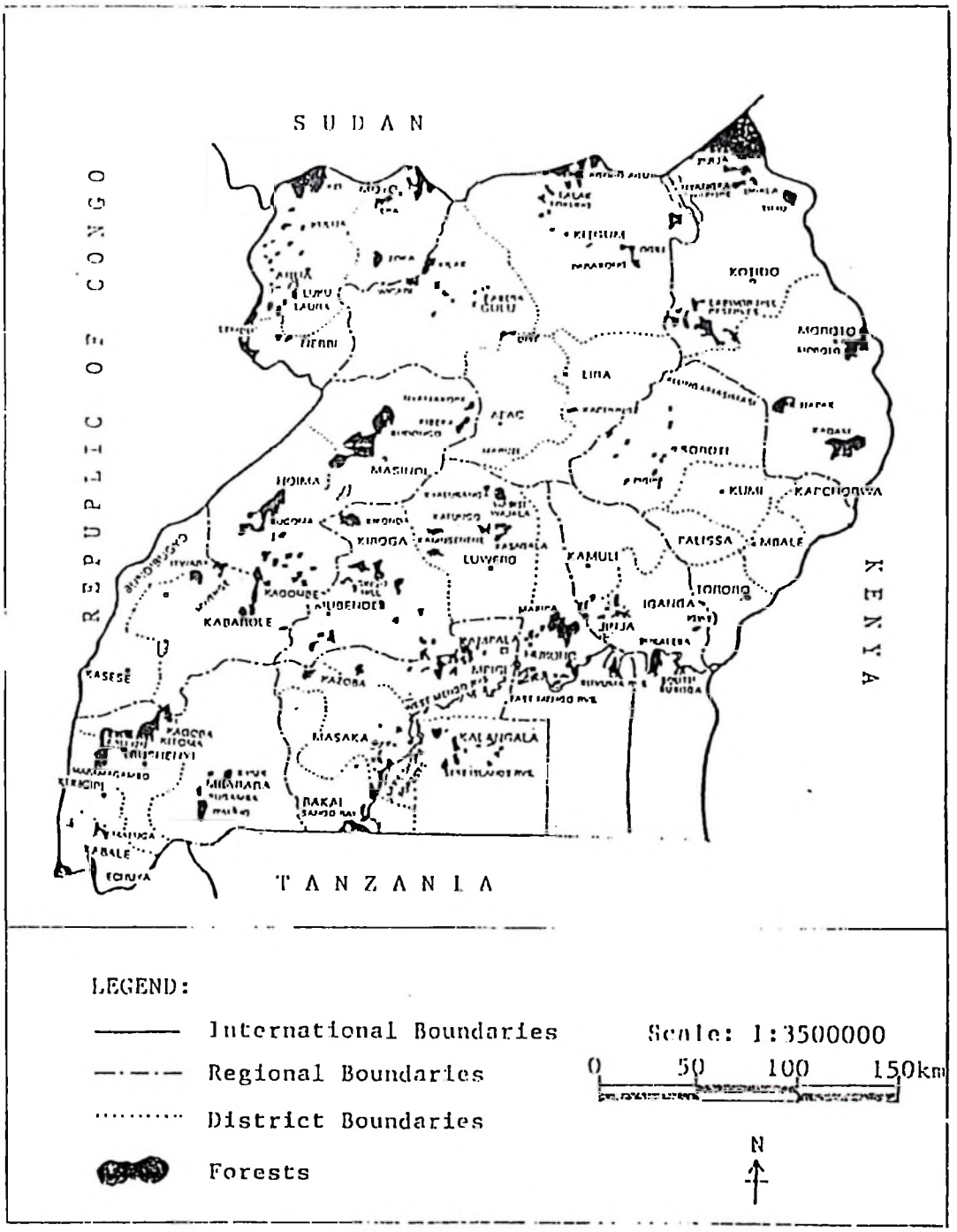

Figure 1. Uganda Forest Reserves Locality Map.

source: Forest Department (1996)

These fast growing trees had been introduced with the main aim of producing general construction and joinery timber (Tack, 1969). Other proposed uses include match manufacture, poles and fence posts, veneer and plywood, wood wool cement composite manufacture, pulp and paper making. However, use for the last five products have not materialised with the withdrawal of NORAD funds.

Ugandan grown exotic plantations of *Pinus* species are ready for harvesting, but the market available cannot fully accept the kind of wood that has been produced (Plumptre and Carvalho, 1989; Natvig, 1996). There is misinterpretation of softwood for wood quality and lack of information on their use characteristics. The expectation has been that these softwoods from the plantations would substitute for or relieve pressure on the hardwoods from natural forests which are now faced with degradation and destruction resulting from over-exploitation.

To date, unfortunately, there exists large volume of under-exploited mature pine trees (Carvalho and Pickles, 1994) and the softwood plantations are now overmature, upto 30 years old above the rotation age of 25 years (Kityo and Plumptre, 1997). Among other factors like low processing capacities, low local market acceptance due to the lack of tradition in the use of softwoods and heavy reliance on

native species,the wood is considered to have many undesirable properties including the perceived low strength.

Little is known about wood qualities and therefore potential uses of pines timbers grown in Uganda, since they have not yet been fully tested (Aluma and Ndimukulaga, 1996). Limited studies were carried out at the Commonwealth Forestry Institute, Oxford on some samples of *Pinus caribaea* and *Pinus oocarpa* logs grown in Uganda (Plumptre, 1972; Andrew and Plumptre, 1973; Goodwin-Bailey, 1982; Ochaki, 1982). However, in such studies assessment of strength and quality of pine grown in Uganda did not cover intra-tree variation. Additionally the data available were obtained from pilot tests on small number of log samples from relatively young trees up to 12 years old (Tack, 1969; Plumptre,1984; Plumptre and Carvalho, 1991; FORI, 1995-96), making it difficult to make concrete conclusions and recommendations. Very little research results on timber properties have been published, many have remained as technical notes, most of them not being available due to looting and destruction during the 1979 liberation war. Consequently it has been recommended that such research to be repeated (Aluma and Ndimukulaga, 1996).

The wood of an exotic tree sometimes greatly differs from that which is obtained in its natural habitat or elsewhere (Plumptre, 1977; Zobel and Talbert, 1984). The variation in basic density and strength properties within and in between trees can be so severe in tropical plantations which have recorded exceptional growth rates.

It is difficult to compare the Ugandan grown wood properties with same species grown elsewhere in East Africa and beyond due to lack of systematically derived technical data. Consequently a strong need for research on wood quality in order to properly and rationally utilize *Pinus* wood grown in plantations.

Wood density and some strength properties as well as variability important in selection and utilization of pine wood for general construction were considered in this research.

This study was done as part of an approved original proposal work relevant to the National Agricultural Research Organization (NARO) of Uganda for the Forestry Research Institute (FORI) in addressing constraints of narrow species range and inadequate knowledge (FORI, 1995-96).

The findings will hopefully, be applied at various stages of the forest-sawmill-user chain as well as form basis for further research. The chain should have no basis of not effectively utilizing the widely available fast growing resource.

The overall objective of this research was to assess the quality of the pine plantation wood. The specific objectives were:

(1) to determine and compare the average basic densities and some strength properties of *P. caribaea*, *P. kesiya* and *P. oocarpa* grown in Katugo, Uganda;

(2) to investigate the variation in basic density and some strength properties within and between trees of the three species;

(3) to identify and establish any relationship between average tree basic density and strength values and growth characteristics such as growth ring width and diameter class .

This study was confined to the determination of basic wood density (BD) and strength properties considered important in general construction. Modulus of rupture (MOR), modulus of elasticity (MOE), work to maximum load (Wmax), maximum compression strength parallel to grain (MCS), maximum shear strength parallel to grain (MSS) and cleavage, resistance to splitting in radial plane (CLR) were studied.

CHAPTER 2. LITERATURE REVIEW

2.1 Nomenclature and distribution

Pinus caribaea and *Pinus oocarpa* originated from South North to Central America whereas the origin of *Pinus kesiya* is traced from South East Asia as reported by Greaves (1978) and Kielland-Lund (1992).

The genus *Pinus* grown in tropical forestry including Uganda are evergreen trees (Pines) of great economic importance. Their fast growth, good silvicultural features and easy availability of seed from South Africa where they were first introduced in late 1900s made them obvious choices for many countries in East, Central and Southern Africa in 1940s. In Uganda, softwood plantation on a large scale started in the late 1950s but not as a major forest activity, also the introduction was much later and at lower scale than in Kenya and Tanzania (Wormald, 1975; Plumptre and Carvalho, 1989, Greaves, 1978).

The three species in this study are vegetatively of similar habitus, they have needles ± 25 cm, and develop a thick and fissured bark. However the resin ducts seen on a cross-section of the needles and their cones are different. According Kielland-Lund (1992) these pines can be separated as follows:

(i) *Pinus caribaea* has large, ovate or conical cones, 10-12 x 6 cm, reflexed on short stalks, and very stiff, bluegreen and robust leaves. Resin ducts near central bundle.

(ii) *Pinus kesiya* has symmetrical cones, 5-7 x 3 cm on short stalks. Resin ducts towards fine grasslike leaf margin.

(iii) *Pinus oocarpa* has thick bark, broadly ovate cones opening, 5-8 x 5 cm on long, often curved stalks. Resin ducts touching both leaf margin and central bundle.

Greaves (1978) reported that in areas where *Pinus caribaea* and *Pinus oocarpa* are found growing in intimate mixtures some trees are found with morphological characteristics intermediate between the two. Hence, the speculation that hybridization occurs. In Uganda at Katugo, *Pinus caribaea* and *Pinus oocarpa* were planted in the same compartment (Forest Department Working Plan, East Buganda Woodlands Reserve, 1969).

All pine species are primarily occurring on extreme or disturbed sites on poor sandy, shallow soils of low fertility but freely drained or after fire Koch (1972). *Pinus caribaea*'s history, silviculture, mensuration and protection are fully reviewed by Lamb (1973). This was followed by a comprehensive study by Plumptre (1984) on the

strength and wood properties from natural and exotic locations. Plumptre (1984) maintained that there is no known reliable way of distinguishing one species from another on the basis of wood anatomical properties.

Following several studies from 1950s Luckoff, 1964; Barret and Golfari, 1962 cited by Greaves (1978), the three varietal names of the *Pinus caribaea*-group now accepted are as follows:

(a) *Pinus caribaea* Mor. var. *bahamensis* Barr. and Golf. to cover natural population or taxa in Bahamas and Caicos Islands.

(b) *Pinus caribaea* Mor. var. *caribaea* typical from Cuba and Isle of Pines.

(c) *Pinus caribaea* Mor. var. *hondurensis* Barr. and Golf. taxa in central America.

Pinus caribaea More. var. *hondurensis* is confined naturally to the central American main land and Island of Guanaja within latitude range of 12^0 13'S-18^0 00'N. It may be found at altitudes up to 800 m above sea level with mean monthly rainfall of at least 100 mm (Greaves, 1978).

Pinus kesiya (*insularis, khasya*) is found in its natural habitat in the Assam hills and north Burma. In Zambia and Malawi it grows at elevations of 1 000 to 4 000 m above sea

level with rainfall from 900 to 1 800 mm. It is the most widely planted of the pines on higher altitude sites in the two countries (FAO, 1974).

Pinus oocarpa has a large natural distribution in the Mexican and Central American highlands. It is the most southerly pine of America, in Nicaragua (FAO, 1974). The natural population occupies sites at higher altitudes with more severe dry seasons than *Pinus caribaea*. *Pinus oocarpa* therefore appears to have the necessary adaptation characteristics for extending the range of conditions in which plantations can be successfully established in other countries (Greaves, 1978). Kielland-Lund (1992) reported *Pinus oocarpa* to be the most planted Pinus species in Zambia and Malawi.

Early trials in the early 1960s of *Pinus oocarpa* as an exotic plantation species in Uganda were discouraging. Most of the seeds had been brought from Mexico and tended to produce crooked stems, as experienced in South Africa (Loock, 1950). In Uganda, *Pinus oocarpa* trials using seed from Honduras Republic origin grew as well as if not better than *Pinus caribaea* More. var. (Greaves, 1978). As a result most of the area in Katugo plantation is planted with *Pinus caribaea* and *Pinus oocarpa* having been the best performing species (Forest Department Working Plan, East

Buganda Woodlands Reserve, 1969). The seed from some locations may produce better plantations than seed from others when grown in new conditions (Greaves, 1978).

2.2 Growth rings

The width of annual rings of a particular species indicates the rate of growth. It is less closely related to strength than specific gravity and strength. However, generally in softwoods, the percentage of latewood is a fairly reasonable guide to strength properties, and often very wide rings contain a relatively small portion of latewood, hence a reduced density. The rapid early growth of the plantation material followed by a gradual narrowing of ring width with increasing age at a given height is typical. (Panshin and de Zeeuw, 1970).

Water supply is expected to influence the nature of growth rings in tropical trees (Zobel and van Buijtenen, 1989). Since both the amount and distribution of rainfall have been known to vary from year to year, multiple growth rings are common, making it often difficult to recognise wood formed in a particular year. Change from earlywood to latewood has also been accounted for by water stress since crown growth slows and auxin levels in the cambium decline causing the shift from earlywood to latewood (Desh, 1973).

According to Larson (1956), false rings (a term normally applied to temperate trees) due to interruption in growth mechanism and caused by various factors including moisture deficit may result in the initiation of latewood formation, followed by reversal to earlywood for slash pine grown in the tropic. This may be a possible cause of the 'unusual, discontinuous and missing' ring in tropical softwoods.

2.3 Wood density: definition, importance and determination

2.3.1 Definition wood density

The density of a material is defined as its mass in relation to its volume. Density is the weight per unit volume and is usually expressed as kg/m^3 (Lavers, 1969). It is the amount of solid substance contained in a volume of dry wood (Ehrenberg, 1970; Elliott, 1970; Panshin and de Zeeuw, 1970; Kubler 1980; Ostal *et al.*, 1981; Zobel and van Buijtenen, 1989).

Dry wood consists of cell walls and air filled cavities (Kubler, 1980). Wood density in this anatomical sense is a function of the ratio of cell void volume and is consequently affected by cell wall structure, average cell dimensions, lumen dimensions, amounts of resin and extractives and the volume of non-fibrous elements such as rays (Spurr, 1954; Berlyn, 1964; Goggans, 1965) cited by Elliott (1970).

2.3.2 Importance of wood density

The results provide the forester with a potential means of controlling wood qualities through silvicultural manipulation, since density and related strength values are known to be strongly influenced by growth conditions (Elliott, 1970; Zobel and van Buijtenen, 1989).
An understanding of the variation patterns in density is essential for assessment of utilization patterns and best age of harvest for *P. caribaea* (Lantican and Hughes, 1973).

Of all the physical properties of wood, density is a major factor determining the strength of a species (Harris, 1993). It is generally an index of the amount of cell wall substance present and of the volume comprised of air spaces (Ishengoma and Nagoda, 1991).

The amount of wood substance is a reliable indicator of its strength properties. It is generally assumed that the quality, basic properties and utilization of wood depend mainly on density or are influenced by density (Kollmann and Côte, 1968; Kellogg, 1981). Several literature exist on the importance of wood density. Elliot (1970) reported the use of wood density as an index for the suitability for various uses, although the selection of wood for a given use embraces other properties (Iddi and Nagoda, 1992).
Wood raw material particularly for fibre board and pulp and

paper has been purchased on the basis of dry matter weight (Kubler, 1980).

2.3.3 Determination of wood density

There are many methods of determining wood density. This can be gravimetric or by radiation and densitometry techniques (Polge, 1965; Panshin and de Zeeuw, 1970). Density can be measured very satisfactorily and rapidly by gravimetric methods, provided that the specimens are not too small and can be accurately prepared (Hughes and Plumptre 1976). The most preferable method for routine analysis of small samples would be the one involving sufficient accuracy at a low cost. American, British, French and German standards for testing materials give full descriptions of these methods (Elliott, 1970). The simplest method is to weigh a piece of wood and find its volume and divide weight by volume. The most common measure of wood density, based on oven dry weight and green volume. Both of these are constant and reproducible (Hughes and Plumptre, 1976; Sardinha, 1977; Zobel, 1984).

2.4 Wood density variation

2.4.1 General considerations

Wood density is a complex property and it exhibits great variability from species to species, between trees of the

same species and within a tree. A complex system of interacting factors associated with this variation include age, position in tree and anatomical characteristics, genetical, silvicultural treatments and environmental factors such as moisture relationship, site, altitude, growth rate and genetical factors (USDA, 1974; Dietz *et.al.*, 1980; Kellogg, 1981; Ishengoma and Nagoda, 1991).

Environmental factors and silvicultural techniques that promote or hinder high growth rates may result in increased or decreased wood density. Normally on better sites, silvicultural practices such as wide initial spacing, thinning and fertilization promote higher growth rates, whereas heavy pruning results in reduced growth (Elliot, 1970; Erickson and Lambert, 1980; Smith, 1980; Zobel and van Buijtenen, 1989).

2.4.2 Wood density variation among the three Pinus species

Within the same genus, the different species do not have the same density and the range is often great. The variation of wood density and other general characteristics among the pine species has been reviewed by Lavers (1969), Elliott (1970) and Koch (1970) have provided

bibliographies. In other publications wood characteristics of a particular country's commercial timber (Bryce, 1967; Tack, 1969; Lavers, 1969; Lamb, 1973). It can be noted from this information that wood density varies considerably amongst the species.

In Colombia, Ladrach (1986) described how *Pinus elliottii* var *elliottii* produced wood density of 400 kg m^{-3} at age 10 years, but *Pinus elliottii* var. *densa*, so named for its dense wood in its natural habitat, averaged only 300 kg m^{-3} at the same age. Ladrach (1986) reported that *Pinus oocarpa* had the highest density (429 kg m^{-3}) followed by *Pinus kesiya* (370 kg m^{-3}) and *Pinus caribaea* with the lowest average density (363 kg m^{-3}) at age 8 years when grown in the same environment. In contrast, Kromhout and Toon (1977) found the densities of *Pinus caribaea* and *Pinus elliottii* were similar in South Africa at same age and site.

2.4.3 Wood density variation between trees of the same species

Several authors such as Bryce (1967), Andrew and Plumptre (1973), Lamb (1973), Ringo (1977) and Plumptre (1984) have reported quite large variation between trees within a given species. In studies on density variation, the variation

between trees component is large in relation to sites and species. This is one of the most constant characteristic of density variation.

There have been many studies done in Tanzania supporting this large variation between trees within a given species. Khiari and Iddi (1989), for example, reported a standard deviation of 66 kg m^3 and a coefficient of variation of 14.3% for *Pinus caribaea* material grown in Zanzibar. Ringo and Klem (1980) reported a mean basic density for 25-year-old *Pinus patula* grown at Sao Hill at 410 kg/m^3 with standard deviation of 32 kg/m^3 while Lema *et al.* (1978) found out a standard deviation of 46 kg m^{-3} for 19-year-old *Pinus patula* grown in Meru. Kubelka (1969) found a wood density range of 210 kg/m^3 in *Pinus patula* grown in Tanzania. Silinge (1989) reported a significant variation in wood basic densities between 19-year-old *Pinus caribaea* trees grown in Kondoa, central Tanzania, ranging from 310 kg m^{-3} to 483 kg m^{-3}.

Whereas Nasser (1990) found no significant differences between provenances of 22-year-old *Pinus patula* grown at Lushoto, Tanzania. Wood basic density was: Kigogo 389 kg m^{-3} , Rhodesia 415 kg m^{-3} and Old Moshi 423 kg m^{-3}. In comparison with different studies, mean basic densities for *Cupressus lusitanica* from Tanzania were reported at 418, 465, and 465

kg/m^3 by, Bryce (1967); Lema *et al.* (1978) and Ishengoma *et al.* (1995) respectively.

There is often a great variation in wood density of trees from the same species taken from different localities. Andrew and Plumptre (1973) found large differences in density between different sites and also much larger differences between trees on the same site while working with trees grown on various sites in East Africa. Between tree differences within same site were more significant than between various site differences. The influence of between tree variation even within same site is strong whether the cause is genetical or micro-environmental to suggest the possibility of increasing mean tree density without serious loss in growth rate (Plumptre,1984).

Density variation between trees of the same species have been attributed to the differences in genetic make-up and the micro-environment in which each tree grows (Panshin and de Zeeuw, 1970). Ong (1978) showed a striking differences in the amount of latewood formed and the formation pattern in breast height discs taken from three trees in the same plot in Fiji. However, various researchers have found poor correlations between tree mean density and growth rate or ring width (Ringo 1983).

2.4.4 Wood density variation within trees of Pinus species

Within a single tree variability is generally not well understood although it has been intensively studied (Dadswell, 1960; Sluder, 1972; Bendstsen, 1978). Research has found out that no two pieces of wood from the same tree have the same basic density, taken from a growth ring and from different radial or height positions (Zobel and van Buijtenen, 1989).

2.4.4.1 Within a growth ring density variation

Within a growth ring, latewood with smaller cavities and thicker walls are roughly three times denser than earlywood with large cavities and thin cell walls (Kollmann and Côte, 1968). In a number of softwoods, latewood is known to have a higher cellulose content and lower lignin content than earlywood (Tsoumis, 1968).

2.4.4.2 Radial density variation

The largest variation within the stem is associated with radial direction (Panshin and de Zeeuw, 1970). For example,

in *Pinus caribaea* and *Pinus oocarpa* grown in Uganda, Ochaki (1982) found distance from the pith accounted for about 58 % and 40 % for the variation in specific gravity, while height accounted for about 29 % and only 16 % for the total observed variation, respectively.

Panshin and de Zeeuw (1970) identified four general patterns of variations in softwoods as follows:

- Monotonic increase of density from pith to bark;
- High density near the pith, followed by a decrease for the first few years and then increase to maximum at the bark;
- Moderate increase of density for the first five years followed by a more or less constant plateau or sometimes a decrease in the last formed increment near the bark;
- A gradual decrease of density from pith to bark.

A general increase in density from pith to bark in *P. caribaea* and *P. patula* have been reported in several investigations in Tanzania (Lema *et al.*, 1978; Ringo and Klem, 1980 ; Khiari and Iddi, 1989; Silinge and Iddi, 1990; Ishengoma *et al.*, 1995).

2.4.4.3 Axial density variation

Within a tree, there are three major patterns of density variation in the axial direction (base to top): decreasing

uniformly, decreasing in the lower trunk and increasing in the upper trunk, and increasing from base to top in a non-uniform pattern (Panshin and de Zeeuw, 1970).

The decrease in density from base to top is the most common trend reported in conifers (Panshin and de Zeeuw, 1970). In the axial direction and according to various authors (Koch, 1972; Ringo, 1977; White *et al.*, 1980; Gashumba, 1982; Ishengoma and Nagoda, 1991) the heaviest wood is found at the base of the tree, and there is a gradual decrease in density with increasing distance from the base, but some variations do exist.

Brown (1971), Lantician and Hughes (1973), Hughes (1973), Ringo and Klem (1980) and Ringo (1983) all reported a general decrease of density with increasing height in *Pinus*.

2.5 Strength properties

2.5.1 Definitions and importance of strength properties

Strength properties of wood define the performance of wood under load (USDA, 1974; Wangaard, 1979). The strength properties of wood reflect its fitness and ability to resist applied external forces which tends to alter its size, shape or deform it in any manner (Ishengoma, 1986).

B.S.:373 (1957) noted that the main purpose of testing small clear specimens is providing data for the comparison of strength properties of different species. The test results may also be used to determine the relationship between strength and such properties as density, the effect on strength of various treatments and to assist in the establishment of design functions for structural timbers.

An understanding of the variation patterns in strength properties of wood is essential for assessment of utilization patterns and best age of harvest for *P. caribaea* (Lantican and Hughes, 1973).

Ishengoma and Nagoda (1991) and Walker (1993) reported that the results of strength properties tests are widely applied in the selection and use of wood. Ishengoma (1986) noted that the knowledge of strength properties of wood is important for determining its fitness for constructional material and other uses except when used as firewood.

2.5.1.1 Static bending

Static bending is one of the most widely used tests because of the general utility of the result and the ease with which the tests can be conducted (Lavers, 1969; Ishengoma and Nagoda, 1991). According to Schniewind (1989) static bending is the most important single test of the mechanical properties of wood. B.S.:373 (1957) gives two methods for

static bending test, the central loading and the four-point methods. It is also noted that the former method is sufficiently accurate for general standard tests to compare different species. These authors explained the tests as follows:

(a) Modulus of rupture is defined as the stress of the extreme fibers at the point of failure. It is the breaking strength of a beam expressed in terms of stress per unit area. The maximum bending moment at maximum load is used to calculate the modulus of rupture. The modulus of rupture is the characteristic bending strength of wood, and its value is intermediate between the tensile and compressive strengths. It serves as a practical strength comparison for different species of timber.

(b) Modulus of elasticity is the ratio of stress to strain in bending within the elastic range of the wood perpendicular to the grain. That property of matter which enables it to resist a force that tends to change its shape when the force is removed. Hence it is a measure of stiffness and only applies to conditions within the elastic limit. It is of importance in determining the deflection of a beam under load. The greater the stiffness, the less the

deflection and for many uses stiffness is the controlling factor in the design (Dick, 1972).

(c) Work to maximum load (Wmax) is a measure of the toughness of timber under bending stress and is determined from the area under the load-deflection curve to the point of maximum load (Lavers, 1969). The curve will be abruptly terminated for brittle wood and will decrease stepwise for tough wood (Ishengoma and Nagoda, 1991).

2.5.1.2 Compression parallel to grain

Compression strength parallel to grain is usually referred to as maximum crushing strength, is the load per unit area sustained by timber on its end grain (Lavers, 1969). The maximum load is used to calculate the stress at failure. B.S.:373 (1957) specifies the resistance to compression to determined both parallel and perpendicular to the longitudinal grain, but noted that the former is confined to the 2 inch standard. This is important in selecting wood for columns, posts and struts, athletic and sporting goods, sleepers and tool handles.

2.5.1.3 Shear parallel to grain

Shear parallel to grain is a condition of stress and resulting strain, acting to cause portions of the sample to move or slide in parallel, but opposite directions to each other (Lavers, 1969). Shear strength of wood is characterized by six principal modes of shear failure (Schniewind, 1989). In shear parallel to grain, both the shear plane or failure plane and the sliding direction are parallel. This is important in selecting wood in situations of critical stress intensity, fracture and cracks in beams and joists, bolted timbers, notched joints and rollers (Tack, 1969).

2.5.1.4 Cleavage

Cleavage is resistance against splitting (Lavers, 1969; Ishengoma and Nagoda, 1991). According to these authors, the resistance against cleavage is important in structural work in respect to types of nails used and their holding power.

2.5.2 Determination of strength properties

Strength properties are measured by standard experimental methods either by means of service tests involving the use

of wood under actual conditions met in practice or by laboratory tests using special testing apparatus (Ishengoma and Nagoda, 1991; Walker, 1993).

Laboratory tests are more efficient and economical when properly conducted. The advantages are in the possibilities to follow standard testing procedures as well as to express results in standard units hence being in position to compare different kinds of wood materials and results obtained by other researchers. Further (Ishengoma, 1986) pointed out that the laboratory tests have made it possible to control random factors which may seriously affect results in service tests. However, the author observed that the results of strength tests on small clear specimen of wood, while enabling species to be compared cannot be used directly as safe working stresses necessary in structural design.

There are many laboratory standard procedures for preparation and strength property tests using small clear wood specimens that have been used internationally (Lavers 1969). The 'Standard Method of Testing Small Clear Specimens of Timber' of American Society for Testing Material (A.S.T.M.) D143-52 (1952), reapproved (1965) and the British Standard No. 373: 1957 'Method of Testing Small Clear Specimens of Timber'(B.S. 373 MTSCST). The later is

in general use because it accommodates samples of small metric sizes of 20 mm standards.

2.5.3 Strength properties variations

According to Dinwoodie (1981), Zobel and van Buijtenen (1989) variation in density is not restricted to different species, but can occur to a considerable extent within any one species and even within a single tree.

2.5.3.1 General considerations

As with density, strength properties have great variability from species to species, between trees of the same species and within a tree.

Drying below the fibre saturation point removes moisture from within the cell wall, allowing wood to shrink and an increase in most strength properties. For an example, small clear specimens at 12 % moisture content have practically twice the strength in bending and compression of the same material when unseasoned (Ishengoma and Nagoda, 1991). Although the changes follow a similar trend for most strength properties, the magnitude of change differs from

one property to another. Compression strength usually changes relatively more than modulus of elasticity, for instance. While shock resistance may show a slight decrease in value with decrease in moisture content (Lavers, 1969).

Many studies (Lavers, 1969; Koch, 1972; Desh, 1973) have shown that within certain limits the relationship between the logarithm of strength values for a property and corresponding moisture content is linear. This is the reason why it is possible to adjust strength values to specified moisture content. It is therefore necessary to adjust strength values obtained at different moisture content levels before any comparison can be made.

2.5.3.2 Strength properties variation among the three Pinus species

The specific gravity of wood substance is for all practical purposes the same for all species. However, the amount of wood substance per unit volume varies from species to species. Strength properties and patterns of variation differ among species of southern pine (Koch, 1972). Differences in anatomical structure may give one wood a greater proportion of latewood cells with small cavities and thicker cell walls than to the another, hence a

corresponding greater amount of solid wood volume. As the case with density, apart from the presence of both extractives and moisture this will result in correspondingly greater strength (Ishengoma and Nagoda, 1991; Koch, 1972).

2.5.3.3 Strength properties variation between trees within species

Within the same species, wood is known to vary between trees. This variation is a product of interacting factors which modify the physiological processes involved in wood formation. Several authors (Panshin and de Zeeuw, 1970: Ong ,1978; Ishengoma, 1986) have held the variation micro-environment in which each tree grows responsible for the variation of wood structure between trees within the same species in different environment. While under the same climatic conditions, genetical differences is a probable main cause for large variation between trees of the same species (Bryce, 1967; Plumptre, 1984; Khiari and Iddi, 1989).

Differences occur in the same site as well as between sites in the same or different geographical localities and latitudes. In certain sites, the variation is very high, generally higher than between sites (Tsoumis, 1968).

2.5.3.4 Strength properties variation within trees

Within a single tree variation in strength properties are known to occur to a considerable extent (Dinwoodie, 1981). Several investigators on pine grown in Tanzania (Lema *et al.*, 1978; Ringo and Klem, 1980 ; Khiari and Iddi, 1989; Silinge and Iddi, 1990; Ishengoma *et al.*, 1995) reported the variations in strength properties with height and radial position within trees. The increases shown in strength values from pith to bark and at different heights for *Pinus patula* are significant (White *et al.*, 1980). Elsewhere, a number of studies have established the systematic within-tree variation in softwoods of mechanical strength properties (Wood, 1970, cited by Sanwo, 1986).

2.6 Relationship among properties

There are established relationship between density as well as among various strength properties (Panshin and de Zeeuw, 1970). The relationship between two or more properties may be described statistically by calculating the regression of one of the variables on one or more of the others (Dinwoodie, 1981).

According to Dinwoodie (1981) there is a high correlation between MOR and MOE, the relationship that forms the basis

of the machine stress grading of timber. The author further reported that there is strong correlation between impact bending and total work; hardness and compression perpendicular to the grain, hence the practice to predict the compression strength from the hardness result.

2.6.1 Relationship between density and strength properties

Ishengoma *et al.* (1995) reported that there is significant simple linear relationship and strong correlation between basic density and strength properties of *Pinus patula*. Research from Queensland, Australia (Siemon *et al.* 1976) found that in green samples of plantation-grown *Pinus caribaea hondurensis*, basic density and percentage latewood explained more than 80% of the variation in maximum compression strength parallel to the grain and stress at the limit of proportionality.

An earlier study by Armstrong (1960) determined that the specific gravity and strength relationship conform to an equation of the form:

$$s = aG^b$$

where: s is the strength value,
G is the specific gravity,
a and ^{b} are constants, the former is the proportionality constant differing for each

> strength property, and the latter is an exponent defining the shape of the curve representing the relationship.

According to Dinwoodie (1981) for most timbers the relationship between density and strength can safely be assumed to be linear with the possible exception of shear and cleavage.

CHAPTER 3. MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Situation and area

The materials used for this study were obtained from Katugo Industrial Softwood Plantation in central Uganda. Katugo plantation is situated in Luwero District some 100 km North of Kampala (Fig. 2). It covers 3318 hectares,between longitude $43^{0}10$ E-$44^{0}01'$E and latitude $12^{0}25'$N-$13^{0}20'$N (Forest Department Inventory Report 1990).

3.1.2 Topography

Katugo lies at an average altitude of 1 080 m above sea level. The entire reserve is characterized by flat, low relief with seasonal swamps 2-3 km. apart cutting through the plantation. The ridges between are low and very gently sloping. The steepest slopes are about 3 degrees.

3.1.3 Climate

The reserve lies in one of the driest parts of south-central Uganda. The annual rainfall average 1230 mm and is bimodal. The long rain falls in February to June. July is

the short dry spell, followed by a short peak wet period, then the long dry period of November to January. A total annual evaporation is high at 1 836 mm resulting in very dry conditions. Average daily temperatures vary between 22-28^{0}C in July and March respectively.

3.1.4 Geology and Soils

The reserve is located on strongly weathered metamorphic and igneous rocks, largely composed of gneisses and granites.

The reserve has three main soil types:-

(a) The Red Buruli soils are derived from laterized gneiss and granite Basement Complex. They are dark reddish, moderately deep, strongly acidic and low in organic matter content. These soils occupy 65 percent of the reserve.

(b) The Lwampanga soils are brown and dark reddish, developed from old alluvial materials. They are deep, strongly acidic and low in organic matter content. These soils occupy some 19 percent of the reserve.

(c) The Alluviums of recent deposits occupy about 18 percent of the reserve.

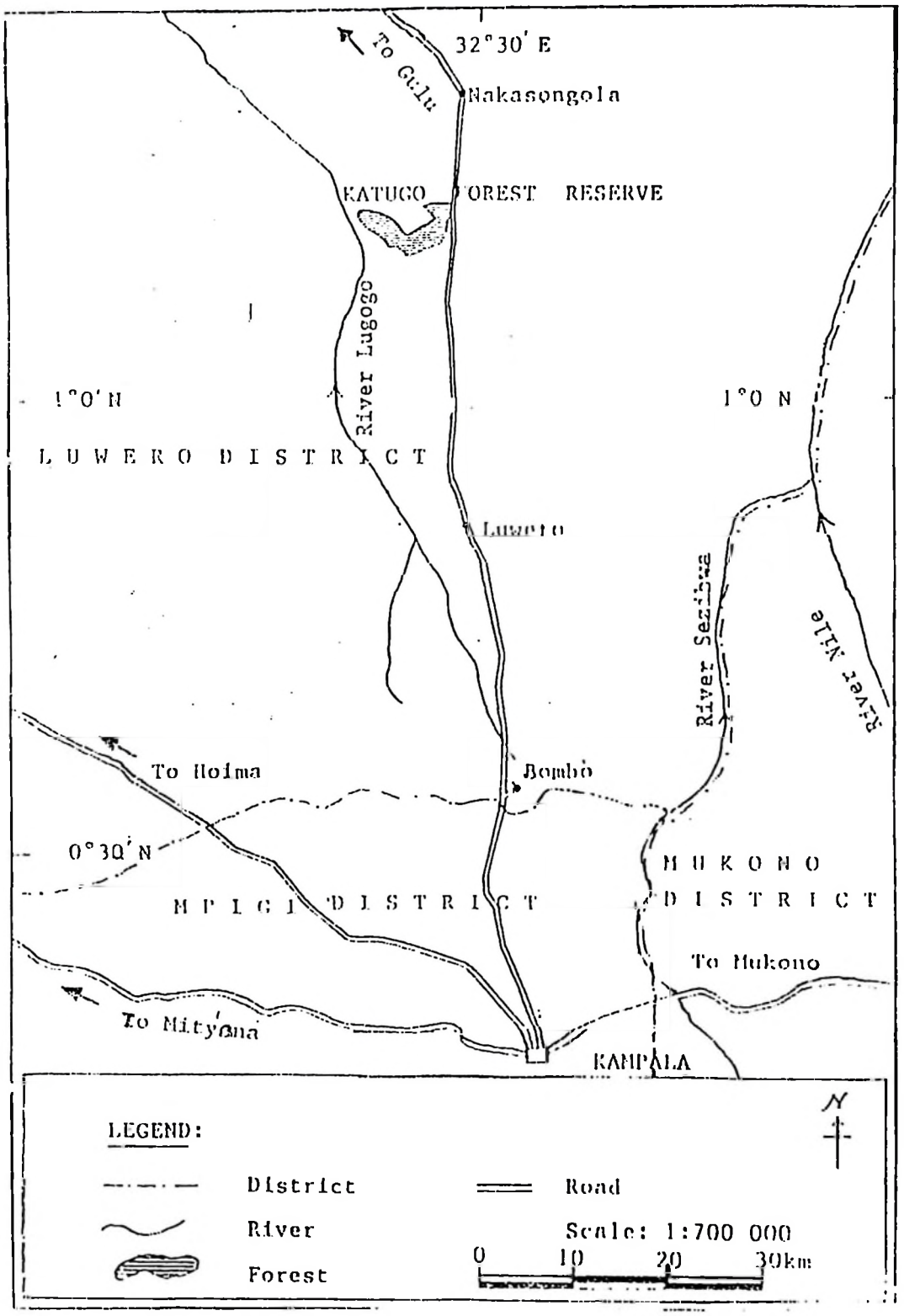

Figure 2. Katugo Forest Reserve orientation map
source: Forest Department Inventory Report (1990)

3.1.5 Growing stock

The Katugo Forest Reserve was established in 1963. Planting on a large scale was started in 1966 using *P.caribaea, P. patula, P.oocarpa, P.kesiya, P.insularis, P.montezumae* and others. The best perfomer, however, has been *P.caribaea* and followed by *P.oocarpa*. As a result most of the area is planted to these two species (Forest Department Working Plan, East Buganda Woodlands Reserve, 1969).

The materials used in this study were obtained from a permanent research plot No. 685 planted in 1971.
This was selected because the stand has reached the rotation age of 25 years and the stand table showed a high stocking density (crown closure: 50-70 %) with a total of 578 trees per hectare and had the best standing volumes in the entire plantation (Forest Department Inventory Report 1990). The sample plots boundaries were demarcated permanently by trenches.

The original plan was to establish pulpwood plant at Katugo financed mainly by Norwegian Agency for Development (NORAD). In 1973, unfortunately, with the withdrawal of NORAD assistance to the Government of Uganda, planting program scaled down and was completely abandoned in 1976.

Very little normal management activities took place in the plantation since 1976, due to breakdown in political and economical situations. No silvicultural operations were carried out and large areas were burned down.

3.2 Sampling

3.2.1 Selection of trees

The present investigation was carried out in a 25-year-old stand from a permanent research plot No. 685 in compartment 6. All trees in the sample site were of the same age and in blocks of 13 x 15 to 30 x 30 trees each of the three species were available for sampling.

Sample blocks were selected for each species to ensure that they had enough trees distributed on small, medium and large diameters classes. Initially 100 trees were selected at random from the three pre-determined blocks.

Six trees of *Pinus caribaea* and *Pinus oocarpa*, three trees of *Pinus kesiya* were selected. All the sample trees were selected on the basis of stem and crown qualities representing good form and free from any visible defects (Burley and Wood, 1976). *Pinus kesiya* proved too defective caused by excessive sweeps and forked trees so that only three trees instead of six trees of the species could be selected. Two trees of *Pinus caribaea* and *Pinus oocarpa*,

and one tree of *Pinus kesiya* from each of the three pre-determined diameter classes of small (10-14 cm), medium (15-19 cm) and large (20-24+ cm) diameter classes, were selected. Similar procedures have been employed by other researchers (Elliott, 1966; Tsoumis and Panagiotidis, 1980, cited by Sanwo, 1986).

Standard methods (Hughes and Plumptre,1976) for recording data and collecting samples were used.
Data from sampling for the selected trees are presented in **Table 2.**

Table 2. Species, diameter at breast height (dbh)-class, total height of sample trees.

Species	Tree No.	DBH (cm)	Dclass	Height (m)
Pinus caribaea	1	11.4	small	18.5
Pinus caribaea	2	12.5	small	19.7
Pinus caribaea	3	19.5	medium	20.1
Pinus caribaea	4	21.0	medium	21.0
Pinus caribaea	5	25.4	large	25.2
Pinus caribaea	6	27.5	large	27.3
Pinus kesiya	1	13.5	small	19.8
Pinus kesiya	2	18.1	medium	27.6
Pinus kesiya	3	21.2	large	29.3
Pinus oocarpa	1	14.0	small	19.8
Pinus oocarpa	2	14.5	small	20.6
Pinus oocarpa	3	16.5	medium	23.0
Pinus oocarpa	4	17.5	medium	22.2
Pinus oocarpa	5	25.2	large	26.0
Pinus oocarpa	6	20.1	large	25.0

The 15 sample trees were felled with a chain saw. Sample billets or bolts 90 cm long were cut at 5-10% (i.e. breast height 1.3 m), 45% and 75% of the total tree height. Similarly, wood discs of 5 cm in thickness were cut at 5-10 % (i.e. breast height 1.3 m), 45% and 75% of the total tree height, adjacent to the top of every sample billets from each sample tree.

This percentage height method of sampling employed is a compromise between the conventional method of sampling at fixed heights and the internodal sampling and has been widely used for the investigation of wood properties (Elliot,1966; Brown, 1971; Hughes and Plumptre,1976; Lema *et al.*,1978; White *et al.* 1980).

Center planks of 65 mm in thickness were sawn by through and through method from each of the billets. The billets and discs were labelled using paint with codes indicating species, tree number, diameter class, position in the tree and North Point.

Samples were treated with antsapstain and insecticidal mixtures, surface dried under shade then wrapped in polythene and boxed for transportation to Sokoine University of Agriculture, Morogoro for laboratory work.

3.3 Laboratory procedures

3.3.1 Ring width determination

Ring width samples were sawn from the wood discs. Diameter strips were cut from the discs with the growth rings as nearly evenly distributed about the pith as possible. The strips were cross-cut into two equal parts, one half was used for ring width measurement and the other half used for density determination.

The ring samples were dried, then smothen to ensure identification of growth rings. Ring width was measured using a micrometer screw gauge which gave readings to 0.01 cm.

3.3.2 Preparation of samples for determination of basic density

Test pieces to measure basic density were taken from the wood discs. Radial strips were cut at the pith into two subsamples representing East and West directions. Then each of these subsamples were divided into three equal parts representing inner/core, middle/transition and outer/mature wood (Fig. 3). The middle of each section was marked and its distance from the pith recorded. That is at 17%, 50% and 83% radius from pith to bark, representing the inner,

middle and outer wood respectively. In all there were 45 wood disc samples for density tests for the three species. And a total of 270 density test specimens were obtained. Similar procedures have been employed by many researchers in the study of wood properties variations in *Pinus* (Elliott, 1966; Ishengoma *et al.*, 1990; Ishengoma and Gillah, 1992; Ishengoma *et al.*, 1994; Ishengoma *et al.*, 1995).

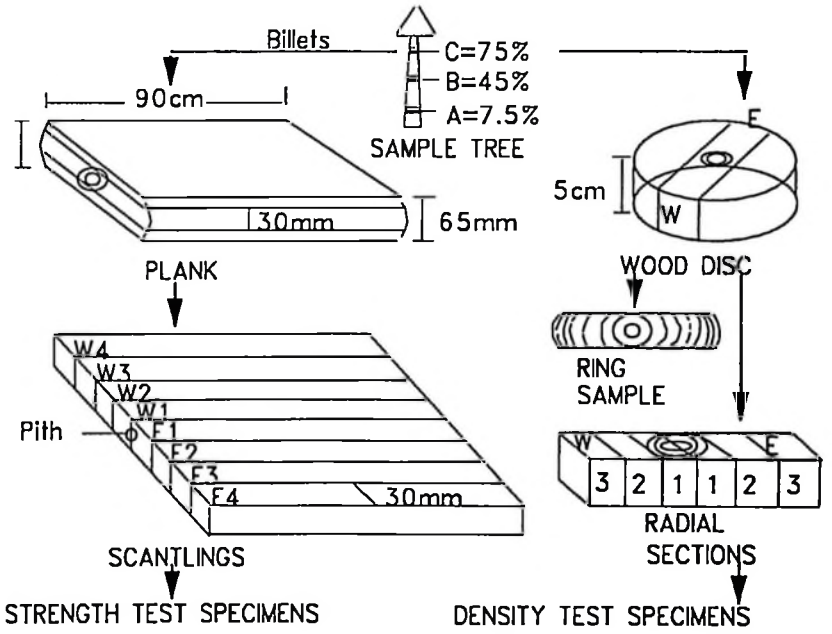

Figure 3. Within tree sampling methods showing test samples extractin and labelling.

3.3.3 Specimen preparation for determination of strength properties

The 45 planks were stacked and air dried at the laboratory in free air circulation. Each of the planks were later radially sawn in the East-West direction into 30 mm wide center boards or scantlings in the woodshop. Then the scantlings were further planed to 20 mm x 20 mm standard square cross-sections and sticks serially labelled for identification from pith to bark.

Clear samples test pieces for the six mechanical strength properties studied were obtained from each of the sticks. Since standard square cross-sections were employed, the total test specimens varied from 200 to 210 pieces (Table 3) depending on the width of the various planks. As expected the number of radial samples decreased up the tree. The sticks were converted to different dimensions for tests as follows (Table 3):

Table 3. Properties, dimensions and number of specimens

Strength Properties	Dimensions	(Number of Specimens)
- static bending	20 * 20 * 300 mm.	(200)
- compression	20 * 20 * 60 mm.	(210)
- shear strength	20 * 20 * 20 mm.	(205)
- cleavage	20 * 20 * 45 mm.	(208)

Preparation of test specimens were based on the international standard procedures (B.S. 373 MTSCST) according to Lavers (1969). This procedures were successfully used in similar studies (Gashumba, 1982; Ishengoma *et al.*, 1990; Ishengoma and Gillah, 1992; Ishengoma *et al.*, 1994; Ishengoma *et al.*, 1995).

3.3.4 Determination of basic density

Methods of test were done in accordance with the international standard procedures B.S.:373 (1957) and ISO 3129 (1975) according to Lavers (1969). Basic density (BD) in kg/m^3 of each of a total of 270 test specimens was calculated as follows:-

BD ($kg\ m^3$) = Section oven dry weight ÷ Section green volume

3.3.4.1 Green volume determination

The samples were soaked in distilled water until they sunk i.e. attained green volume. Green volumes of the sections were then measured by water displacement method.

3.3.4.2 Oven dry weight determination

After measuring the green volumes, the sections were then dried in an oven at 105^{0}C to constant weight. The oven dry sections were then cooled in a desiccator over silica gel before weighing on an analytical balance and data recorded.

3.3.5 Evaluation of Wood Properties

Tests of various strength properties were measured on each specimen using a Monsanto Tensiometer machine and deflection curves were plotted manually. The tests were carried out in the laboratory room with temperatures of 20 ± 3^{0}C and relative humidity of 65 ± 3 % as specified in B.S.:373 (1957).

The samples were weighed before carrying out the tests. After testing the specimens were then dried in an oven at 105^{0}C to constant weight. The oven dry sections were cooled in a desiccator over silica gel before weighing on an analytical balance. The data recorded were used for calculation of moisture content at the time of testing (MCw) as follows:

$$MCw = \frac{\text{green weight - oven dry weight}}{\text{oven dry weight}}$$

Strength values were adjusted to 12 percent moisture content in accordance with the accepted procedures described by Desch (1973). Modulus of rupture, modulus of elasticity, work to maximum load, maximum compression strength parallel to grain, maximum shear strength parallel to grain and cleavage, resistance to splitting in radial plane were determined as follows:

3.3.5.1 Static Bending

The load was applied centrally to each specimen which was supported over a span of 280 mm. For all the specimens and all tests, constant rates and conditions were applied according to standard methods B.S.:373 (1957). The specimens were loaded on the radial face. Deflections of the specimens during the tests were derived from the chart record which were plotted manually. The area under the stress/strain curves were measured using a digital planimeter.

(a) Modulus of rupture (MOR), modulus of elasticity (MOE) and work to maximum load (Wmax) all in N/mm^2 were calculated respectively using the formulas as shown below:

Modulus of rupture (MOR) of each test piece at a moisture content w, at the moment of test was calculated as

$$MORw\ (N/mm^2) = 3* F_{max}*L \div 2*w*h^2$$

where: Fmax is maximum load in Newtons at limit of proportionality.
L is the span length in mm equal to 280 mm.
w is the width of the sample equal to 20 mm.
h is the depth of the specimen equal to 20 mm.

The multiply factor used was as follows:

$$MOR = F_{max} * 0.0525$$

(b) Modulus of elasticity (MOE) of each test piece at a moisture content w, at the moment of test was calculated as follows:

$$MOEw\ (N/mm^2) = P_{max}*L^3 \div 2*s*h^2$$

where: Pmax is maximum load in Newtons to the elastic limit.
L is the span length in mm equal to 280 mm.
s is the actual deflection to the elastic limit (mm).
w is the width of the sample equal to 20 mm.
h is the depth of the specimen equal to 20 mm.

The multiply factor used was as follows:

$$MOE = P_{max} * 34.3$$

(c) Work to maximum load (Wmax) in N/mm^2 of each test piece at a moisture content w, at the moment of test was calculated as follows:

$$Wmax\ (N/mm^2) = A * Q \div V$$

where: A is the area under the curve to maximum load
Q is the work equivalent to 1 mm^2 on the load deflection curves.
V is the volume of specimen equal to 280*20*20 = 112 000 mm^3.

Modulus of rupture (MOR), modulus of elasticity (MOE) and work to maximum load (Wmax) all in N/mm^2 were adjusted respectively using the formulas as shown below to 12 % moisture content by the following formular which is valid for moisture content of 12 ± 3% :

$$Y_{12} = Y_w\ (1+Z)^n$$

where: Y_{12} is the value at 12 % moisture content.
Y_w is the value at test moisture content.
Z is the correction factor equal 0.04, 0.02 and 0.01 for MOR, MOE and Wmax respectively (Desch, 1981).
^{n} is the difference in m.c. at test from 12 %.

Work to total fracture (Total work) was in this study left out since the area under the curve to total fracture could not be determined, the specimens were failing abruptly to maximum load, indicating brittle and not tough wood.

3.3.5.2 Compression parallel to grain

Dimensions and number of specimens employed in this tests are shown on Table 3. Like in the case of the previous

tests constant rates and conditions were applied according to standard methods B.S.:373 (1957).

Maximum compression strength parallel to grain (MCS) in N/mm^2 was calculated as follws:

$$MCS = P_{max} \div a*b$$

where: P_{max} is the maximum crushing load in N
a and b are the cross sectional dimensions in mm.

Adjusted MCS to 12 % moisture content by the following formular which is valid for moisture content of 12 ± 3 %:

$$MCS_{12} = MCS_w \ (1+Z)^n$$

where: MCS_{12} is the maximum crushing load at 12 % moisture content.
MCS_w is the maximum crushing force at test moisture content.
Z is the correction factor equal 0.04 (Desch, 1981).
^{n} is the difference in m.c. at test from 12 %.

3.3.5.3 Shear strength parallel to grain

As with other tests, all the specimens were subjected to constant rates and conditions were applied according to standard methods B.S.:373 (1957).

Maximum shear strength parallel to grain (MSS) in N/mm^2 was

calculated as follows:

$$MSS = P_{max} \div b*l$$

where: P_{max} is the maximum shear force in N
b is the specimen thickness in mm.
l is the specimen length in mm.

Adjusted MSS to 12 % moisture content by the following formular which is valid for moisture content of 12 ± 3 %:

$$MSS_{12} = MSS_w (1+Z)^n$$

where: MSS_{12} is the maximum shear force at 12 % moisture content.
MSS_w is the maximum shear force at test moisture content.
Z is the correction factor equal 0.04 (Desch 1981).
^{n} is the difference in m.c. at test from 12 %.

3.3.5.4 Cleavage

For all the specimens and all tests totalling 208, constant rates and conditions were applied according to standard methods B.S.:373 (1957).

Cleavage in N/mm, resistance to splitting in radial plane (CLR) was calculated as follows:

$$CLR = P_{max} \div b$$

where: P_{max} is the maximum cleavage force in Newtons (N).
b is the specimen width in mm.

3.5 Methods of statistical analysis.

Nested levels design was employed for the analysis of variance (ANOVA) to study the nature of variation in basic density and the six strength properties of small clear specimens. Species to species variability, between and within even-aged trees from the same site were studied. A computer software application program called Statistical Analysis System (SAS) was used. The general linear models procedure class levels from higher to lower were: 3 species, 6 trees in each of *Pinus caribaea* and *Pinus oocarpa* (3 trees in *Pinus kesiya*), 3 diameter classes, 3 axial positions and 4 radial positions (3 for basic density). The class levels from which the specimens were collected formed sources of variations.

The basic density and strength values for the radial and axial positions were calculated as the mean of the results for all the specimens and all tests. While the mean values for each tree were calculated as the arithmetic mean basic densities and strength values for all positions. Then the overall mean values for each species pooled from all the six trees for each of *Pinus caribaea* and *Pinus oocarpa*, similarly the three trees of *Pinus kesiya* were determined.

A summary of major results reported.

The analysis of variances were followed by the Duncan's Multiple Range tests whenever F-ratio indicated significant difference between means to determine which means caused the significance. Graphical analysis were also used to establish the systematic variation of the strength properties. For a better understanding and possible prediction, simple linear regression equations were developed for relationships between average tree basic density and strength values with diameters and heights. Results on ring width was descriptive only.

The last part of the results involved simple linear regression analysis to study the relationship between density and strength properties. The regression equations were derived that can be used to easily predict strength properties (dependable variables) from a given basic density (independable variable).

The regression equation was as follows:

$$y = a + bx$$

where: x = mean basic density
y = mean strength values for MOR, MOE, Wmax, MCS, MSS and CLR.
a = y intercept.
b = regression coefficient constants

The 5% level of significance was used in all the analysis.

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Growth ring width

Growth ring width (GRW) is an important indicator of wood development and of its quality. An attempt was made to try and relate ring width with basic density. However, measurement of ring width was complicated by the presence of numerous and multiple growth rings, the fact that no distinct annual growth rings were observed. It was therefore not possible to compare wood formed in the same period, since this could affect the trend of results. Hence, the descriptive nature of the results on ring width. Comparisons of the effect of growth rate on wood properties can only be made on rings of the same age (Zobel and van Buijtenen, 1989).

It is important to note that all the trees were even-aged at 25 years for the three species. However, the number of growth rings found were much higher up to double the age (in years) of the trees.

A consistent pattern of growth ring bands were observed in one tree as well as in different trees of *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa*. The number of latewood bands was much higher in the bottom discs and decreased

towards the top. The first growth rings (about ten) near the pith were between 5 and 15 mm while the outer (16 rings) growth rings were rarely more than 3 mm. Nearer to the bark it was difficult to demarcate earlywood from latewood, and the distance between the latewood bands decreased toward the bark.

The influence of ring width or growth rate on basic density in Pines has attracted the attention of many researchers (Bendtsen, 1978; Elliott, 1970; Ringo, 1983). Direct correlation between ring number (age) and its wood density has been difficult to substantiate due to the decrease in ring width and increase in tree age (Larson, 1956, Elliott, 1970). Ringo (1983) reported on the relationship between basic density and ring width for rings 4,8,12,16 and 20 in *Pinus patula* and showed that ring width does not affect wood density significantly.

4.2 Wood density values determined

The overall mean basic density values for each species were pooled from all the six trees in both *Pinus caribaea* and *Pinus oocarpa* , similarly the three trees of *Pinus kesiya* were determined and gave the results in **Table 5.** The results indicated that the overall mean basic densities

were 424.33 kg/m^3, 431.37 kg/m^3 and 444.37 kg/m^3 respectively in *Pinus caribaea, Pinus kesiya* and *Pinus oocarpa*.

4.3 Wood density variation

Analysis for basic density variation between and within all the trees in *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* were obtained by laboratory tests. The results in **Table 4.1** show statistical significant difference at $P < 0.05$ for basic density variation between trees, within trees in both axial and radial positions with exception in diameter classes in *Pinus caribaea*.

Table 4.1. Summary, analysis of variance for basic density showing between and within trees variation in *Pinus caribaea*.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F	Sig
Trees	5	29910.89	5982.18	9.93	0.0001	*
Dclass	2	17622.11	8811.06	14.62	0.1098	NS
Vposi	2	27672.11	13836.06	22.96	0.0001	*
Rposi	2	130069.33	65034.67	107.91	0.0001	*
Vposi*Rposi	6	130696.56	21782.76	36.14	0.0001	*
Error	40	24106.44	602.66			
Total	57	229380.90				

R-Square = 0.89

Interaction = Vertical position(Vposi) * Radial position (Rposi).
* = statistical significant difference at P < 0.05.
NS = no statistical significant difference at the 5% probability level.

R-Square, the explanatory power of the model can explain that 89% of the causes of total variations in basic density are due to between and within trees variation in *Pinus caribaea*.

The results in **Table 4.2** show no statistical significant difference at $P < 0.05$ for basic density variation between trees and diameter classes, but statistical significant difference in both axial and radial positions in *Pinus kesiya*.

Table 4.2. Summary, analysis of variance for basic density showing between and within trees variation in *Pinus kesiya*.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F	Sig
Trees	2	3588.96	1794.48	2.53	0.1108	NS
Dclass	2	3588.96	1794.48	2.53	0.8117	NS
Vposi	2	6728.07	3364.04	4.75	0.0241	*
Rposi	2	186237.85	93118.93	131.43	0.0001	*
Vposi*Rposi	6	186527.56	31087.93	43.88	0.0001	*
Error	16	11335.70	708.48			
Total	30	398007.10				

R-Square = 0.95

Interaction = Vertical position(Vposi) * Radial position (Rposi).
* = statistical significant difference at $P < 0.05$.
NS = no statistical significant difference at the 5% probability level.

The R-Square obtained is high, it indicates that the model

can explain 95% of total variations in basic density data in *Pinus kesiya*.

The results in **Table 4.3** show statistical significant difference at $P < 0.05$ for basic density variation between trees, within trees in both axial and radial positions including diameter classes in *Pinus oocarpa*. This huge difference between trees is a clear indication that there is enormous potential of increasing density, example through selection.

Table 4.3. Summary, analysis of variance for basic density showing between and within trees variation in *Pinus oocarpa*.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F	Sig
Trees	5	40780.59	8156.12	16.01	0.0001	*
Dclass	2	27759.37	13879.69	3.38	0.0418	*
Vposi	2	214141.04	10707.02	21.02	0.0001	*
Rposi	2	152363.82	76181.91	149.56	0.0001	*
Vposi*Rposi	6	1545446.89	25757.81	50.57	0.0001	*
Error	40	20375.07	509.38			
Total	57	2000866.00				

R-Square = 0.91

Interaction = Vertical position(Vposi) * Radial position (Rposi).
* = statistical significant difference at $P < 0.05$.
NS = no statistical significant difference at the 5% probability level.

The R-Square obtained is high, it indicates that the number

of trees, diameter classes, vertical and radial positions selected can explain 91% of total variations in basic density data in *Pinus oocarpa*.

4.3.1 Wood density variation among species

The results in **Table 5** indicated that the overall mean basic densities were 424.33 kg/m^3, 431.37 kg/m^3 and 444.37 kg/m^3 respectively in *Pinus caribaea, Pinus kesiya* and *Pinus oocarpa*.

Table 5. Main results showing the overall mean basic density values mean values (kg/m^3) for the three *Pinus* species.

	Pinus caribaea	*Pinus kesiya*	*Pinus oocarpa*
Mean	424.33	431.37	444.37
s.d.	63.30	89.48	66.89
Duncan	A	A	A
CV	14.92	20.74	15.05

The mean basic densities results presented in **Table 5** where subjected to analysis of variance to test if significant differences existed. The analysis of variance results shown in **Table 6** indicate that the overall basic densities of the three species were not significantly different.

Table 6. Analysis of variance for overall basic density showing species to species variation.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F	Sig
Species	2	11032.04	5516.02	1.11	0.3336	NS
Error	132	657682.89	4982.45			
Total	134	668714.93				

R-Square = 0.016

NS = no statistical significant difference at the 5% probability level.

The R-Square obtained is very low, it indicates that the different species contribute 1.6% of total variations in basic density data.

The results may suggest that the types of cells, their proportions and arrangements differ slightly from amongst the species studied (Panshin and de Zeeuw, 1970). This could possibly be attributed to similar growing conditions and silvicultural treatments.

A comparison of basic density mean values for the species under study with those reported by other researchers is also shown in **Table 7**. The mean values found in this experiment are not comparable with those earlier reported possibly due to interacting factors such as differences in age, genetical, silvicultural treatments and environmental

Table 7. Comparison of basic density values for species under study with those reported by other authors.

Authors Locality	species	Age (years)	Basic Density (kg/m^3)
This study (1997) Katugo,Uganda	*P.caribaea*	25	424
	P.kesiya	25	431
	P.oocarpa	25	444
Ringo and Klem (1980) Sao Hill,Tanzania	*P.patula*	25	410
Ringo (1983) Sao Hill,Tanzania	*P.patula*	25	448
Ladrach (1986) Colombia	*P.caribaea*	8	363
	P.kesiya	8	370
	P.oocarpa	8	429
Silinge (1989) Masawi,Tanzania	*P.caribaea*	19	403
Khiari and Iddi (1989) Zanzibar,Tanzania	*P.caribaea*	12	460
Ishengoma *et al.* (1990) Meru Proj.Tanzania	*P.patula*	29	425

factors. For example, the younger stands of *P.caribaea* grown in Zanzibar at lower altitude site showed a higher mean basic density reported by Khiari and Iddi (1989) than older stands found in this study. However, the order of mean density results in this study coincides very well with results in Colombia (Ladrach, 1986). Ladrach (1986) reported at same age and locality that *P.oocarpa* had the highest density, followed by *P.kesiya* and *P.caribaea* was found with the lowest density.

4.3.2 Wood density variation between trees

Several studies have shown large variation in basic density between Pine trees within a given species and even within same sites (Ong, 1978; Ringo and Klem, 1980; Plumptre,1984; Khiari and Iddi, 1989). This is one of the most constant source of density variation studied. The results of tree to tree basic density variation from this study are shown in **Figure 4**. This may be due to genetical differences between trees of the same species (Zobel and van Buijtenen, 1989).

In order to quantify and describe the nature of variation in wood properties it was necessary to examine the class levels from which the specimens were collected that formed sources of variations.

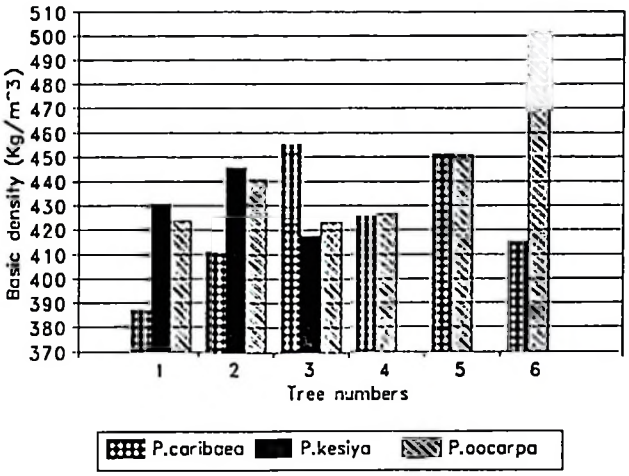

Figure 4. Between trees basic density variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

The results of analysis of variance given in **Table 4.1, 4.2** and **4.3** showed that some source of variation contributed more to the observed overall variation than others. The percentage contribution by different sources to the total variation in basic density were revealed by examining the respective sum of squares and reported in **Table 8.** The second highest variation was contributed by differences between trees within species which accounted for **13.0%,**

1.7% and 15.5% of the total variation observed in basic density in *P.caribaea*, *P. kesiya* and *P. oocarpa* respectively.

Table 8. Percentage variation in basic density contributed by different sources of variation by species.

Source	Sum of Squares (percentage of variation contributed)		
	P.caribaea	*P. kesiya*	*P. oocarpa*
Trees	29910.89 13.0%	3588.96 1.7%	40780.59 15.5%
Diameter class	17622.11 7.7%	3599.96 1.7%	21414.04 8.2%
Axial position	27672.11 12.1%	6728.07 3.2%	27759.37 10.2%
Radial position	130069.33 56.7%	152363.82 88.1%	1865237.56 58.0%
Error	24106.44 10.5%	11335.70 5.5%	20375.07 7.8%
Total	220380.90 100%	211479.50 100%	262692.90 100%

The results showed statistical significant difference in basic density between trees of *P.caribaea* and *P. oocarpa* (P=0.05).

The results of Duncan's Multiple Range Test showed some significant differences between the tree means in *Pinus caribaea* and summarised as follows:

Tree no.	3	5	4	6	2	1
mean	455.56	451.00	425.89	415.22	411.11	387.22
Grouping	A	A	A	A	A	A
		B	B	B	B	B	B	B	B	B

Means with the same letter are not significantly different (P=0.05).

The results of Duncan's Multiple Range Test showed some significant differences between the tree means in *Pinus oocarpa* and summarised as follows:

Tree no.	6	5	2	4	1	3
mean	506.67	460.67	440.44	426.56	423.67	423.22
Grouping	A	A	A	A	A
		B	B	B	B	B	B	B	B	B

Means with the same letter are not significantly different (P=0.05).

However, density of the three trees studied of *Pinus kesiya* were not significantly different at P=0.05 (Pr > F = 0.1108). Thus the Duncan's Multiple Range Test was not employed to determine which means caused the significance.

This no significant differences between the tree means in *Pinus kesiya* may also indicate lack of potential in increasing density through selection.

The variation in basic density between trees were found to have been statistical significant, ranging from 456 to 387, and 423 to 502 kg/m^3 in *Pinus caribaea* and *Pinus oocarpa*, respectively. Similar considerable large range between trees were reported in *Pinus caribaea:* in 12 years old trees grown in Zanzibar which varied from 345 to 637 kg/m^{-3} (Khiari and Iddi, 1989); in 19 year old trees grown in Masawi, Tanzania that varied from 310 to 480 kg/m^3 (Silinge, 1989). It is supported by a later study in *Pinus patula* from the Meru Project which shows range from 355 to 484 kg/m^3 (Ishengoma *et al.* 1990).

Pinus kesiya showed no statistical significant difference between the trees. However, this can not be ascertained based on a limited number of trees studied. This study found statistical significant differences in both *Pinus caribaea* and *Pinus oocarpa*, this may be either due to presence and lack of compression wood or due to increase in angle of bole inclination (Jain and Seth, 1980). Much of the tree to tree variation within species of same age and on same site may be attributed to genetical differences in individual trees (Zobel and van Buijtenen, 1989). Also the

micro-environment of individual trees due to competition and other localised site factors may partly contribute to the variation (Ringo and Klem, 1980; Ishengoma *et al.* 1990).

4.3.3 Wood density variation between diameter classes

The results of the analysis of variance for basic density to test differences between the three diameter classes showed no significant differences between large (l=20-24+cm), medium (m=15-19 cm) and small (s=10-14 cm) diameter trees in *Pinus caribaea* and *Pinus kesiya*. However, *Pinus oocarpa* showed some significant differences between diameter classes. Pr > F were 0.1098, 0.8117 and 0.0418 in *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* and are presented in Table 4.1, 4.2 and 4.3 respectively. The Duncan's Multiple Range Tests followed since F-ratio indicated significant differences in basic density mean values. The results show that the large tree was significantly different from medium and small diameter trees (P=0.05).

The Duncan's Multiple Range Test result for *Pinus oocarpa* may be summarised as follow:

Dclass	l	s	m
mean	476.17	432.06	424.89
Grouping	A	B B	B

Means with the same letter are not significantly different (P=0.05).

Pinus oocarpa therefore appears to have the necessary adaptation characteristics for successful establishments at Katugo in Uganda (Forest Department Working Plan, East Buganda Woodlands Reserve, 1969; Greaves, 1978) and enormous potential of increasing density through selection.

In order to have a better understanding and possible prediction, simple linear regression equations were developed for relationship between mean tree basic density with diameters. The regression analysis of basic density with diameter at breast height (dbh) based on values from Table 2 gave the following equations in **Table 9.**

The regression and correlation analysis between basic density and diameter class shows that the relationship between basic density and diameter classes were very weak with low R-Squares (R^2 = 0.0009, 0.0009 and 0.0523), indicating that the differences in diameter class can only explain little of the observed variation in basic density. That is, only 0.09% in both *P.caribaea* and *P. kesiya*, and 5.23% in *P. oocarpa*.

Table 9. Regression equations and correlation coefficients for the relationship between basic density and tree dbh.

Species	Regression equation (BD = a + bD)	R-Square
P. caribaea	BD = 430.71 - 0.83D	0.0009
P. kesiya	BD = 469.76 - 1.01D	0.0009
P. oocarpa	BD = 381.82 - 3.48D	0.0523

where BD = basic density (kg/m^3).
D = diameter at breast height, dbh (cm).
a = y intercept.
b = regression coefficient.

The lowest variation was contributed by differences between diameter classes within species which accounted for 7.7%, 1.7% and 8.2% of the total variation observed in basic density in *P.caribaea*, *P. kesiya* and *P. oocarpa* respectively (**Table 8**). The results in **Table 4.1** and **4.2** showed no statistical significant difference in basic density between large, medium and small diameter trees (P=0.05) in both *P.caribaea* and *P. kesiya*, implying that a tree could grow fast and produce wood as dense as wood produced by a slow growing tree. In *P. oocarpa*, however, tree no. 1 and 3 showed both low rate of growth and low density (**Fig. 4**). While tree no. 6 showed both high growth rate and a high basic density suggests that in some cases regardless of rate of growth, wood of high density may be

formed (Ishengoma, 1980). Growth rate has no significant effect on tree density. This also suggest the possibility of increasing tree density without loss in growth rate (Plumptre, 1984).

4.3.4 Variation within trees

Basic density vary substantially within trees of the three species examined with positions within trees. The two major sources of variation considered were with levels in axial and radial positions.

4.3.4.1 Axial basic density variation

This study showed that in the axial direction, basic density decreased significantly with different tree height levels in all the three species. The variation in basic density with height levels from base upwards in percentage of total tree height for pooled tree data in the three species are reported in Table 10.

Table 10. Summary, results showing mean values in basic density (kg/m^3) with height in trees between species.

Species mean values (kg/m^3)		height levels from butt to top percentage 7.5%	45%	75%
P. caribaea	mean	452.78	422.83	397.39
	s.d.	57.51	64.10	58.73
	Duncan	A	AB	B
	CV	12.70	15.16	14.78
P. kesiya	mean	452.00	428.44	413.67
	s.d.	92.50	93.81	88.45
	Duncan	A	AB	B
	CV	20.46	21.90	21.38
P. oocarpa	mean	468.83	444.22	420.06
	s.d.	67.22	66.13	61.61
	Duncan	A	AB	B
	CV	14.34	14.89	14.67

Means with the same letter are not significantly different (P=0.05).

Variation in basic density from base upwards accounted for 12.1%, 3.2% and 10.2% of the total variation observed in basic density in *P.caribaea*, *P. kesiya* and *P. oocarpa* respectively (Table 8).

The decrease in basic density from 7.5% to 45% height levels was slight while the decrease from 45% to 75% height levels was sharper. For example, density decreased slightly from 452.78 kg/m^3 to 422.83 kg/m^3 then decreased sharply

from 422.83 kg/m^3 to 397.39 kg/m^3 in *P. caribaea*. **Figure 5** is a plot of basic density with proportional tree height for the three species, indicating the trend. Similar trends in Pines were reported by Ringo (1977); Khiari and Iddi (1989).

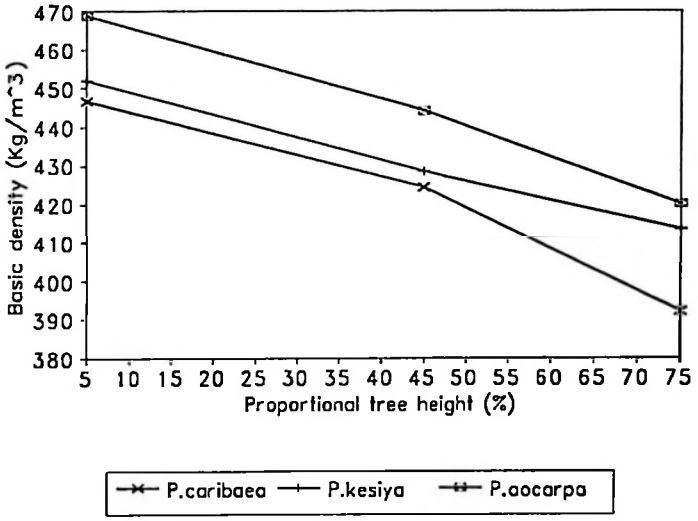

Figure 5. Axial basic density variation for the three species.

A simple linear regression analysis was conducted relating wood basic density with stem height levels. The regression analysis of basic density at different stem height levels with tree height levels gave the following significant equations in **Table 11.**

Table 11. Regression equations and R-Square coefficients for the relationship between basic density and tree height.

Species	Regression equation (BD = a + bH)	R-Square
P. caribaea	BD = 450.65 - 3.17H	- 0.8793
P. kesiya	BD = 454.73 - 2.15H	- 0.9187
P. oocarpa	BD = 470.43 - 2.69H	- 0.9417

where BD = basic density (kg/m^3).
H = height in stem (m).
a = y intercept.
b = regression coefficient.

In all species, with the individual trees as well as using pooled data, the general trend found was a decrease of basic density from base upwards (Fig.5). The decrease of basic density may be explained in terms of crown effect. Crown influence auxin production which directly regulate cell dimensions in the stem both across the growth rings and spatially down the stem. Wood within the vicinity of the crown is mostly corewood and the proportion of corewood is known to increase with height (Elliott, 1970; Larson, 1956). Corewood or juvenile wood is significantly lower in density than mature wood (Ishengoma and Gillah, 1992).

The regression analysis of basic density at different stem height levels with tree heights in **Table 11.** gave a

significant negative relationship between basic density and tree height. The negative R-Square coefficients implies that axial positions can explain upto 88%, 92% and 94% decrease in basic density with increase in height in *P.caribaea*, *P. kesiya* and *P. oocarpa* respectively. Similar results reporting density decrease with increase in height have been reported by Plumptre, 1972; Ringo, 1977; Ringo and Klem, 1980; Silinge, 1989.

4.3.4.2 Radial basic density variation

Radial basic density variation in stems from pith outwards was studied at 17%, 50% and 83% of radius. The results indicated significant difference, and therefore the Duncan multiple range test was employed and shown in **Table 12.**

The highest within trees variation was contributed by radial variation from the pith to the bark which accounted for 56.7%, 88.1% and 58.0% of the total variation observed in basic density in *P.caribaea*, *P. kesiya* and *P. oocarpa* respectively (Table 8).

The trends of radial basic density variation from pith to bark with different tree height levels for *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* are shown in **Figure 6.1, 6.2** and **6.3** , respectively.

Table 12. Summary, results showing mean values of radial variations in basic density (kg/m^3) in stems for the three species.

Species		radial levels from pith to bark in percentage		
		BD17%	BD50%	BD83%
P. caribaea	mean	370.56	413.22	489.22
	s.d.	31.60	48.26	38.91
	Duncan	C	B	A
	CV	8.53	11.68	7.95
P. kesiya	mean	341.89	410.22	542.00
	s.d.	29.26	37.13	22.54
	Duncan	C	B	A
	CV	8.57	9.05	4.16
P. oocarpa	mean	389.33	427.61	516.17
	s.d.	33.41	33.21	52.60
	Duncan	C	B	A
	CV	8.58	7.77	10.19

Means with the same letter are not significantly different (P=0.05).

The increase in basic density from 17% to 50% of radius was slight while the increase from 50% to 83% of radius was sharper at all height levels and for all the three species. For an example, in *Pinus caribaea*:

- at height level A, density increased slightly from 380.00 kg/m^3 (17% radial level) to 416.50 kg/m^3 (50% radial level) then increased sharply to 509.33 kg/m^3 (83% radial level),
- at height level B, density increased slightly from 355.17 kg/m^3 (17% radial level) to 392.17 kg/m^3 (50% radial level) then increased sharply to 481.17 kg/m^3 (83% radial level), and

- at height level C, density increased slightly from 345.00 kg/m^3 (17% radial level) to 376.83 kg/m^3 (50% radial level) then increased sharply to 437.50 kg/m^3 (83% radial level).

Statistical analyses showed a significant increase in basic density from the pith towards the bark with different tree height levels (Appendix 1). The results followed the expected trend for pine (Panshin and de Zeeuw, 1970). A similar trend is reported in *P.caribaea* grown in Tanzania by Khiari and Iddi (1989). Other authors supported the trend in *P.patula* Lema *et al.*(1978, White *et al.*(1980), Ringo and Klem (1980) and Silinge (1989).

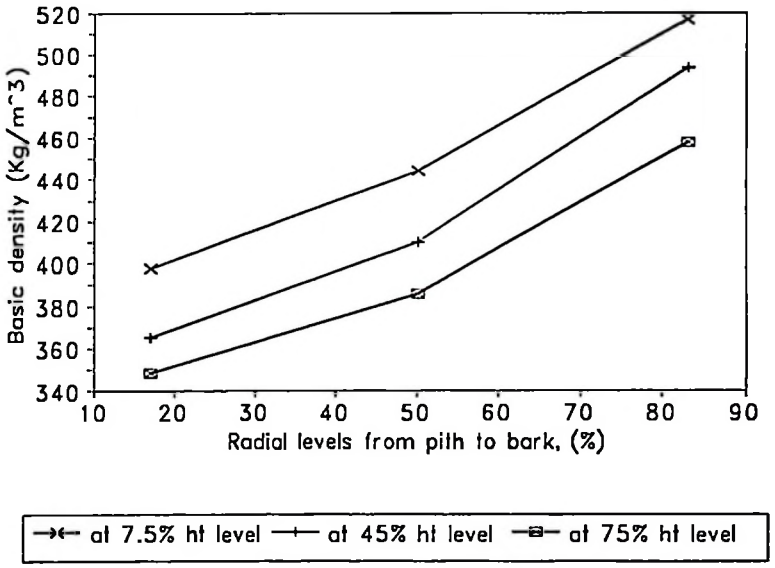

Figure 6.1 Radial basic density variation at different tree height levels in *P.caribaea*.

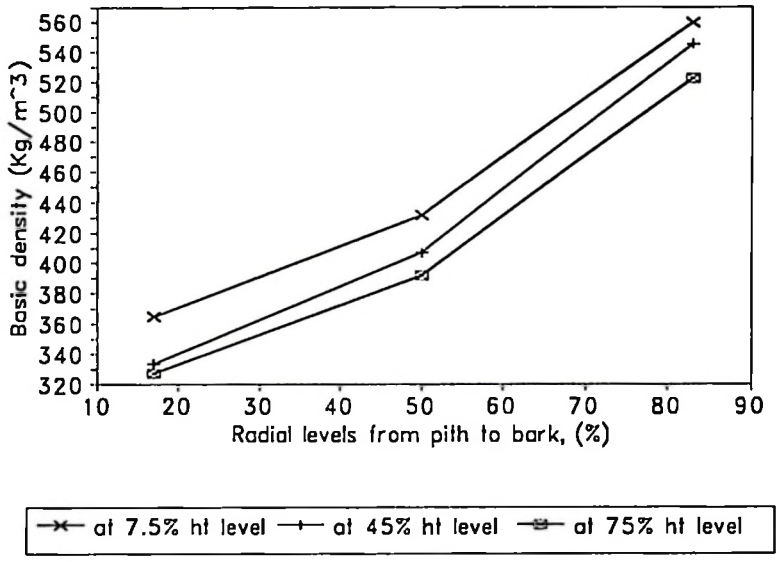

Figure 6.2. Radial basic density variation at different tree height levels in *P.kesiya*.

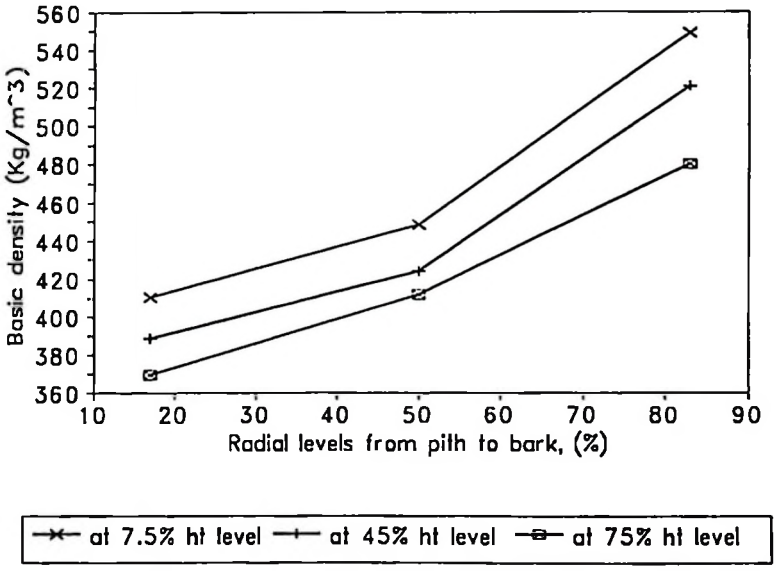

Figure 6.3. Radial basic density variation at different tree height levels in *P.oocarpa*.

In this investigation basic density was found to increase from 371 to 489, 342 to 542 and 389 to 516 kg/m^3 in *P.caribaea*, *P. kesiya* and *P. oocarpa* respectively. In each species, the first figure shown in Table 12 indicates the low strength of the juvenile wood near the pith and points out the low real value of first thinning and top logs (Ringo and Klem, 1980). While the second figure shows the high real strength value and dry matter content of the outer mature wood and provides a strong reason for considering basic density alongside volume information when deciding on the rotation age of the crop (Ringo, 1983).

The increase of basic density from pith outwards may be related to the proportion of earlywood to latewood (Zobel and van Buijtenen, 1989). A research in Sitka spruce indicates very weak relationship between growth ring width and density (Ishengoma, 1986). It is supported by earlier works according to Panshin and deZeeuw (1970) that growth ring width is not a dependable criterion of density unless it is evaluated with particularly the percentage and quality of summerwood. Although in this investigation it was not possible to measure growth ring width for regression analysis, it was clearly evident that the thickness of individual latewood bands increased from pith to bark.

4.4 Strength values determined

The overall mean strength values presented in **Table 13** for the three species studied were determined by laboratory tests and subjected to statistical analysis to test for significant differences. Small clear wood specimens for all tests were obtained from 4 radial positions, 3 axial positions and 3 diameter classes in all the 6 tree samples in each of *Pinus caribaea* and *Pinus oocarpa*, similarly the three trees of *Pinus kesiya*.

All the three species and especially *Pinus kesiya* showed much variability in MOR as indicated by the CV in Table 13. A possible explanation for the variability in *Pinus kesiya* could be that the species proved too defective in the selection of trees (section 3.2.1) caused by poor form. The results suggest the possibilities for the reduction of variability and improving tree form by silvicultural techniques and genetic control. Similarly, huge variability were showed in Wmax for all the three species. The high degree of variation in all the three species with trees at the same age indicates the potential for improvement by selection (Zobel and van Buijtenen, 1989). For examples: seed selection from sources with good stem form, thinning at the best time for development of good stem form, and pruning the trees to obtain the maximum production of clear wood.

Table 13. Summary, main results showing mean values of the wood properties and Duncan multiple range test for the three *Pinus* species.

Properties at 12% mc		*Pinus caribaea*	*Pinus kesiya*	*Pinus oocarpa*
BD (kg/m^3)	mean[a]	424.33(63.30)	431.37(89.48)	444.37(66.89)
	Duncan	A	A	A
	CV	14.92	20.74	15.05
MOR (N/mm^2)	mean	54.51(16.46)	56.31(20.69)	60.69(18.38)
	Duncan	A	A	A
	CV	30.20	36.74	30.54
MOE (N/mm^2)	mean	8590.51 (2225.69)	8752.24 (2371.73)	8825.37 (2003.76)
	Duncan	A	A	A
	CV	25.91	27.10	22.70
Wmax (mmN/mm^3)	mean	0.088(0.035)	0.099(0.046)	0.101(0.040)
	Duncan	A	A	A
	CV	40.18	46.04	38.79
MCS (N/mm^2)	mean	33.38(8.08)	33.83(9.70)	34.66(6.79)
	Duncan	A	A	A
	CV	22.42	26.74	18.29
MSS (N/mm^2)	mean	9.43(2.01)	9.80(2.02)	10.37(1.94)
	Duncan	A	A	A
	CV	21.35	20.59	18.72
CLR (N/mm)	mean	11.79(2.02)	12.15(1.38)	12.48(2.011)
	Duncan	A	A	A
	CV	17.16	11.37	16.11

For each strength properties, means with the same letter are not significantly different.
a = standard deviations shown in brackets.

4.5. Strength properties variation

Table 14. shows summary of analysis of variance for MOR variation between and within trees in *Pinus caribaea*. This analysis of variance for MOR suffice to highlight the significant systematic variation pattern found for all the other five strength properties in all the three species under the study. Summaries of analysis of variance for all the other strength properties in all the three species are given in **Appendix 2.1** to **2.17.**

Table 14. Summary, analysis of variance for MOE showing between and within trees variation in *Pinus caribaea*.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F	Sig
Trees	5	29910.89	5982.18	9.93	0.0001	*
Dclass	2	17622.11	8811.06	14.62	0.1098	NS
Vposi	2	27672.11	13836.06	22.96	0.0001	*
Vposi*Rposi	6	130696.56	21782.76	36.14	0.0001	*
Rposi	2	130069.33	65034.67	107.91	0.0001	*
Error	40	24106.44	602.66			
Total	57	229380.90				

R-Square = 0.92

The results in **Table 14** show statistical significant difference at $P < 0.05$ for MOE variation between trees,

within trees in both axial and radial positions with exception in diameter classes in *Pinus caribaea*.

The overall mean strength values found in this investigation for the three species are within range reported by other authors (Table 15).

Table 15. Comparison of strength values with those reported by various authors

Authors Locality	Species	Age (years)	MOR N/mm²	MOE N/mm²	Wmax mmN/mm³	MCS N/mm²	MSS N/mm²	CLR N/mm
This study (1997) Katugo,Uganda	*P.caribaea* *P.kesiya* *P.oocarpa*	25 25 25	54.5 56.3 60.7	8590.5 8752.2 8825.4	0.088 0.099 0.101	33.38 33.83 34.66	9.43 9.80 10.37	11.79 12.15 12.48
Ishengoma and Gillah (1992) Meru Proj. Tanzania	*P.patula*	22	74	9716	0.094	37.12	10.21	-
White *et al.* (1980)	*P.patula*	-	81	9794	0.085	39	-	-
Bryce (1967) Tanzania	*P.patula*	22	67.6	8140	-	33.7	-	-
Lavers (1969) Kenya	*P.radiata*	25	85	9000	0.112	48.1	12.8	13.0

Source: the authors

4.5.1 Strength properties variation among species

All the results of the analysis of variance showed no significant differences in all strength properties mean

values investigated among species. Summary analysis of variance in strength values for the three species are shown in Table 16.

Table 16. Analysis of variance showing species to species variability in strength properties.

Source[a]	DF	Sum of Squares	Mean Square	F Value	Pr > F	Sig
Species[1]	2	1222621.6	611310.8	1.13	0.8785	NS
Species[2]	2	721.03	369.51	1.10	0.3363	NS
Species[3]	2	0.0054	0.0027	1.74	0.1799	NS
Species[4]	2	42.31	21.15	0.34	0.7108	NS
Species[5]	2	21.79	10.89	2.76	0.0674	NS
Species[6]	2	10.7108	5.3554	1.45	0.2402	NS

a = Strength properties (units) = 1: MOR(N/mm^2), 2:MOE(N/mm^2), 3:Wmax(mmN/mm^3), 4:MCS(N/mm^2), 5:MSS(N/mm^2) and 6:CLR(N/mm).

Table 13. indicates that the three species exhibit roughly the same strength properties at same age and site. This is confirmed by the subsequent analysis of variance in Table 16 indicating that the all strength properties studied in the three species were not significantly different. This may suggest that the three species differ slightly from each other in the types of cells especially cell wall thickness, their proportions and arrangements (Zobel and van Buijtenen, 1989). Possibly attributed to similar genetical, growing conditions and silvicultural treatments. The mean values found in this experiment are comparable with those earlier reported by various authors (Table 13).

4.5.2 Strength properties variation between trees

The results of the analysis of variance performed on the data for all the six strength properties showed significant differences to exist between trees in each of *Pinus caribaea* and *Pinus oocarpa*. Whereas in *Pinus kesiya* the analysis of variance showed no significant differences in all strength properties. Graphical analyses are given in **Figures 7.1, 7.2, 7.3, 7.4, 7.5** and **7.6.**

The Duncan multiple range test showed that *P. caribaea* had the highest MSS N/mm^2 between tree variation than other strength properties and summarised as follows:

Tree no.	3	5	4	6	2	1
mean	11.06	10.46	9.28	9.01	8.67	7.96
Grouping			C	C C C C C		
	A	A A A A	A			
		B	B B B B B B			

Means with the same letter are not significantly different (P=0.05).

In *P. oocarpa* the Duncan multiple range test showed tree number six significantly different from tree number three in all strength properties. There are great potentials of genetical improvements through selection.

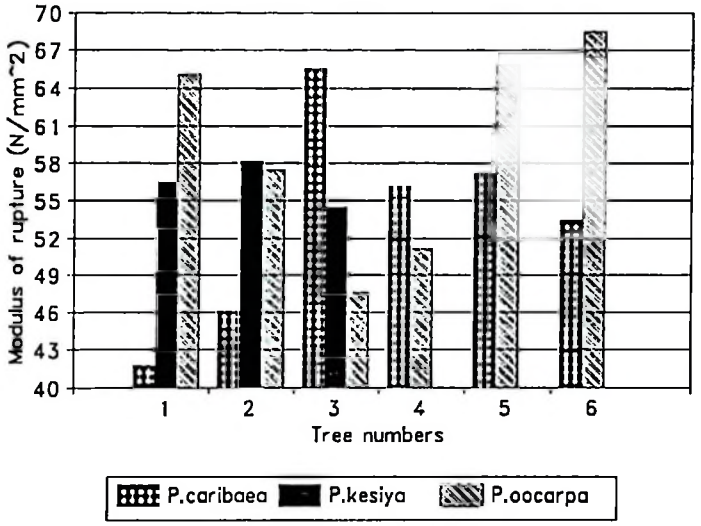

Figure 7.1. Between trees MOR variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

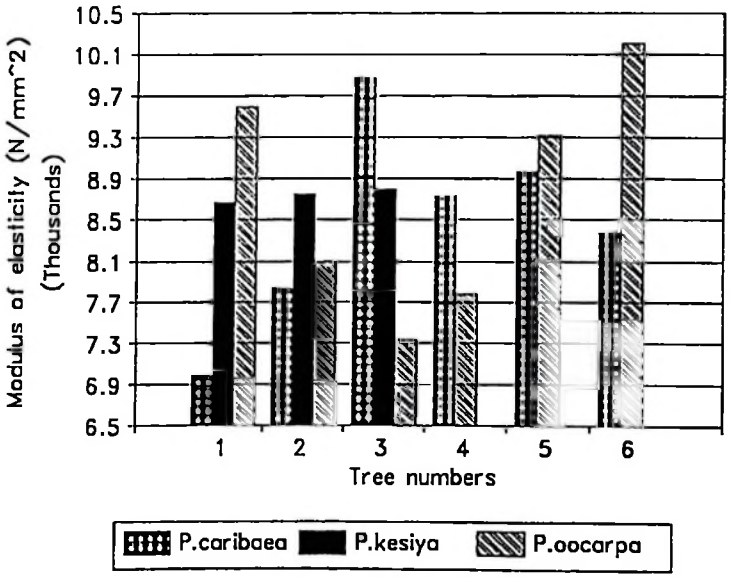

Figure 7.2. Between trees MOE variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

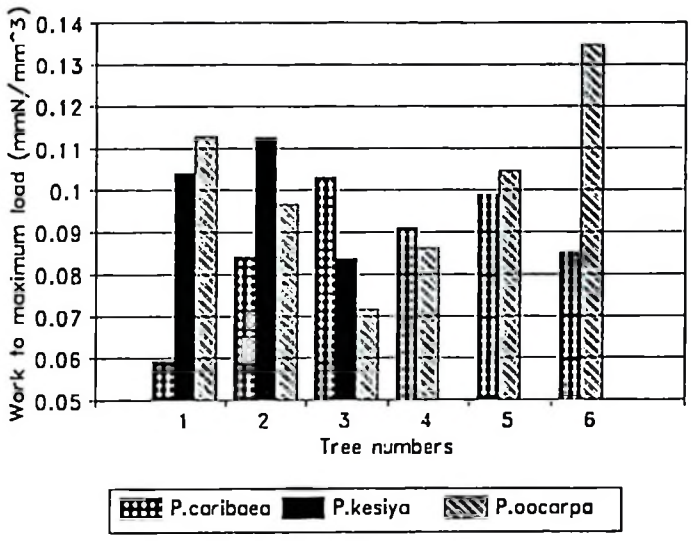

Figure 7.3. Between trees Wmax variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

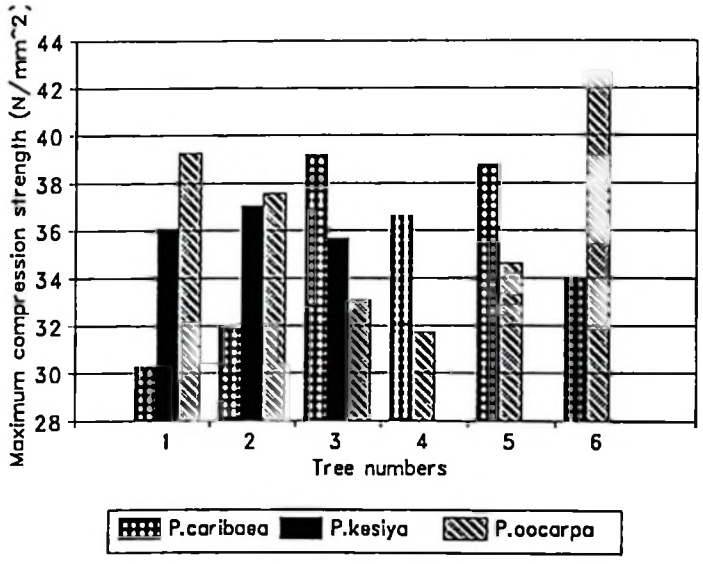

Figure 7.4. Between tress MCS variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

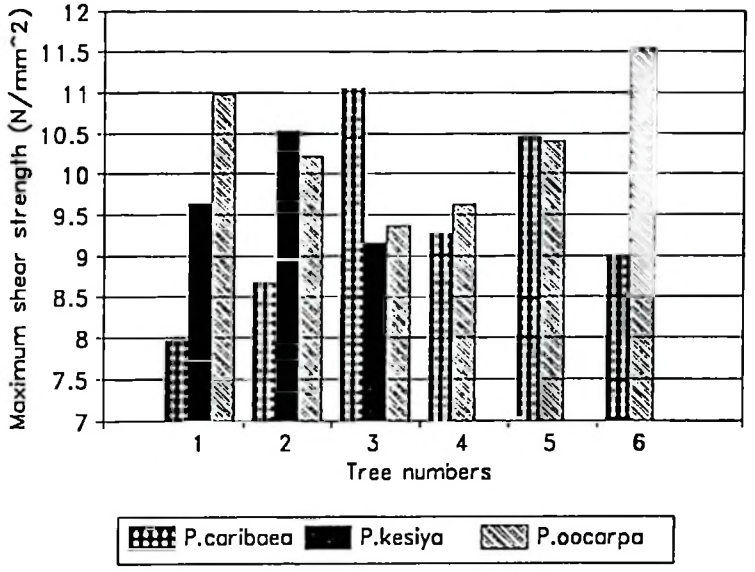

Figure 7.5. Between trees MSS variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

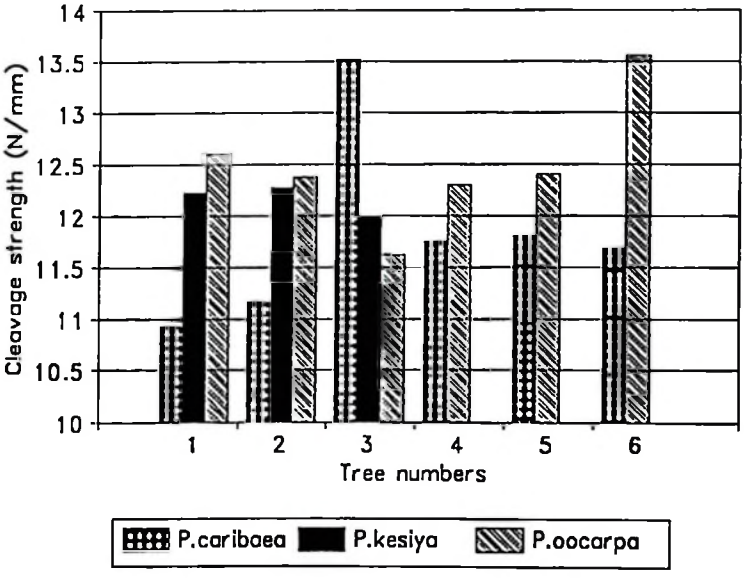

Figure 7.6. Between trees CLR variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

The results of analysis of variance for the various strength properties shows that some source of variation contributed more to the total observed variation than the others. The percentage contribution by different sources to the total variation in strength properties were revealed by examining the respective sum of squares and reported in **Table 17.**

The variation in all strength properties between trees were found to have been statistical significant in *Pinus caribaea* and *Pinus oocarpa* but insignificant in *P.kesiya* possibly attributed to a limited number of trees studied. In *P.caribaea* tree differences accounted for 13.2%, 10.0%, 10.8%, 11.8%, 19.8% and 10.9% of the total variation observed in MOR, MOE, Wmax, MCS, MSS and CLR respectively. While in *P.oocarpa*, tree differences accounted for 11.2%, 19.1%, 11.8%, 22.3%, 12.0% and 10.2% of the total variation observed in MOR, MOE, Wmax, MCS, MSS and CLR respectively. The results in Table 17 show statistical significant differences at $P < 0.05$ for strength properties variation between trees, within trees in both axial and radial positions including diameter classes in both *P.caribaea* and *Pinus oocarpa*. This huge between trees is a clear indication that there is enormous potential of increasing strength properties values through breeding programs utilizing plus trees that may contribute to strength in lumber and plywood (Zobel and van Buijtenen, 1989).

Table 17. Percentage variation in strength properties contributed by different sources of variation by species.

Species / Sources	Strength properties (percentage of variation contributed) MOR N/mm²	MOE N/mm²	Wmax mmN/mm³	MCS N/mm²	MSS N/mm²	CLR N/mm
P.caribaea						
Trees	13.2	10.0	10.8	11.8	19.8	10.9
Diameter class	10.5	7.2	6.5	7.9	10.1	6.0
Axial position	23.3	29.4	26.7	27.2	29.9	36.9
Radial position	47.1	47.4	41.6	44.4	35.0	33.6
Error	5.9	6.1	14.3	8.7	5.3	12.6
Total	100.0	100.0	100.0	100.0	100.0	100.0
P. kesiya						
Trees	0.5	0.0	6.1	0.3	7.4	0.8
Diameter class	0.5	0.0	6.1	0.3	7.4	0.8
Axial position	47.2	41.0	38.9	30.9	19.2	35.2
Radial position	44.7	53.7	42.6	63.7	47.2	58.1
Error	7.2	5.3	6.3	4.8	18.9	5.2
Total	100.0	100.0	100.0	100.0	100.0	100.0
P.oocarpa						
Trees	11.5	19.1	11.8	22.3	12.0	10.2
Diameter class	10.3	14.9	7.9	13.6	8.4	5.4
Axial position	26.8	19.0	27.2	15.6	29.5	17.4
Radial position	45.1	42.1	44.4	42.2	44.6	59.1
Error	6.4	4.9	8.7	6.3	5.2	8.0
Total	100.0	100.0	100.0	100.0	100.0	100.0

4.5.3 Strength properties variation between diameter classes

The regression analysis between strength properties and diameter at breast height (dbh) showed no significant relationship and gave the following equations in **Table 18.**

Table 18. Regression equations and R-Square coefficients for the relationship between strength properties and tree dbh.

Properties[a] at 12 % mc	Species[b]	Regression[c] equation (y = a + bD)	R-Square coefficients (R^2)
MOR	c	y = 61.65 - 3.17D	0.02
(N/mm^2)	k	y = 73.90 - 2.24D	0.02
	o	y = 73.22 - 1.89D	0.19
MOE	c	y = 9486.52 - 139.20D	0.04
(N/mm^2)	k	y = 10757.30 - 255.07D	0.14
	o	y = 10002.81 - 161.85D	0.13
Wmax	c	y = 0.11 - 0.003D	0.12
(mmN/mm^3)	k	y = 0.14 - 0.005D	0.16
	o	y = 0.134 - 0.004D	0.00
MCS	c	y = 38.74 - 0.49D	0.01
(N/mm^2)	k	y = 43.08 - 0.88D	0.04
	o	y = 40.55 - 0.51D	0.00
MSS	c	y = 10.41 - 0.13D	0.002
(N/mm^2)	k	y = 10.9 - 0.15D	0.12
	o	y = 11.73 - 0.18D	0.09
CLR	c	y = 12.97 - 0.15D	0.11
(N/mm)	k	y = 13.3 - 0.14D	0.15
	o	y = 14.16 - 0.22D	0.07

a = strength properties .
b = species c: *P.caribaea*, k: *P.kesiya* and o= *P.oocarpa*.
c = regression equations
where y = strength properties
D = diameter at breast height, dbh (cm).
a = y intercept.
b = regression coefficient.

In all strength properties variation between diameter classes represented the least contribution to the total estimated strength values variation in the three species (**Table 17**). In *P.kesiya* diameter class differences accounted for only 0.5%, 0.0%, 6.1%, 0.3%, 7.4% and 0.8% of the total variation observed in MOR, MOE, Wmax, MCS, MSS and CLR respectively.

The results of regression and correlation analysis between strength properties and diameter class are presented in **Table 18**. The relationship between all strength properties and diameter class were very weak and insignificant with very low R-Square coefficients (R^2= 0.002 to 0.19), indicating that the differences in diameter class can only explain very little about 2% to 19% of the observed variation in basic density.

4.5.4 Strength properties variation within trees

Because basic density varies substantially within trees of the three species examined, it is expected that strength properties will vary greatly within trees.

4.5.4.1 Axial strength properties variation

In the axial direction all the strength properties decreased significantly with increasing tree height levels in all the three species.

The mean strength properties values determined at the three height levels in percentage of total tree height for the three species are reported in Table 19. The results of the Duncans multiple range tests show that all the strength properties varies significantly at the three height levels in the three species under study (Appendix 3.1 to 3.6).

Table 19. Results showing mean values of strength properties at percentage tree height level from butt to top in the three species studied.

Species	Height levels	Strength properties					
		MOR N/mm^2	MOE N/mm^2	Wmax mmN/mm^3	MCS N/mm^2	MSS N/mm^2	CLR N/mm
P.caribaea							
	7.5%	64.25	10113.3	0.109	40.91	10.83	13.29
	45%	52.04	7889.3	0.080	34.54	8.99	11.20
	75%	39.42	6748.5	0.059	29.43	7.76	9.88
P. kesiya							
	7.5%	71.59	10368.0	0.130	41.62	10.69	12.93
	45%	45.00	7886.5	0.078	33.25	9.41	11.82
	75%	31.75	5674.9	0.046	25.41	7.87	10.56
P.oocarpa							
	7.5%	71.52	9877.7	0.131	40.35	11.56	13.89
	45%	55.02	8637.5	0.094	36.85	9.84	12.02
	75%	41.80	7194.4	0.067	32.16	8.56	10.49

The patterns of variation with different tree height levels in the three species are shown in **Figure 8.1, 8.2, 8.3, 8.4, 8.5** and **8.6** for MOR, MOE, Wmax, MCS, MSS and CLR respectively. It is observed that the variation at height levels 7.5% to 45% is lower than at 45% to 75% of the total tree heights.

Axial strength properties variation represented the second highest contribution to the total estimated strength values variation (**Table 16**). Axial position differences accounted for 23.3% to 36.9%, 19.2% to 47.2% and 17.4% to 29.55% the total variation observed in the various strength properties for *P. caribaea, P. kesiya and P. oocarpa* respectively.

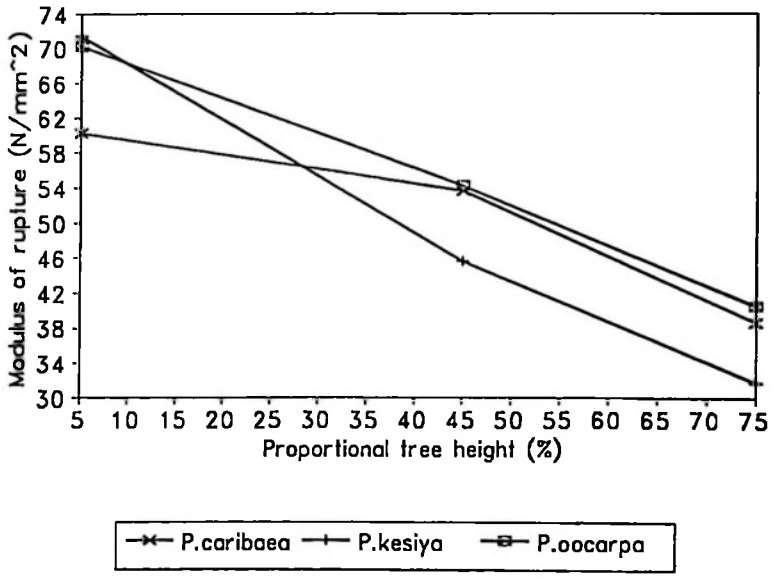

Figure 8.1. Axial MOR variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

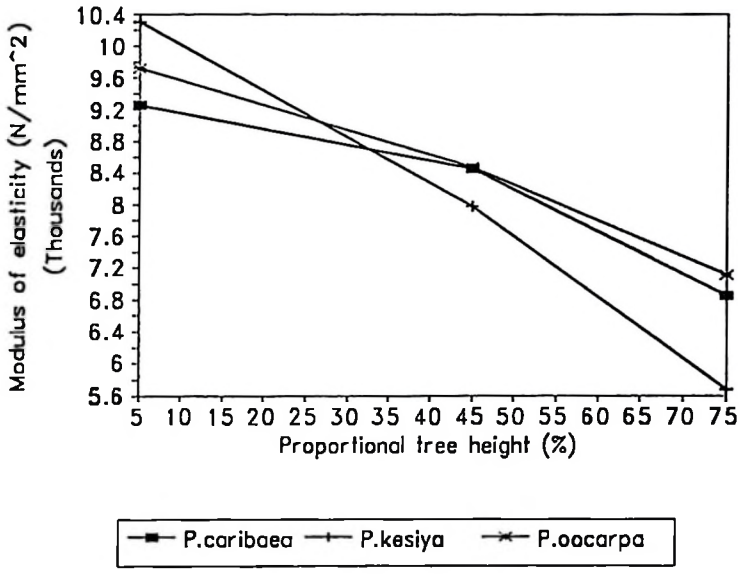

Figure 8.2. Axial MOE variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

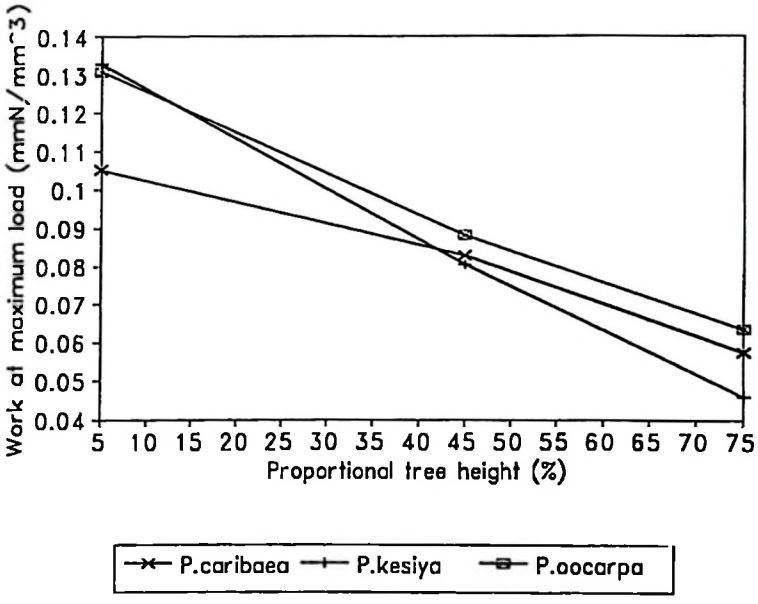

Figure 8.3. Axial Wmax variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

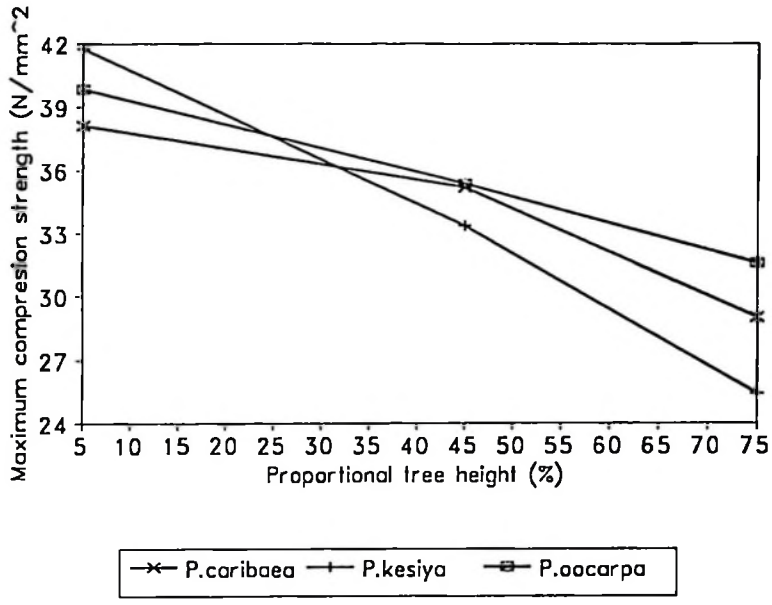

Figure 8.4. Axial MCS variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

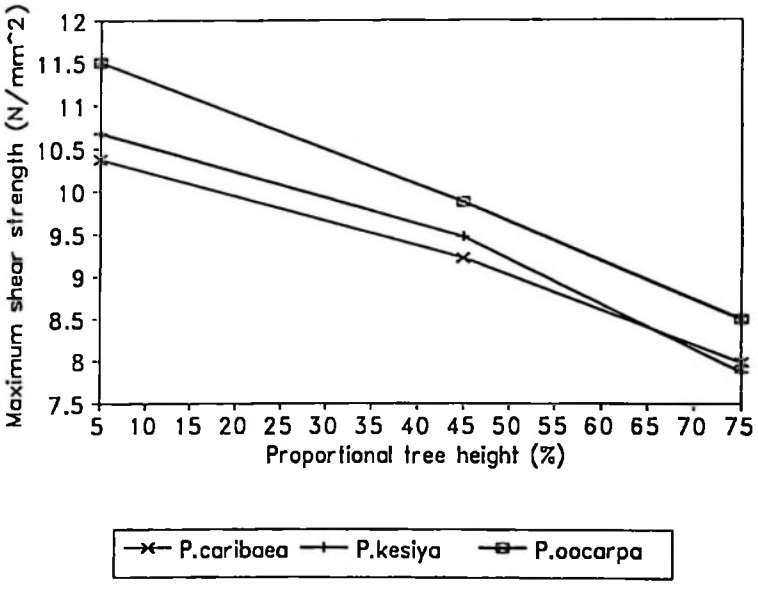

Figure 8.5. Axial MSS variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

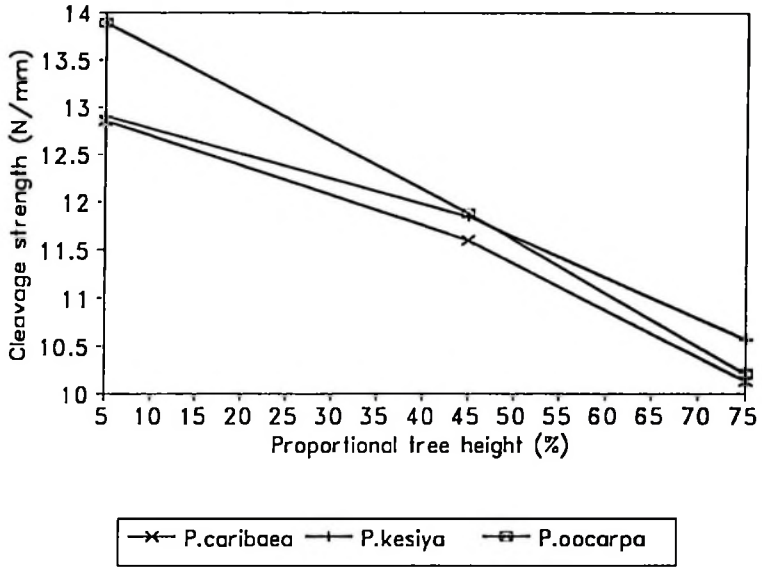

Figure 8.6. Axial CLR variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

In order to understand the relationship between strength properties and stem height levels, regression analysis was employed.

The regression analysis of strength properties at different stem height levels gave the following significant equations in Table 20.

Table 20. Regression equations and R-Square coefficients for the relationship between strength properties and tree height.

Properties[a] at 12 % mc	Species[b]	Regression[c] equation (y = a + bH)	R - Square coefficients (R^2)
MOR (N/mm^2)	c	y = 61.65 - 3.17H	- 0.94
	k	y = 73.90 - 2.24H	- 0.96
	o	y = 73.22 - 1.89H	- 0.68
MOE (N/mm^2)	c	y = 9486.52 - 239.20H	- 0.84
	k	y = 10757.30 - 255.07H	- 0.95
	o	y = 10002.81 - 161.85H	- 0.66
Wmax (mmN/mm^3)	c	y = 0.11 - 0.005H	- 0.89
	k	y = 0.14 - 0.005H	- 0.88
	o	y = 0.134 - 0.004H	- 0.84
MCS (N/mm^2)	c	y = 38.74 - 0.51H	- 0.89
	k	y = 43.08 - 0.88H	- 0.93
	o	y = 40.55 - 0.51H	- 0.79
MSS (N/mm^2)	c	y = 10.41 - 0.14H	- 0.86
	k	y = 10.9 - 0.15H	- 0.56
	o	y = 11.73 - 0.18H	- 0.63
CLR (N/mm)	c	y = 12.97 - 0.15H	- 0.85
	k	y = 13.3 - 0.14H	- 0.97
	o	y = 14.16 - 0.22H	- 0.64

a = strength properties MOR: modulus of rupture etc.
b = species c: P.caribaea, k: P.kesiya and o= P.oocarpa.
c = regression equations
where H : height in stem (m) ,
a: y intercept and
b: regression coefficient.

The results of the regression analysis gave a significant negative relationship between all strength properties and height levels in the stem at which samples were taken. The high negative R-Square coefficients implies that much of percentage decrease in strength properties can be explained by increase in height in *P.caribaea*, *P. kesiya* and *P. oocarpa* respectively. The negative regression coefficients found implies strength properties decreased with increased height.

4.5.4.2 Radial strength properties variation

Radial strength properties variations in stems from pith outwards were studied at four class levels of radius. The results indicated significant differences, thus the Duncan's multiple range tests were employed. These results are summarized in Appendix 4.1 to 4.6 for MOR, MOE, Wmax, MCS, MSS and CLR respectively. Figure 9.1,9.2, 9.3, 9.4, 9.5 and 9.6 illustrate the trend of radial strength properties variation from pith to bark with different tree height levels for *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* respectively.

The highest within trees variation was contributed by radial variation from the pith to the bark which accounted

for 47.1% 47.4% 41.6% 44.4% 35.0% 33.6% of the total variation observed in MOR, MOE, Wmax, MCS, MSS and CLR respectively for *P.caribaea*. In *P.kesiya* radial position accounted for 44.7%, 53.7%, 42.6%, 63.7%, 47.2% and 58.1% of the total variation observed in MOR, MOE, Wmax, MCS, MSS and CLR respectively. While in *P. oocarpa* radial position differences accounted for 45.1%, 42.1%, 44.4%, 42.2%, 44.6% and 59.1% of the total variation observed in MOR, MOE, Wmax, MCS, MSS and CLR respectively (**Table 16**). Similar studies have shown same trend (Ringo, 1983; Plumptre, 1984; Ishengoma and Gillah 1992).

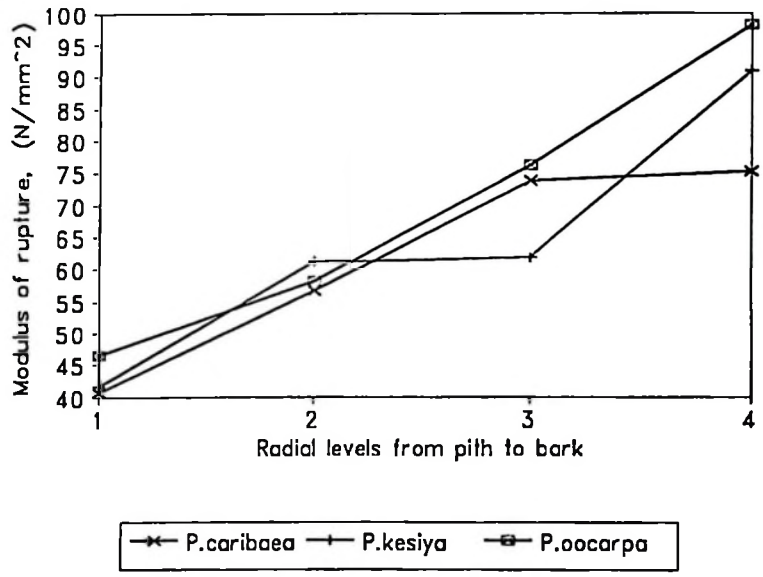

Figure 9.1. Radial MOR variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

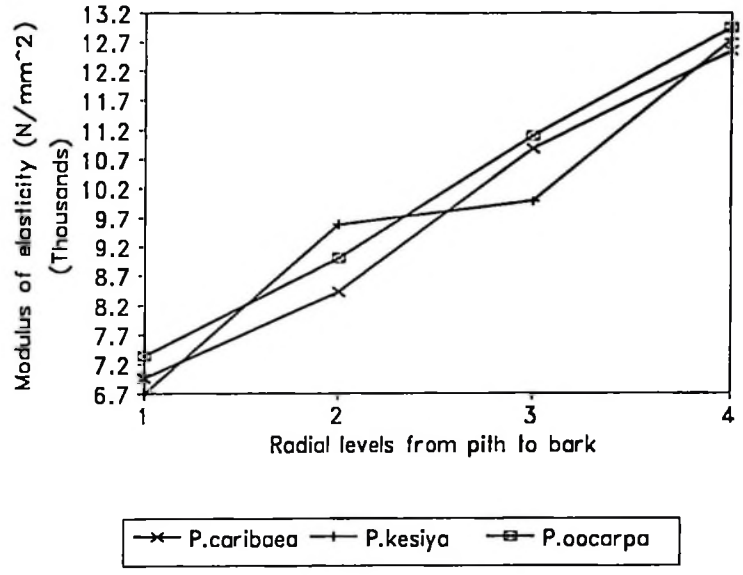

Figure 9.2. Radial MOE variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

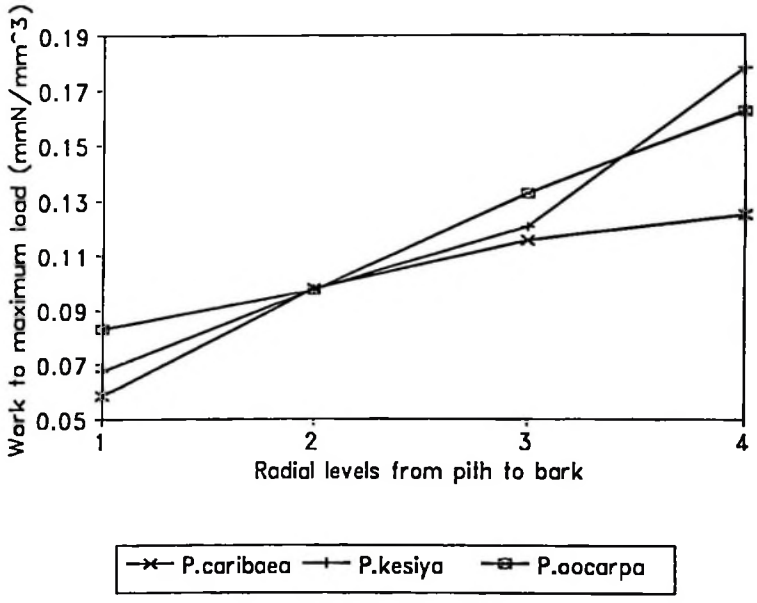

Figure 9.3. Radial Wmax variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

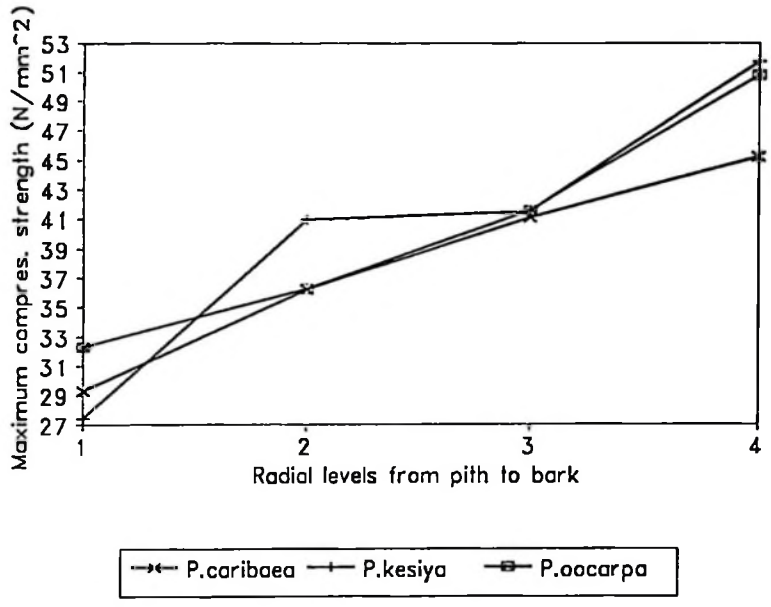

Figure 9.4. Radial MCS variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

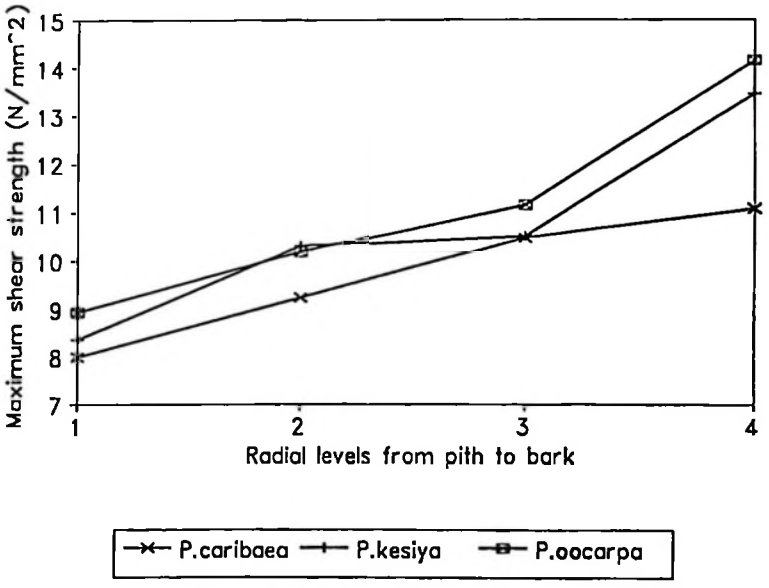

Figure 9.5 Radial MSS variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

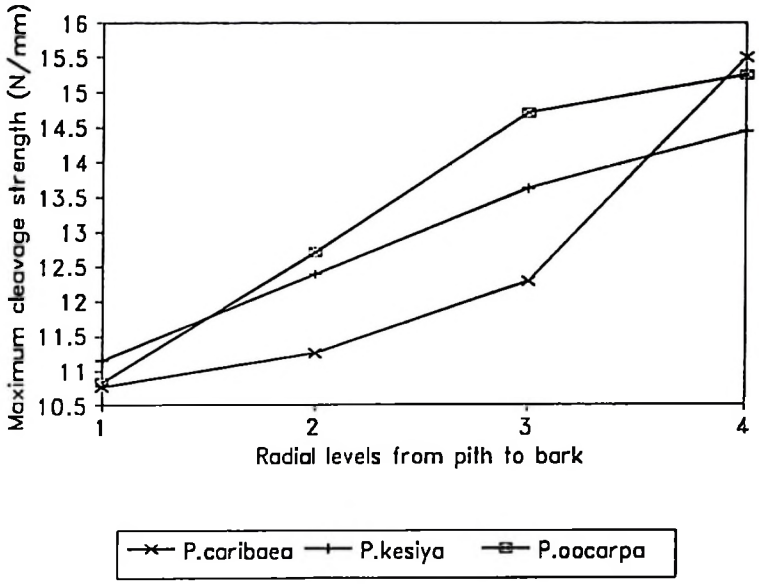

Figure 9.6 Radial CLR variation in *P.caribaea, P.kesiya* and *P.oocarpa*.

4.6 Relationship between strength properties and basic density.

The results of simple linear regression analysis showed strong significant relationships exist between all strength properties and basic densities in the three species investigated (Table 21).

Table 21. Regression and R-Square results for the relationship between strength properties and basic density for the three *Pinus* species.

Strength properties at 12 % mc	Species[ä]	Regression[ß] equation (y = a + bx)	R-Square coefficients (R^2)
MOR (N/mm^2)	c	y = 0.304x - 75.7	0.86
	k	y = 0.13x - 0.250	0.99
	o	y = 0.187x - 24.04	0.91
MOE (N/mm^2)	c	y = 0.36.73x - 7122.4	0.91
	k	y = 4.22x - 75.78	0.86
	o	y = 0.304x - 75.78	0.86
Wmax (mmN/mm^3)	c	y = 0.0006 - 0.156	0.92
	k	y = 0.0001x - 0.338	0.93
	o	y = 0.006x - 0.155	0.63
MCS (N/mm^2)	c	y = 0.14x - 23.66	0.94
	k	y = 0.048x - 15.56	0.97
	c	y = 0.096x - 5.99	0.86
MSS (N/mm^2)	c	y = 0.044x - 9.31	0.97
	k	y = 0.0.49x - 11.34	0.98
	o	y = 0.020x - 1.52	0.53
CLR (N/mm)	c	y = 0.29x - 0.446	0.66
	k	y = 0.0097x - 75.78	0.85
	o	y = 0.018x - 4.59	0.73

ä = c: P. caribaea, k: P. kesiya and o= P. oocarpa.
ß = x: basic density, y: strength values a: y intercept
b: regression coefficient.

The relations between strength properties and basic density is an important relationship (Zobel and van Buijtenen, 1980). It has long been recognised that, a side from actual strength tests, density is the most satisfactory criterion of clear wood strength (Elliott, 1970). It is a measure of the amount of wood substance in a piece of wood and a reliable indicator of its strength properties (Kollmann and Côte, 1968). Thus by influencing the basic properties including dimensional stability, basic density plays an important role in determining wood utilization (Ishengoma and Nagoda, 1991).

For all strength properties investigated, positive regression coefficients were found between strength properties and basic density. This indicates that as basic density increases, strength properties also increase from the pith outwards, that is from corewood or juvenile wood to outerwood or mature wood. The explanation is that the load a wooden member bears is determined to great extent by the amount of cell wall substance it contains per unit volume. Basic density continues to be the best prediction of timber strength since high correlation between strength and density are a common feature in timber studies (Dinwoodie, 1981). The high values of the R-Square coefficients R^2 shown in Table 21 indicates that the

relationship is very strong, and can explain much upto 99% of the observed variation.

The negative y-intercept for all strength properties shown in Table 19 indicates that there are factors which reduce strength values in the Pinus. The presence of resin could have lowered the cohesion between fibers and the grain slope to explain the reported lower values for MOR (Kollmann and Côte, 1968). Also the presence of extractives could have lowered Wmax since the specimen used were unextracted (Ishengoma and Gillah, 1992).

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Based on the six trees each of *Pinus caribaea* and *Pinus oocarpa* and three of *Pinus kesiya* examined, the results and conclusion of the research findings were as follows:

- Mean basic density with standard deviation shown in brackets of *Pinus caribaea*, *Pinus kesiya* and Pinus oocarpa was 424.33(63.30) 431.37(89.48) 444.37(66.89) kg/m^3 , and of CV 14.9%, 20.7% and 15.1%, respectively.

- The overall mean MOR in this study was 54.51, 56.31 and 60.69 N/mm^2 with a coefficient of variation of 30.20%, 36.7% and 30.5% N/mm^2 in *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* respectively.

- The overall mean MOE in this study was 8590.51, 8752.24 and 8825.37 N/mm^2 with a coefficient of variation of 25.9%, 27.1% and 22.7% N/mm^2 in *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* respectively.

- The overall mean Wmax in this study was 0.088, 0.099 and 0.101 mmN/mm^3 with a coefficient of variation of

40.2%, 46.0% and 38.8%) mmN/mm^3 in *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* respectively.

- The overall mean MCS in this study was 33.38, 33.83 and 34.66 N/mm^2 with a coefficient of variation of 22.4%, 26.7% and 18.7% N/mm^2 in *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* respectively. .

- The overall mean MSS in this study was 9.43, 9.80 and 10.37 N/mm^2 with a coefficient of variation of 21.4%, 20.6% and 18.7% N/mm^2 in *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* respectively.

- The overall mean CLR in this study was 11.79, 12.15 and 12.48 N/mm with a coefficient of variation of 17.6%, 11.4% and 16.1% N/mm in *Pinus caribaea*, *Pinus kesiya* and *Pinus oocarpa* respectively.

- The result of this study have shown no statistical significant differences in basic densities and all strength properties between the three species.

- Between trees variation in mean basic density and strength properties were statistically significant.

- No statistical significant difference in basic density and strength properties were found between large,

medium and small diameter trees (P=0.05), indicating that diameter do not influence strength.

- Based on the combined trees data, all the wood properties studied exhibited to varying extent systematic variation within the trees of the three species. Basic density and all strength properties decreased significantly in stem from stump to tree top in all the species.

- Regression analyses showed significant negative relationship between basic density and tree height. Strength properties of the three Pinus species were strongly correlated to basic density.

- Basic density and all strength properties increased significantly from pith to bark with different tree height levels in all the species.

5.2 Recommendations

The results of the research findings from this study suggest the possibilities for expanding the use of the three species investigated:

The none significant differences in basic densities and all strength properties between the three species implies that

there is little to choose between these species for all wood products as well as selection.

The statistical significant differences in basic densities and strength properties between trees indicate that seed trees with high density should be selected for improved wood quality breeding since wood strength is highly correlated with its density.

Since basic density and strength properties decreased significantly in the stem towards the top, log assortment should be done and butt logs with higher proportion of mature wood be priced higher and used for structural purposes while top logs with core wood be priced lower and used for less exacting non-structural uses.

Strength properties were strongly correlated to basic density and increased significantly from pith outwards at all heights. It is proposed that the high basic density values of mature wood should be used to determine the rotation age of the crop at Katugo, thus the clearfelling age of 25 can be maintained. Cutting patterns that avoids production of purely core lumber should be adopted. And if the inner and core wood are separated, then the inner wood can be used for non-structural applications and the outer for structural purposes, joinery and even light duty flooring.

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Appendix 1. Summary, main results showing mean values of radial basic density (kg/m^3) variation with height levels in stems and Duncan multiple range test for the three *Pinus* species.

Species mean values (kg/m^3)	Height levels		radial levels from pith to back in percentage BD17%	BD50%	BD83
P. caribaea	A	mean	380.00	416.50	509.33
		s.d.	30.66	33.29	32.53
		Duncan	C	B	A
		CV	8.07	7.99	6.39
	B	mean	355.17	392.17	481.17
		s.d.	34.37	62.53	39.90
		Duncan	C	B	A
		CV	9.68	15.95	8.29
	C	mean	345.00	376.83	437.50
		s.d.	20.30	34.96	32.53
		Duncan	C	B	A
		CV	5.88	9.28	45.62
P. kesiya	A	mean	351.67	386.00	556.00
		s.d.	31.34	31.10	26.96
		Duncan	C	B	A
		CV	8.91	8.06	4.85
	B	mean	321.67	395.67	545.00
		s.d.	13.58	10.97	8.00
		Duncan	C	B	A
		CV	4.44	2.77	1.47
	C	mean	333.67	408.67	516.67
		s.d.	16.01	23.01	24.70
		Duncan	C	B	A
		CV	4.80	5.63	4.78
P. oocarpa	A	mean	394.83	425.33	538.00
		s.d.	34.76	36.98	33.90
		Duncan	C	B	A
		CV	8.80	8.87	6.30
	B	mean	380.33	424.67	511.00
		s.d.	31.94	28.03	44.63
		Duncan	C	B	A
		CV	8.40	6.60	8.73
	C	mean	362.83	402.83	469.50
		s.d.	30.81	34.68	58.38
		Duncan	C	B	A
		CV	8.49	8.61	12.43

Means with the same letter are not significantly different (P=0.05).

Appendix 2.1 Analysis of variance for MOR showing between and within trees variation in *Pinus caribaea*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	2111.11	422.22	13.00	0.0001	*
Dclass	2	1668.81	834.40	3.44	0.0419	NS
Vposi	2	3720.31	1860.15	57.29	0.0001	*
Rposi	3	7501.88	2500.63	25.14	0.0001	*
Vposi*Rposi	6	4607.89	767.98	23.65	0.0001	*
Error	40	941.52	32.47			
Total	57	11380.84				

R-Square = 0.92

Appendix 2.2 Analysis of variance for Wmax showing between and within trees variation in *Pinus caribaea*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	0.0078	0.0016	0.70	0.0001	*
Dclass	2	0.0047	0.0023	1.94	0.1563	NS
Vposi	2	0.0192	0.0096	29.00	0.0001	*
Rposi	3	0.0299	0.0099	16.01	0.0001	*
Vposi*Rposi	6	0.0182	0.0030	9.06	0.0001	*
Error	31	0.0103	0.0003			
Total	44	0.0553				

R-Square = 0.81

Appendix 2.3 Analysis of variance for MCS showing between and within trees variation in *Pinus caribaea*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	436.22	87.24	8.38	0.0001	*
Dclass	2	293.36	146.68	2.41	0.1012	NS
Vposi	2	1076.72	538.36	51.72	0.0001	*
Rposi	3	1643.38	547.79	17.81	0.0001	*
Vposi*Rposi	8	1130.61	141.33	13.58	0.0001	*
Error	31	322.71	10.41			
Total	46	2966.28				

R-Square = 0.89

Appendix 2.4 Analysis of variance for MSS showing between and within trees variation in *Pinus caribaea*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	52.69	10.54	26.88	0.0001	*
Dclass	2	26.92	13.46	3.67	0.0328	*
Vposi	2	79.51	39.75	101.40	0.0001	*
Rposi	3	93.06	31.02	13.10	0.0001	*
Vposi*Rposi	8	60.37	7.55	19.25	0.0001	*
Error	36	14.11	0.39			
Total	51	206.69				

R-Square = 0.93

Appendix 2.5 Analysis of variance for CLR showing between and within trees variation in *Pinus caribaea*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	25.32	5.06	5.37	0.0011	*
Dclass	2	13.86	6.93	1.75	0.1861	NS
Vposi	2	85.36	42.68	45.27	0.0001	*
Rposi	3	77.78	25.93	10.23	0.0001	*
Vposi*Rposi	7	44.30	6.33	6.71	0.0001	*
Error	31	29.23	0.94			
Total	45	184.20				

R-Square = 0.84

Appendix 2.6 Analysis of variance for MOR showing between and within trees variation in *Pinus kesiya*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	2	50.87	25.44	0.33	0.7272	NS
Dclass	2	50.88	25.44	0.05	0.9480	NS
Vposi	2	5086.30	2543.15	32.89	0.0015	*
Rposi	3	4809.01	1603.00	20.73	0.0048	*
Error	10	773.29	77.33			
Total	19	10770.35				

R-Square = 0.90

Appendix 2.7 Analysis of variance for MOE showing between and within trees variation in *Pinus kesiya*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	29269156.41	5853831.28	9.95	0.0701	NS
Dclass	2	20863586.10	10431793.05	2.23	0.4074	NS
Vposi	2	85843055.83	42921527.91	72.96	0.0010	*
Rposi	3	138330192.50	46110064.20	24.70	0.0001	*
Error	30	17649612.40	588320.40			
Total	43	213008183.30				

R-Square = 0.93

Appendix 2.8 Analysis of variance for Wmax showing between and within trees variation in *Pinus kesiya*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	2	0.0033	0.0017	4.85	0.0601	NS
Dclass	2	0.0033	0.0017	0.78	0.4744	NS
Vposi	2	0.0211	0.0106	31.03	0.0001	*
Rposi	3	0.0231	0.0077	22.65	0.0001	*
Error	10	0.0034	0.0003			
Total	19	0.0542				

R-Square = 0.91

Appendix 2.9 Analysis of variance for MCS showing between and within trees variation in *Pinus kesiya*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	2	6.93	3.47	0.31	0.7386	NS
Dclass	2	6.93	3.47	0.31	0.7386	NS
Vposi	2	707.37	353.69	5.14	0.0291	*
Rposi	3	1457.45	485.82	26.82	0.0001	*
Error	10	110.88	11.09			
Total	19	2289.56				

R-Square = 0.94

Appendix 2.10 Analysis of variance for MSS showing between and within trees variation in *Pinus kesiya*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	2	7.73	3.87	2.14	0.1636	NS
Dclass	2	7.73	3.87	2.14	0.1636	NS
Vposi	2	20.17	10.09	5.59	0.0151	*
Rposi	3	49.61	16.54	9.17	0.0101	*
Error	11	19.83	1.80			
Total	20	105.07				

R-Square = 0.76

Appendix 2.11 Analysis of variance for CLR showing between and within trees variation in *Pinus kesiya*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	2	0.31	0.16	0.67	0.5378	NS
Dclass	2	0.31	0.16	0.07	0.9299	NS
Vposi	2	14.21	7.11	30.41	0.0001	*
Rposi	3	23.49	7.83	21.91	0.0002	*
Error	9	2.10	0.23			
Total	18	40.42				

R-Square = 0.94

Appendix 2.12 Analysis of variance for MOR showing between and within trees variation in *Pinus oocarpa*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	2590.51	518.10	10.76	0.0001	*
Dclass	2	2318.95	1159.48	24.08	0.0419	NS
Vposi	2	6057.88	3028.94	62.91	0.0001	*
Rposi	3	10199.22	3399.74	70.61	0.0001	*
Error	30	1444.36	48.15			
Total	42	22610.93				

R-Square = 0.90

Appendix 2.13 Analysis of variance for MOE showing between and within trees variation in *Pinus oocarpa*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	46537092.96	9307418.39	21.96	0.0001	*
Dclass	2	36365727.10	18180014.05	42.90	0.0077	*
Vposi	2	46365727.07	23182864.91	54.71	0.0001	*
Rposi	3	138330192.50	34207678.20	44.85	0.0001	*
Error	28	11864716.40	423739.90			
Total	40	244008183.30				

R-Square = 0.93

Appendix 2.14 Analysis of variance for Wmax showing between and within trees variation in *Pinus oocarpa*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	0.0187	0.0037	9.77	0.0001	*
Dclass	2	0.0130	0.0064	16.98	0.0143	*
Vposi	2	0.0310	0.0155	40.50	0.0001	*
Rposi	3	0.0279	0.0093	24.30	0.0028	*
Error	29	0.0111	0.0004			
Total	41	0.1017				

R-Square = 0.84

Appendix 2.15 Analysis of variance for MCS showing between and within trees variation in *Pinus oocarpa*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	739.45	147.89	22.49	0.0001	*
Dclass	2	451.98	225.99	5.93	0.0052	*
Vposi	2	516.80	258.40	39.30	0.0001	*
Rposi	3	1399.38	466.46	70.94	0.0001	*
Error	32	210.42	6.58			
Total	44	3318.04				

R-Square = 0.90

Appendix 2.16 Analysis of variance for MSS showing between and within trees variation in *Pinus oocarpa*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	27.72	5.54	13.50	0.0001	*
Dclass	2	19.39	9.69	23.61	0.0328	*
Vposi	2	68.03	34.01	82.83	0.0001	*
Rposi	3	102.75	34.25	83.40	0.0001	*
Error	31	12.73	0.41			
Total	43	230.61				

R-Square = 0.92

Appendix 2.17 Analysis of variance for CLR showing between and within trees variation in *Pinus oocarpa*.

Source	DF	Sum of squares	Mean square	F value	Pr > F	Sig
Trees	5	19.25	3.85	7.90	0.0001	*
Dclass	2	10.14	5.07	10.40	0.2916	NS
Vposi	2	32.88	16.44	33.73	0.0001	*
Rposi	3	111.73	37.24	76.41	0.0001	*
Error	31	15.11	0.49			
Total	43	189.11				

R-Square = 0.92

Appendix 3.1 Summary, results showing mean values in MOR with height in trees with Duncan,s multiple range tests for the three species.

Species mean values (N/mm^2)		height levels from butt to top percentage 7.5%	45 %	75 %
P. caribaea	mean	64.25	52.04	39.42
	s.d.	17.35	10.59	9.57
	Duncan	A	B	C
	CV	27.00	20.34	24.28
P. kesiya	mean	71.59	45.00	31.75
	s.d.	16.07	11.01	4.49
	Duncan	A	B	C
	CV	22.45	24.47	14.13
P. oocarpa	mean	71.52	55.02	41.80
	s.d.	17.72	10.75	8.95
	Duncan	A	B	C
	CV	24.77	19.54	21.41

Means with the same letter are not significantly different (P=0.05).

Appendix 3.2 Summary, results showing mean values in MOE with height in trees with Duncan,s multiple range tests for the three species.

Species mean values (N/mm^2)		height levels from butt to top percentage 7.5%	45 %	75 %
P. caribaea	mean	10113.25	7889.28	6748.50
	s.d.	2195.05	1440.60	1147.13
	Duncan	A	B	C
	CV	21.70	18.26	17.00
P. kesiya	mean	10368.00	7886.52	5674.93
	s.d.	2040.18	1430.67	317.30
	Duncan	A	B	C
	CV	19.68	18.14	5.59
P. oocarpa	mean	9877.74	8637.50	7194.13
	s.d.	1951.69	1760.93	1179.14
	Duncan	A	B	C
	CV	19.76	20.39	16.39

Means with the same letter are not significantly different (P=0.05).

Appendix 3.3 Summary, results showing mean values in Wmax with height in trees with Duncan,s multiple range tests for the three species.

Species mean values (mmN/mm^3)		height levels from butt to top percentage 7.5%	45 %	75 %
P. caribaea	mean	0.109	0.080	0.059
	s.d.	0.035	0.027	0.03
	Duncan	A	B	C
	CV	29.40	33.03	51.16
P. kesiya	mean	0.130	0.078	0.046
	s.d.	0.040	0.026	0.007
	Duncan	A	B	C
	CV	30.66	33.41	15.68
P. oocarpa	mean	0.131	0.094	0.067
	s.d.	0.038	0.029	0.014
	Duncan	A	B	C
	CV	29.35	31.19	20.92

Means with the same letter are not significantly different (P=0.05).

Appendix 3.4 Summary, results showing mean values in MCS with height in trees with Duncan,s multiple range tests for the three species.

Species mean values (N/mm^2)		height levels from butt to top percentage 7.5%	45 %	75 %
P. caribaea	mean	40.91	34.54	29.43
	s.d.	7.78	6.65	4.34
	Duncan	A	B	C
	CV	19.01	19.24	14.73
P. kesiya	mean	41.62	33.25	25.41
	s.d.	9.57	6.56	0.20
	Duncan	A	B	C
	CV	22.99	19.74	0.80
P. oocarpa	mean	40.35	36.85	32.16
	s.d.	6.46	6.63	4.37
	Duncan	A	B	C
	CV	16.01	18.00	13.59

Means with the same letter are not significantly different (P=0.05).

Appendix 3.5 Summary, results showing mean values in MSS with height in trees with Duncan,s multiple range tests for the three species.

Species mean values (N/mm^2)		height levels from butt to top percentage 7.5%	45 %	75 %
P. caribaea	mean	10.83	8.99	7.76
	s.d.	1.98	1.40	1.08
	Duncan	A	B	C
	CV	18.26	15.60	13.92
P. kesiya	mean	10.69	9.41	7.87
	s.d.	2.03	1.67	1.50
	Duncan	A	B	C
	CV	18.96	17.77	19.08
P. oocarpa	mean	11.56	9.84	8.56
	s.d.	1.91	1.32	0.93
	Duncan	A	B	C
	CV	16.53	13.38	10.83

Means with the same letter are not significantly different (P=0.05).

Appendix 3.6 Summary, results showing mean values in CLR with height in trees with Duncan,s multiple range tests for the three species.

Species mean values (N/mm)		height levels from butt to top percentage 7.5%	45 %	75 %
P. caribaea	mean	13.29	11.20	9.88
	s.d.	1.80	1.05	1.29
	Duncan	A	B	C
	CV	13.51	9.42	13.02
P. kesiya	mean	12.93	11.82	10.56
	s.d.	1.37	0.81	0.92
	Duncan	A	B	C
	CV	10.56	6.82	8.73
P. oocarpa	mean	13.89	12.02	10.49
	s.d.	1.43	1.49	1.53
	Duncan	A	B	C
	CV	10.31	12.42	14.58

Means with the same letter are not significantly different (P=0.05).

Appendix 4.1 Summary, results showing mean values of radial variations for MOR (N/mm^2) in stems of different species.

Species (units)		Radial levels from pith to bark mean value at 12 % mc 1	2	3		4
P.caribaea	mean	40.66	58.03	73.88		75.26
	s.d.	7.18	8.70	16.56		4.72
	Duncan	C	B	A	A	A
	CV	17.66	14.99	22.41		6.27
P.kesiya	mean	41.71	61.26	67.13		90.90
	s.d.	11.88	16.62	20.03		3.01
	Duncan	C	B	A	A	A
	CV	28.48	27.14	29.83		4.68
P.oocarpa	mean	46.54	59.54	77.87		98.21
	s.d.	9.72	10.86	11.31		9.41
	Duncan	C	B	A	A	A
	CV	20.90	18.24	14.53		9.58

Means with the same letter are not significantly different (P=0.05).

Appendix 4.2 Summary, results showing mean values of radial variations for MOE (N/mm^2) in stems of different species.

Species (units)		Radial levels from pith to bark mean value at 12 % mc 1	2	3	4
P.caribaea	mean	6976.8	8563.9	11094.2	12572.5
	s.d.	1139.2	1276.8	2092.3	973.6
	Duncan	C	B	A	A
	CV	16.3	14.9	18.8	7.7
Pinus kesiya	mean	6727.8	9608.3	10018.3	12761.8
	s.d.	1047.7	1835.0	1509.0	451.3
	Duncan	C	B	A	A
	CV	15.6	19.1	15.1	3.5
Pinus oocarpa	mean	7361.4	9143.1	10988.5	12969.9
	s.d.	1356.8	1331.1	893.3	361.5
	Duncan	C	B	A	A
	CV	18.4	14.6	8.2	2.8

Means with the same letter are not significantly different (P=0.05).

Appendix 4.3 Summary, results showing mean values of radial variations for Wmax (mmN/mm^3) in stems of different species.

Species (units)		Radial levels from pith to bark mean value at 12 % mc 1	2	3	4
P.caribaea	mean	0.058	0.100	0.119	0.125
	s.d.	0.02	0.03	0.03	0.012
	Duncan	C	B	A A	A
	CV	38.29	27.25	23.82	9.83
P.kesiya	mean	0.068	0.116	0.106	0.178
	s.d.	0.026	0.040	0.035	0.02
	Duncan	C	B	A A	A
	CV	38.57	34.48	32.58	4.68
P.oocarpa	mean	0.083	0.100	0.138	0.166
	s.d.	0.028	0.035	0.037	0.030
	Duncan	C	B	A A	A
	CV	33.42	35.05	26.84	18.07

Means with the same letter are not significantly different (P=0.05).

Appendix 4.4 Summary, results showing mean values of radial variations for MCS (N/mm^2) in stems of different species.

Species (units)		Radial levels from pith to bark mean value at 12 % mc 1	2	3		4
P.caribaea	mean	29.29	36.73	42.38		46.72
	s.d.	4.06	6.36	6.89		4.32
	Duncan	C	B	A	A	A
	CV	13.87	17.32	16.25		9.24
P.kesiya	mean	27.40	40.99	43.08		51.71
	s.d.	2.34	6.65	5.38		2.43
	Duncan	C	B	A	A	A
	CV	8.55	16.21	12.49		4.69
P.oocarpa	mean	8.92	10.32	11.79		14.13
	s.d.	0.98	1.13	1.67		1.75
	Duncan	C	B	A	A	A
	CV	10.97	10.96	14.16		12.36

Means with the same letter are not significantly different (P=0.05).

Appendix 4.5 Summary, results showing mean values of radial variations for MSS (N/mm^2) in stems of different species.

Species (units)		Radial levels from pith to bark mean value at 12 % mc 1	2	3		4
P.caribaea	mean	7.99	9.23	11.08		11.80
	s.d.	1.17	1.67	1.80		1.55
	Duncan	C	B	A	A	A
	CV	14.58	18.14	16.24		13.15
P.kesiya	mean	8.33	10.30	10.53		13.45
	s.d.	1.27	1.91	0.38		0.49
	Duncan	C	B	A	A	A
	CV	15.27	18.50	3.59		3.68
P.oocarpa	mean	8.92	10.32	11.79		14.13
	s.d.	0.98	1.13	1.67		1.75
	Duncan	C	B	A	A	A
	CV	10.97	10.96	14.16		12.36

Means with the same letter are not significantly different (P=0.05).

Appendix 4.6 Summary, results showing mean values of radial variations for CLR (N/mm) in stems of different species.

Species (units)		Radial levels from pith to bark mean value at 12 % mc 1	2	3		4
P.caribaea	mean	10.77	11.49	13.13		15.50
	s.d.	1.36	1.83	1.43		2.05
	Duncan	C	B	A	A	A
	CV	12.62	15.93	10.90		13.20
P.kesiya	mean	11.15	12.40	13.87		14.44
	s.d.	0.85	0.79	1.00		.
	Duncan	C	B	A	A	A
	CV	7.60	6.34	12.49		.
P.oocarpa	mean	10.83	12.77	14.88		15.24
	s.d.	1.34	1.39	0.81		0.52
	Duncan	C	B	A	A	A
	CV	12.37	10.86	5.44		3.38

Means with the same letter are not significantly different (P=0.05).