Genetic Parameters and Improvement Strategies of Wood Properties and Growth Traits of Pinus kesiya Planted in Malawi

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Genetic Parameters and Improvement Strategies of Wood Properties and Growth Traits of *Pinus kesiya* Planted in Malawi

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Genetic Parameters and Improvement Strategies of Wood Properties and Growth Traits of *Pinus kesiya* Planted in Malawi

By

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Doctor of Philosophy

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CHAPTER 1

General Introduction

1.1 Species description

Pinus kesiya Royle ex Gordon is a softwood tree species of the family Pinaceae. It is naturally distributed in the Himalaya region of Asia, which includes: China, India, Laos, Myanmar, Philippines, Thailand, Tibet and Vietnam (Figure 1.1). Its common name "Khasi pine" is from the Khasi hills in India. It grows well at altitudes from 300 to 2700 m above the sea level with mean annual precipitation of between 700 and 1800 mm and mean annual temperature of 14 – 23 ^{0}C (Missio et al. 2005, Nyunai 2008). Within its native range it attains a height of 45 m and diameters of over 100 cm. It grows on a range of soil types, but prefers well-drained, neutral to acid soils (Gogoi et al. 2014).

The wood of *P. kesiya* has a high wood density, is low in extractives and is suitable for a number of wood products. It provides high class value of timber. The wood saws easily and can be worked to a smooth surface with all tools. The wood is essentially used for paneling, construction, cabinet work, joinery and sometimes poles. It is also suitable for ship and boat building, agricultural implements, turnery, veneer, plywood and railway sleepers (Eerikainen 2003, Nyunai 2008). In addition, oleoresin of good quality is tapped from the trees. The oleoresin is distilled to give turpentine and rosin. Turpentine is used in the paint industry, and rosin in the production of paper, soap and glue (Nyunai 2008). These attributes and its fast growth make *P. kesiya* the most important and widely exotic planted softwood in many tropical Africa countries including Malawi (Figure 1.1). Its success as an exotic is also attributed to its wide adaptability. Once established the tree is fairly resistant to drought and frost (Missio et al. 2005).

Figure 1.1 Distribution of *Pinus kesiya* in native countries and in countries where it is established as an exotic (Adapted from Nyunai 2008 and Orwa et al. 2009)

1.2 Tree improvement

Tree improvement is the process of improving the genetic quality of a tree species (Zobel and Talbert 1984). The aim of tree improvement is to maximise its: adaptability of the species to potential planting sites; growth rate; resistance to pests and diseases; and the quality of the end use of the trees. In addition, the objectives of any tree improvement programme should be defined in accordance with the immediate as well as the short term and long term requirements of the national and regional afforestation programmes (Li et al. 1999, Barner et al. 1992).

Zobel and Jett (1995) state that wood improvement is most needed in pines that are grown as exotics in tropics and sub-tropics. Plantations of genetically improved forest trees are critical to maintaining sustainable wood supplies. Investment in genetic improvement has increased forest productivity and enhanced timber supply. Forest genetics has made significant contributions to forest productivity and plantation management throughout the world in the past 70 years. Li et al. (1999) and Zobel and Jett (1995) reported that productivity improvement from forest genetics has helped to provide a reliable, ecologically sustainable, and economically affordable supply of wood. However, in most cases, very little or nothing is known about wood properties of pines species when they are grown as exotics in plantations.

Pinus tree species (including *P. kesiya*) were first introduced in Malawi in 1935 with seedlings from Zimbabwe. Then large planting was done with seeds from South Africa and Zimbabwe in 1950’s. Currently, the government owns 73,000 hectares of timber plantations, most of which are covered in pine (68,000 hectares). The largest single unit is the 53,000 hectare Viphya plantations. Out of the 68,000 hectares, about 60% is planted with *Pinus patula*, 32% with *Pinus kesiya* and 8% with other pine species (Luhanga 2009, Kafakoma and Mataya 2009, AAS 2012). During 2008/09 harvesting season, about 150 hectares was harvested for *Pinus kesiya* in Viphya plantations and about 35,000 m^3 of round wood was harvested. Timber produced was about 16,000 m^3 (Kafakoma and Mataya 2009).

Tree improvement programmes for forestry species (including *P. kesiya*) started in Malawi during the 1970's and were conducted by Forestry Research Institute of Malawi (FRIM). The main selection criteria of these early breeding programmes were restricted to stem volume and stem form (FRIM 1989).

In the first generation of breeding, volume improvements of between 12 and 25% have been achieved in the tree improvement programme of *P. kesiya* in Malawi (Missanjo et al. 2013). Selection of the second plus trees is ongoing but to date there has been no information on wood properties of *P. kesiya* in Malawi. To develop an appropriate tree breeding strategy and wood utilization, information on both wood properties and growth traits must be known (Zobel and Talbert 1984). This information would also help to monitor genetic progress. In addition, there has been an increase in building construction in Malawi. This has also increased the need to improve both productivity and wood quality traits of this species. It is therefore critically important to include wood quality traits in tree selection programmes of *P. kesiya* to ensure future wood suppliers have the appropriate mechanical properties for structural applications and other end uses.

1.3 Study objectives

1.3.1 General objective

The overall objective of this study was to assess wood properties and growth traits important for sawn timber production of *P. kesiya* planted in Malawi. The results should provide information to wood industry experts on the potential use and sustainable use of the species when processing logs for timber. The results should also provide tree breeders with relevant information to establish and refine breeding and deployment programmes of the species. Finally, the results should provide foundation for machine grading of *P. kesiya* timber in Malawi.

1.3.2 Specific objectives

I To determine the radiation variation in tracheid length and growth ring width.

II To demarcate the boundary between juvenile wood and mature wood.

III To estimate wood density and mechanical properties (modulus of elasticity-MoE and modulus of rupture-MoR).

IV To estimate genetic parameters for wood quality traits (wood density, MoE and MoR) and growth traits (diameter at breast height-DBH, tree height and volume).

V To develop a multi-trait selection index for simultaneous improvement of both wood properties and growth traits.

1.4 Thesis structure

The thesis is organised into seven chapters. Figure 1.2 shows the research framework and outlines the interrelationships of the chapters. The scientific articles that compose the core of this thesis (four chapters) were published in international journals. The papers are reprinted in this thesis as chapters with the kind permission of the publishers.

Chapter 3 - Missanjo E. & Matsumura J. (2016). Radial variation in tracheid length and growth ring width of *Pinus kesiya* Royle ex Gordon in Malawi. *International Journal of Research in Agriculture and Forestry*, 3(1), 13 – 21.

Chapter 4 - Missanjo E. & Matsumura J. (2016). Wood density and mechanical properties of *Pinus kesiya* Royle ex Gordon in Malawi. *Forests*, 7(7), 135; doi:10.3390/f7070135

Chapter 5 - Missanjo E. & Matsumura J. (2016). Genetic improvement of wood properties in *Pinus kesiya* Royle ex Gordon for sawn timber production in Malawi. *Forests,* 7(11), 253; doi:10.3390/f7110135

Chapter 6 - Missanjo E. & Matsumura J. (2017). Multiple trait selection index for simultaneous improvement of wood properties and growth traits in *Pinus kesiya* Royle ex Gordon in Malawi. *Forests,* 8(4), 96; doi:10.3390/f8040096

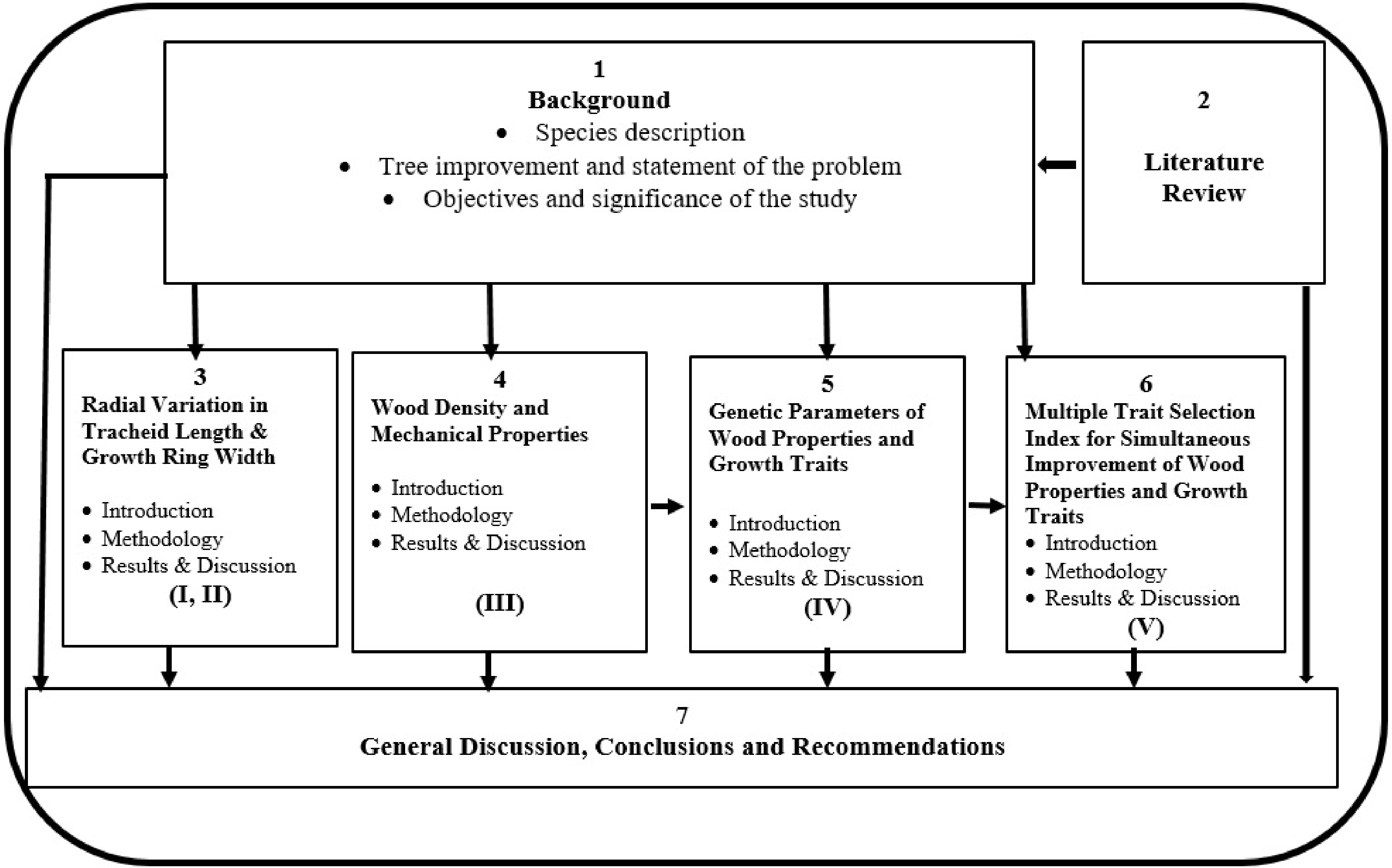

Figure 1.2 Research Framework: The Arabic numerals in each box corresponds to a thesis chapter, while the Roman numerals corresponds to a specific objective achieved in the chapter

CHAPTER 2

Literature Review

2.1 Introduction

This chapter provides an overview of radial variation in tracheid length and growth ring width of fast grown plantation trees for effective utilization of wood. Further, it outlines the demarcation between juvenile wood and mature wood in conifer species. The chapter also provides a review of relevant research on wood density and mechanical properties of some coniferous species. The review also discusses the genetic parameters in wood properties and growth traits of some fast grown plantation tree species important for tree improvement programmes. Finally, the review discusses the development and use of selection indexes in tree breeding programmes.

2.2 Variation in tracheid length and growth ring width

Variation in wood is a common phenomenon. Eliciting information on the pattern and extent of variation in tracheid length and growth ring width is crucial to knowing the end use of wood species. This to a larger extent helps in the efficient and sustainable utilization of wood (Adenaiya and Ogunsanwo 2016). The variability in tracheid length and growth ring width has profound influence on the properties of wood (Dinwoodie 1961, Kiaei 2011). Tracheid length and growth ring width are among the most important wood quality attributes for pulp (Beaulieu 2003) and solid wood (Erickson and Harrison 1974, Mvolo et al. 2015a). Tracheid length and growth ring width vary with and within species (Lindström 1997). Tracheids represent over 95% of wood volume in Pinus species (Harris 1991). Thinning (Herman et al. 1998, Mvolo et al 2015a) and spacing (Lasserre et al. 2009) are known to favor an increase of growth ring width. When stands are heavily thinned, a negative influence can be registered on tracheid length (Erickson and Harrison 1974). This is an indication that information on radial variation pattern in tracheid length and growth ring width can facilitate tree growth and wood quality in forest management and wood utilization (Kiaei 2011, Mvolo 2015a, 2015b).

2.2.1 Tracheid length

Tracheids are the principal element that is responsible for the strength of the wood (Zobel and van Buijtenen 1989) and tracheid length is one of the quality parameters for pulp (Bisset et al. 1951). It has been extensively studied in relation to tree age and within tree position (Fabisiak and Moliński 2002, Buksnowitz et al. 2010). Fabisiak et al. (2014) reported a rapid increase of tracheid length from pith to bark. The increases in tracheid length from pith to bark are due to the increasing age of the tree with a resulting effect on cell wall development (Zobel and van Buijtenen 1989). The radial pattern of variation for tracheid length shows a marked transition from juvenile to mature wood. A similar conclusion was drawn in other studies (Dinwoodie 1961, Bendtsen and Senft 1986, Zobel and van Buijtenen 1989, Saranpää 1994, Moliński et al. 2007).

Radial variation in tracheid length of *Picea abies* L. grown in the mountain of Slovakia were studied (Fabisiak et al. 2014). The results showed that from pith outward tracheid length increased with the increase of growth rings, reached a maximum in a certain year and then decrease or level off. These results are comparable to those reported by other researchers on *Pinus sylvestris* L. (Atmer and Thornqvist, 1982) and on *Picea sitchensis* Carr. (Dinwoodie 1963). Likewise, Bisset et al. (1951) reported an increase in tracheid length from pith to bark in *Pinus pinaster* Sol. and Herman et al. (1998) found a similar variation pattern in *Picea abies* (L.) Karst.

A literature review conducted by Panshin and de Zeeuw (1980) on longitudinal and radial variations in wood anatomical properties reported three patterns in tracheid length: (1) a rapid increase followed by constant length from pith to bark; (2) a smooth and continuous increase from pith to bark; and (3) an increase from pith to bark up to a maximum, followed by a smooth decrease.

Makinen and Hynynen (2014) studied the radial variation in tracheid length of thinned and unthinned planted trees of *Pinus sylvestris* L. in southern Finland. They reported no major detrimental differences in tracheid length between thinned and unthinned trees. However, tracheid length increased with increase in age both in thinned and unthinned trees, generally an increase from innerwood to outerwood. Similar results had been reported in the wood of planted *Pinus radiata* (Evans et al. 1995) and *Pinus sylvestris* L. (Havino et al. 2009). In literature, there is a general increase of tracheid length due to the length increase of cambial initials with increasing cambial age for teak wood (Jaakkola et al. 2005, 2007, Rautiainen and Alen 2009, Makinen and Hynynen 2012). Conversely, radial variation in tracheid length of *Pinus sylvestris* L. from drained peatland stands in central Finland were investigated and as a result significant differences in tracheid length were observed between core and outerwood (Makinen et al. 2015). Variation within tree of wood anatomical properties of *Picea mariana* in Ontario, Canada were also examined (Yang and Hazenberg 1994). Their results indicated an initial rapid and then gentle increase in tracheid length from pith to outwards.

Significant differences among anatomical characteristics (including tracheid length) of wood have been recognized in radial direction. The variations in the structure of wood have a significant impact on the wood quality and yield of pulp and paper products, and on the strength and utility of solid wood products. Therefore, information of radial variation in wood properties is important. Radial variation directly influences wood homogeneity, and its study may provide a more rational use of material (Erickson and Harrison 1974, Carlquist 1988).

2.2.2 Growth ring width

Growth ring is a layer of wood formed in plant during a single period of growth. Growth rings in pine species are visible as concentric circles of varying width when a tree is cut crosswise. They represent layers of cells produced by vascular cambium. Most growth rings reflect a full year's growth. Growth rings are often identified by the colour contrast between the light-coloured earlywood and the dark-coloured latewood (Figure 2.1). Earlywood is part of the wood in a growth ring of a tree that is produced earlier in the growing season. The cells of earlywood are larger and have thinner walls than those produced later in the growing season. On the other hand, latewood is part of the wood in a growth ring of a tree that is produced later in the growing season. The cells of latewood are smaller and have thicker cell walls than those produced earlier in the season (Panshin and Zeeuw 1980, Larson 1994).

Growth ring width is one of the most important variables for studying tree growth and climate influence (Tian et al. 2009), and growth rate helps to clarify forest dynamics, an important factor in the sustainable management of forest resources (Priya and Bhat 1997, Pant 2003, Sousa et al. 2012). Growth ring width are often considered as a useful predictor of some wood properties (for example, density and mechanical strength) (Tirak-Hizal and Erdin 2016).

Radial variation in growth ring width of thinned and unthinned planted trees of *Pinus sylvestris* L. in southern Finland were investigated (Makinen and Hynynen 2014). They reported that thinning considerably enhanced growth ring width. However, growth ring width decreased with cambial age in both thinned and unthinned stands. Furthermore, in unthinned stands they observed no uniformity in growth ring width among individual trees. Uniformity of growth rate has an effect on wood structure and density variation both within and between growth rings.

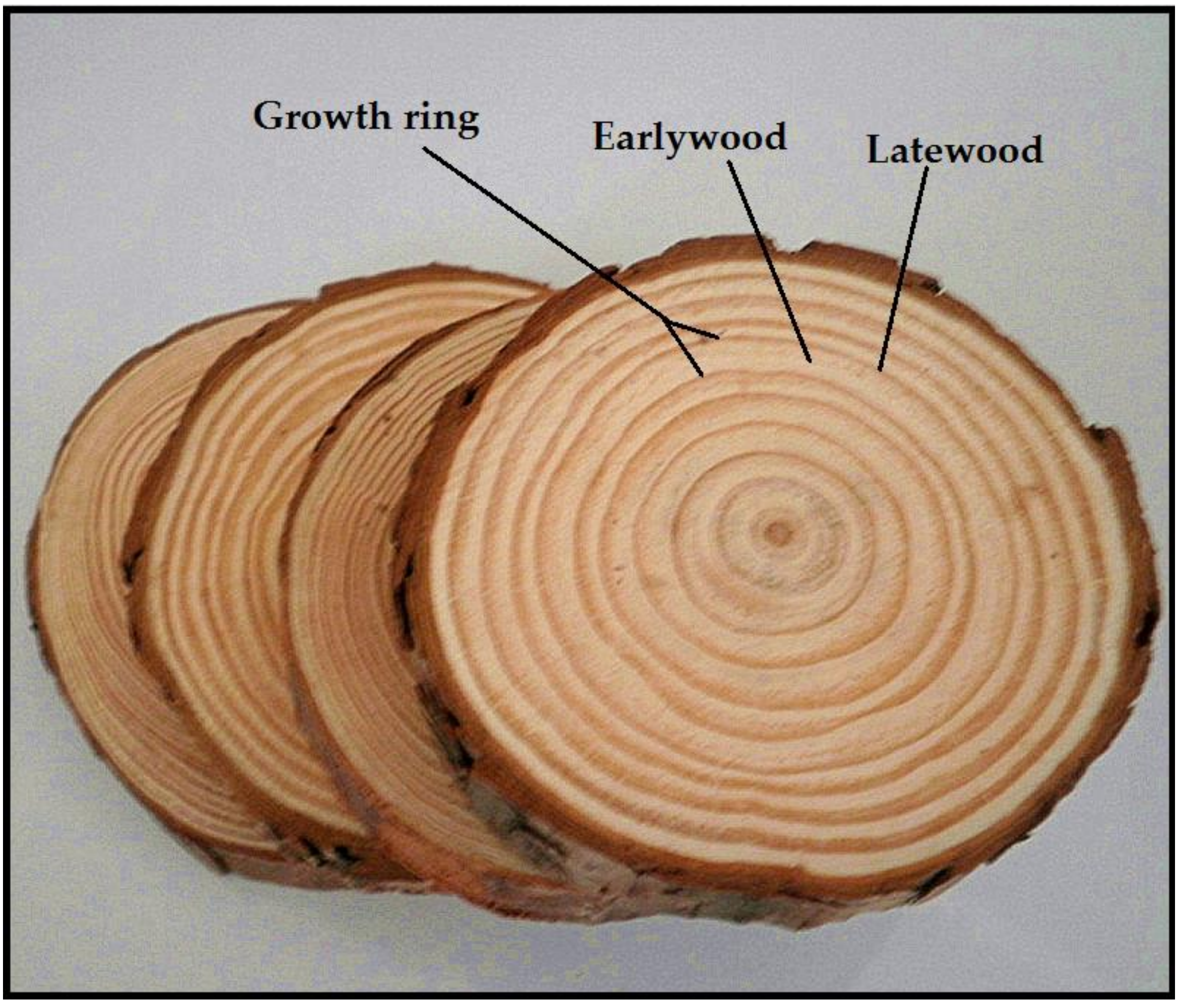

Figure 2.1 Growth ring (earlywood and latewood) of a pine tree (Adapted from Rollinson 2012)

Tirak-Hizal and Erdin (2016) explained that lack of uniformity represents one of the greatest wood quality problems facing all wood-using industries. Uniform wood is desirable not only for manufacture of fiber products but for solid wood products as well. Within-ring density variation often presents a problem when painted and exposed to the elements. Such wood is also difficult to machine to a smooth condition or to peel on a veneer lathe because of differing hardness between earlywood and latewood bands (Shmulsky and Jones 2011).

Radial variation in growth ring width of *P. mariana* at different initial planting spacing were studied (Yang and Hazenberg 1994). They reported a wider growth ring width in wider planting spacing. There is acceleration of growth for widely spaced trees than crowded trees, because widely spaced trees do not compete for growth elements such as nutrients, water and sunlight, hence they tend to have wider growth ring width (Zhu et al. 2000).

Campelo et al. (2006) studied growth ring width of *P. pinea* in dry Mediterranean area in Portugal. They reported that radial growth of *P. pinea* was strongly correlated with precipitation. A lower mean growth ring width was observed in the inland area compared to the coastal area. This can be attributed to the more favourable climatic conditions in the coastal area and the lower water holding capacity of the soils in the inland area. Furthermore, trees in the inland area, growing under drier conditions, showed higher latewood/earlywood ratio. Latewood/earlywood ratio increases with increasing drought stress (Fritts et al. 1965). The higher latewood/earlywood ratio in the inland trees reflects a higher water stress (Creber and Chaloner 1984). According to Domec and Gartner (2002), a higher latewood/earlywood ratio could be a strategy for coniferous growth in wet conditions in spring and dry conditions in summer.

Additionally, Campelo et al. (2006) reported negative correlations between temperature in summer and latewood formation. Latewood formation is dependent on carbohydrates produced by photosynthesis, which is very sensitive to water stress and temperature (Kozlowski et al. 1991). As a result, summer drought can reduce the net photosynthesis that decreases the supply of carbohydrates for latewood formation and secondary thickening of cell walls.

2.3 The boundary between juvenile wood and mature wood

Juvenile wood is a term derived to clarify why growth rings close to the pith have certainly different wood properties (Seth et al. 2005). The concept of juvenile wood is an important consideration in relation to wood properties and explains why upper logs in mature stands have juvenile characteristics. In comparison to mature wood, juvenile wood is characterized by disadvantageous traits reducing its quality, thus limiting their potential processability (Bendtsen and Senft 1986). Therefore, demarcation of the boundary between juvenile wood and mature wood is essential for the optimization of timber utilization, quality and value of final products (Alteyrac et al. 2006). Juvenile wood tends to have higher microfibril angles, lower wood density, thinner cell walls, shorter tracheid lengths, greater spiral grain, lower cellulose to lignin ratio, higher longitudinal shrinkage, lower latewood percentage and higher growth ring width (Zobel and Sprague 1998). Sometimes juvenile wood (Figure 2.2) is referred to as core wood while mature wood as outerwood (Cown 1992).

Juvenile wood is produced near the center of the tree and would be related to the number of rings from the pith. It would be controlled by auxin production in the tree crown and results from close proximity to the foliage (Zobel and Talbert 1984). The most accepted concept is that juvenile wood is directly related to the age of the cambium (Zobel and van Buijtenen 1989, Tasissa and Burkhart 1998). Plumptre (1983) studied the factors that influence juvenile wood in *Pinus caribaea.* They reported that the pattern of juvenile wood formation and transition to mature wood varies with the genetic make-up of the tree, the site, the climate and the silviculture practiced.

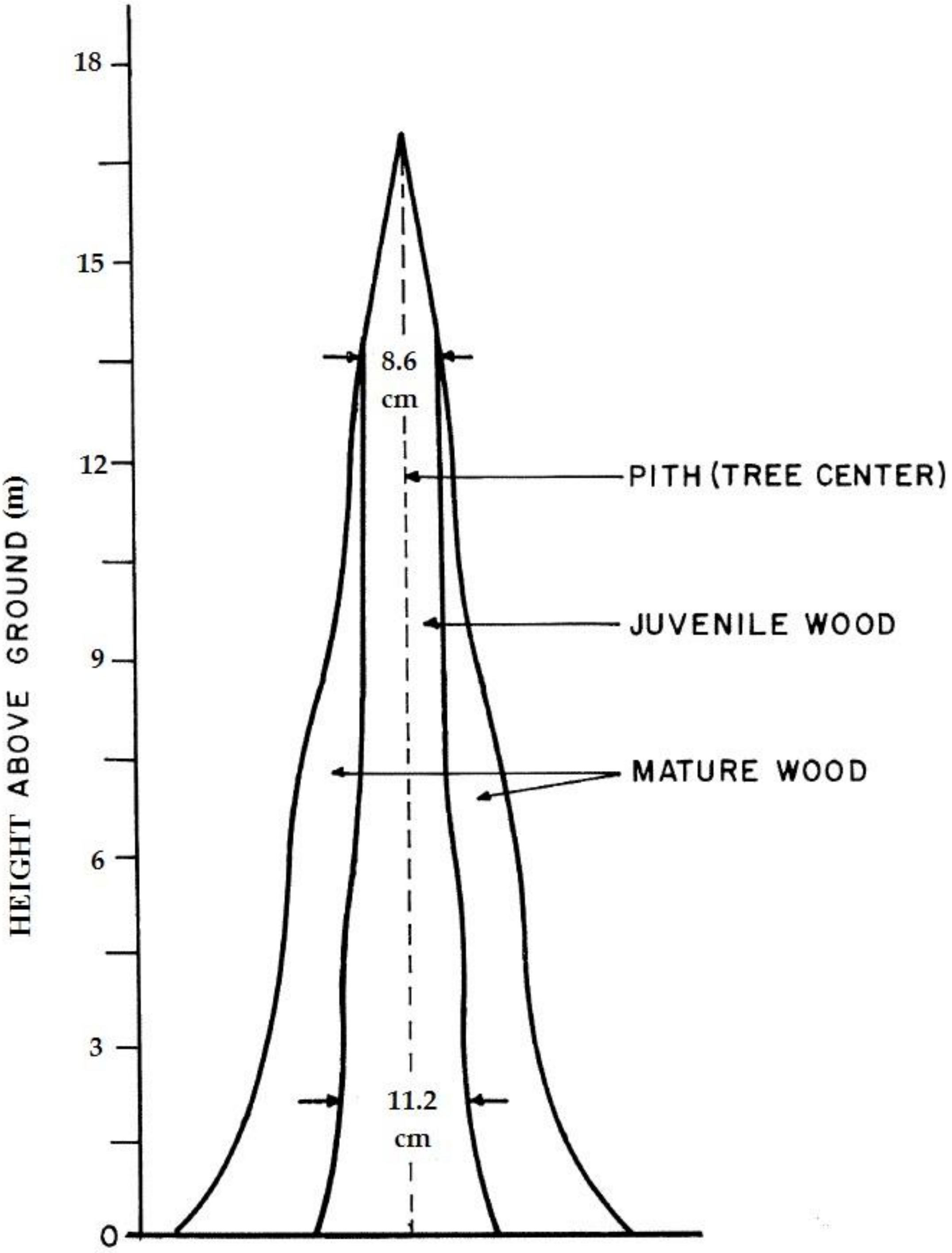

Figure 2.2 Sketch of the juvenile zone of a number of 17-years-old pines, indicating the high proportion of juvenile wood towards the top of the tree and a lesser amount in the basal part (Adapted from Zobel and Talbert 1984)

Zobel and Talbert (1984) noted that in conifers, the 15-year-old trees have a large proportion of juvenile wood and 10-year-old trees are essentially all juvenile (Figure 2.3). However, Shmulsky and Jones (2011) reported that there is typically no sharp demarcation between juvenile and mature wood. Instead, a gradual transition in properties occurs from the tree center outward (Figure 2.4).

Groom et al. (2002) examined a number of wood properties by growth ring and along the stem length. They found the juvenile zone to be biconical, tapering from the stump to just below the live crown and then again from the live crown to the bole tip. This is attributed to two regions that promote juvenility: the stump height and the live crown. Various studies report that juvenile wood in softwoods is lower in quality than mature wood (Guan et al. 1997, Bao et al. 2001, Nawrot et al. 2014). There are relatively few latewood cells in the juvenile zone, and a high proportion of cells have thin wall layers. The result is low density and a corresponding low strength in comparison with mature wood (Shmulsky and Jones 2011).

Furthermore, comparing between juvenile and mature woods, there appears to be a greater tendency for spiral grain in juvenile wood (Shmulsky and Jones 2011). Within the cell, the MFA in the S_2 part of the secondary wall is characteristically greater in juvenile wood. Deresse et al. (2003) recorded mean ring MFA of 30° in 2-year-old red pine compared with 15°–18° MFA at age 20. This kind of secondary wall microfibril orientation also occurs in compression wood that commonly develops in juvenile wood zones. As reported by Shmulsky and Jones (2011), the large S_2 MFA causes a high degree of longitudinal shrinkage and a corresponding decrease in transverse shrinkage; along-the-grain shrinkage of juvenile wood has been reported to average from three times that of mature wood to 10 times as much as mature wood (Senft et al. 1986, Walker and Butterfield 1995, Shmulsky and Jones 2011).

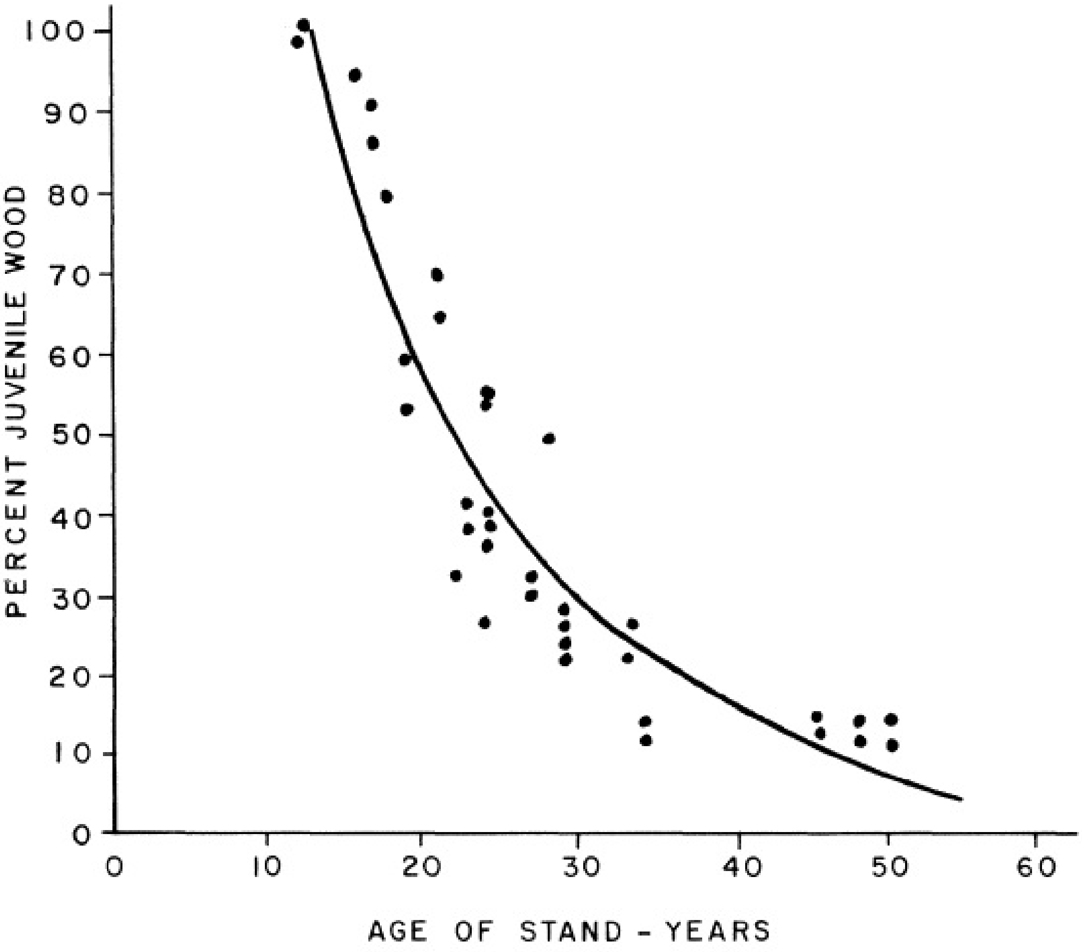

Figure 2.3 Proportion of juvenile wood in rapidly grown conifer trees (Adapted from Zobel and Talbert 1984)

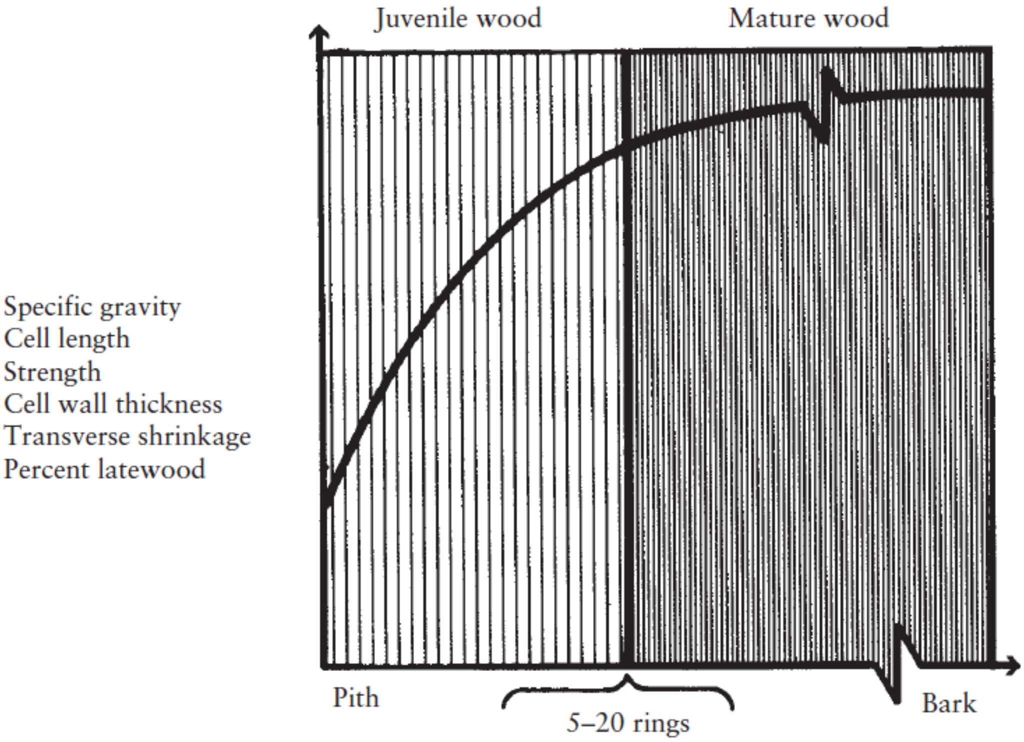

Figure 2.4 Juvenile to mature wood transition (Adapted from Shmulsky and Jones 2011)

Numerous researchers have reported that not all juvenile wood shows excessive longitudinal shrinkage and that pieces may actually increase in length upon drying, possibly due to growth stresses (McAlister and Clark 1992). Large fibril angles are also associated with low tensile strength (Krahmer 1986). Besides, veneer produced from juvenile wood has been found to be rougher and to contain more splits and deeper lathe checks, thereby producing greater thickness variation (Kellogg and Kennedy 1986, Shmulsky and Jones 2011).

Juvenile wood is said to be a matter of concern to construction in general and to the laminating industry in particular, due to low strength and high longitudinal shrinkage (Senft et al. 1985). Considering all these factors; reduced strength, occurrence of spiral grain, a high degree of longitudinal shrinkage and problems in use, juvenile wood is generally undesirable when used in many wood products (Table 2.1).

Shmulsky and Jones (2011) reported that as a raw material for high grade and high strength paper, juvenile wood has long been regarded as inferior, in part because of its low cellulose and high lignin content. It has been viewed as undesirable by pulp and paper specialists as more has become known about it. Early research found juvenile wood to have significantly lower density and to yield less pulp per ton of material processed than mature wood. Higher chemical consumption in the pulping process and up to a 10 percent increase in manufacturing costs were also noted (Zobel and Kellison 1972).

Studies on growth of jack and lodge pole pine and bleachable grade kraft pulps by Hatton (1993) and Hatton and Gee (1994), confirmed earlier findings regarding strength of paper. They reported that paper made of juvenile wood and top wood pulps exhibits better inter fiber bonding than paper made of mature wood pulp. Both of these studies concluded that finer fibers from juvenile wood will provide new opportunities to tailor make pulps with specific properties sought by papermakers.

Table 2.1 Some properties of juvenile wood compared with mature wood

Wood property	**Juvenile wood**	**Mature wood**
Specific gravity (green)	0.42[a]	0.48
Density (kgm^{-3})	427.2[a]	489.2
Fiber length (mm)	2.98[a]	4.28
Cell wall thickness (µm)	3.88[a]	8.04
Lumen size (µm)	42.25[a]	32.78
Cell diameter (µm)	50.01[a]	48.86
S_2 layer fibril angle (^{o})	55[b]	20
Longitudinal shrinkage, green to 12% moisture content (% of green dimension)	0.90[c]	<0.10
Breaking strength or MoR (psi)	4924[d]	9147[d]
Stiffness index or MoE (10^6 psi)	0.59[d]	1.55[d]
Compression strength parallel to the grain index	100[e]	124

Adapted from Shmulsky and Jones (2011); [a] data from 11-year-old (juvenile) versus 30-year-old (mature) loblolly pine; [b] information from coniferous wood; [c] data based on tests of Caribbean pine; [d] data from test of juvenile and mature wood of 36-year-old loblolly pine; [e] data based on tests of plantation-grown conifers

Hatton (1997) working with Douglas fir and jack pine, also confirmed earlier findings on strength relationships. They reported that when kraft pulping juvenile wood, pulp yields at a given lignin content were consistently lower (approximately 5 percent lower) than when using mature wood as raw material. Kraft pulping of juvenile wood yielded pulps with shorter average fiber length (15-24 percent shorter) and a lower proportion of long fibers (16-58 percent less). The reasons for different strength properties in juvenile wood pulps have been outline elsewhere (Jackson and Megraw 1986). They pointed out that the thinner cell walls of juvenile wood result in tighter packing of fiber in a paper sheet, with more contact between adjacent fibers. The result is higher sheet density and higher tensile and burst strength. Tear strength, on the other hand, is directly and negatively influenced by a short fiber length and thin cell wall (Shmulsky and Jones 2011).

Although separation of juvenile and mature wood has been recommended as a way to improve yields and pulp quality, a growing number of studies have found little difference in pulp quality obtained from young and mature trees as long as trees are not extremely young at the time of harvest. Goyal et al. (1999), for example, examined fiber length and tensile and tear strength of hand sheets made of kraft pulp from short rotation tree crops and concluded that after 7-8 years of tree growth, papermaking properties may not change significantly.

Most studies recently have focused on answering the question: what effect juvenile wood might have on the properties of wood composite products? These include: particle board, flake board, and fiber board. Composite products technology offers an opportunity for production of greater quantities of large dimension structural materials without the need to use large size trees as raw material. In such products, juvenile wood has generally been found to be undesirable. In agreement to this, Wasniewski (1989) found decreasing strength and increasing linear expansion in randomly oriented flake board as the proportion of juvenile wood was progressively increased. The strength of Douglas fir flake board made of 50-year-old wood was 10 percent greater than that made of juvenile wood formed in the first several years of growth. In contrast, the strength of 50-year-old solid wood from the same tree was 30-40 percent higher than early formed juvenile wood.

In an extensive study of southern pine in Georgia and Arkansas, Pugel et al. (1989, 1990) found flake board, standard particle board, and fiber board panels made of juvenile wood to have strength and durability comparable with otherwise identical composite panels made of mature wood. However, both thickness swelling and linear expansion, two undesirable properties, were significantly greater in the juvenile wood panels. Similar results were obtained by Geimer et al. (1997), who studied oriented flake board and plywood made of juvenile (1- to 12-year-old) and mature (13-to 35-year-old) loblolly pine (*Pinus taeda*). They found significantly greater linear expansion in both plywood and three-layer oriented wafer board made of juvenile wood than in similar panels made from mature wood.

Fascinatingly, no significant difference was found in linear expansion of randomly oriented single layer flake boards made of juvenile and mature wood. A comprehensive examination of the impact of juvenile wood on properties of composites made of southern pine (Pugel and Shupe 2004) resulted in the conclusion that “although juvenile wood is clearly inferior to mature wood for most applications, the same is not necessarily true for properties of most wood composites.” It was noted that in those cases where juvenile wood leads to undesirable properties, such as increased linear expansion, the proportion of juvenile wood should be controlled. Therefore, Shmulsky and Jones (2011), suggested that based on these and other studies, it appears that juvenile wood is generally suitable raw material for wood panel products but that monitoring and control is nonetheless needed to control dimensional stability.

2.4 Variation in wood density and mechanical properties

Wood quality assessment involves the consideration of wood density and mechanical properties (strength and stiffness). Modulus of Elasticity (MoE) and Modulus of Rupture (MoR) are important properties for use of wood as structural material. MoE is an indication of stiffness of board or structural member while MoR is an indication of strength (Johnson and Gartner 2006). Reports from several researchers indicate that wood density is the most important property controlling MoE and MoR (Panshin and Zeeuw 1980, Zobel and van Buijtenen 1989, Steffenrem et al. 2007, Kord et al. 2010). Therefore, determination of MoE and MoR together with wood density is important to understand their relationships. The relationship among these properties are species specific (Shmulsky and Jones 2011).

2.4.1 Wood density

Wood density is recognized as a major wood characteristic. It is considered a vital wood property for imparting strength and stiffness to solid lumber as well as affecting the physical yields of fibre for composite products and pulp and paper (Shmulsky and Jones 2011). In general, higher wood density is desirable. Wood density is also an important component of carbon sequestration in trees. The amount of carbon stored in trees depends on the biomass as well as the carbon content of the wood and other tissues. Therefore, wood density and stem volume alone may control carbon storage at the tree level (Fukatsu et al. 2013). Vavrčík et al. (2009) reported that variations in wood density are very important for wood industry. In addition, wood density data can be used to estimate intra-species and inter-species variation of the wood density and indicate variations available for selection in tree improvement programmes. Furthermore, knowledge of wood density profile is likely to improve the accuracy of estimates of stem biomass.

Wood density varies greatly within any species because of a number of factors. These include location in a tree, geographic location within the range of the species, site condition (soil, water, and slope), genetic source and silvicultural practices (Shmulsky and Jones 2011). McKinley (1995) specified that average density is influenced most strongly by the mean annual temperature of the site, which means there is indirect effect of both altitude and latitude. Forests with higher elevation and latitudes tend to have lower average wood density. In addition, Cown (1992) and McKinley (1995) reported that combinations of seedlot, site and silviculture can result in the late development of the wood density radial trend with mature stems exhibiting some juvenile characteristics. Similarly, Guilley et al. (1999) investigated wood density variation in *Quercus petraea* and they proved that regional, site quality and silvicultural significantly influenced wood density. In contrast, site was not a significant source of variation of wood density in *Acacia melanoxylon* (Machado et al. 2014)

Several studies have documented a response of wood density to thinning and pruning (Cown and McConchie 1981, Cown 1992, McKinley 1995). Thinning results in a slight decrease in density in the rings. The impact of pruning is less clearly defined, but there is some evidence that the removal of branches can increase density slightly (McKinley 1995). Cown and McConchie (1982) working with radiata pine in New Zealand reported that rotational age has influence on wood density irrespective of site or silviculture. They found that younger trees tend to have lower wood density.

Shmulsky and Jones (2011) concluded that in many coniferous trees wood density generally increases from pith to bark and decreases from butt up wards. The increase in wood density from the pith to the bark is due to the increasing age of the cambium (Izekor et al. 2010). The decrease in wood density from bottom to top agrees with the auxin gradient theory (Larson 1969). The theory states that the endogenous auxin arising in the apical region of growing shoots stimulates cambial division and xylem differentiation. Therefore, high production of earlywood near the crown contributes significantly to low wood density at the top.

2.4.2 Mechanical properties (strength and stiffness)

Strength and stiffness are important mechanical properties that determine the wood's suitability for structural uses (Sotelo-Montes et al. 2007). Wood density is usually a good predictor of strength and stiffness (Panshin and de Zeeuw 1980), but these properties can be influenced by other factors, including the variability among trees within species and environmental conditions that affect tree growth (Montes et al. 2007). For example, significant differences between sites were observed in DBH and MoE of juvenile wood of selected clones of *Cryptomeria japonica* (Nakada et al. 2003). In contrast, Sotelo-Montes et al. (2007) observed no significant differences in mechanical properties between the two planting zones, even though there were significant differences in tree growth between the zones.

It is generally believed that high density gives high MoE and high MoR and vice versa, but MoE and MoR also depends on the microfibril angle (MFA) in S_2 layer (Moliński et al. 2014). This indicate that in most coniferous trees MoE and MoR increases from pith to bark and decreases from butt to the top (Kamala et al. 2014). However, this trend is dependent on species (Cave and Walker 1994, Rozenberg et al. 1999, Evans and Ilic 2001, Yang and Evans 2003).

2.4.3 Relationship between wood density and mechanical properties

Wood density is major predictor of strength and stiffness. However, the relationship between wood density and mechanical properties is species specific (Cave and Walker 1994, Rozenberg et al. 1999, Evans and Ilic 2001, Yang and Evans 2003). For example, Stanger

2003 and Kamala et al. 2014 reported a strong relationship between wood density and mechanical properties in *Pinus patula*. On the other hand, Deresse (1998) reported a weak relationship between wood density and mechanical properties in *Pinus resinosa* and there was no relationship between wood density and mechanical properties in *Pinus radiata* (Cave and Walker 1994).

Low density correlations with mechanical properties were in some cases attributed to the influence of MFA (Cave and Walker 1994, Yang and Evans 2003, Machado and Cruz 2005). The reasoning is that density increases while MFA decreases with age, thereby impacting the mechanical tests and resulting in poor correlations when density alone is considered (Cave and Walker 1994, Machado et al. 2014). The grain angle can also affect the correlation between density and mechanical properties (Green et al. 1999, Machado et al. 2014).

2.5 Genetic parameters for effective tree breeding programmes

Knowledge of genetic parameters in wood properties and growth traits is the basis of sound tree improvement programmes. Estimates of heritabilities and genetic correlations are essential population parameters required in tree breeding research and in design and application of practical tree breeding programmes (Hung et al. 2015).

2.5.1 Heritability

One of the most important properties of quantitative traits is that they can be described in terms of heritability. Heritability indicates the relative contribution of genetics and the environment to the phenotypic differences among individual trees or families. It expresses the proportion of the phenotypic difference (phenotypic variance), among individual trees or families that on average is attributable to the genetic difference. Strictly defined, heritability

(h^2) is the ratio of the additive genetic variance (σ^2_A) to the phenotypic variance (σ^2_p). (Hong et al. 2014).

Heritability is of great significance to tree breeders since it represents the degree to which the phenotype is determined by the genes transmitted from parents to progeny (Lenz et al. 2010). Heritability can range from 0 to 1.0. A heritability of zero indicates a lack of additive genetic influence on the differences observed among individual trees or families. A heritability of one indicates that all differences among individual trees or families are due to additive genetic causes. Thus, high values of heritability indicate a strong contribution of the general breeding value on a trait's variation, good possibilities to estimate the breeding value as well as good and rapid response to selection (Hong et al. 2014).

The importance of heritability in the genetic study of metric characters is that it has a predictive role because it expresses the reliability of the phenotypic value as a guide to the breeding value. A change in any one of the components of σ^2_p will produce a corresponding change in heritability estimates. Estimation of heritabilities cannot be done with any great precision; hence most heritability estimates tend to have large standard errors (Falconer and Mackay, 1996).

Heritability estimates for wood quality traits and growth traits have been reported by different researchers (Hannrup et al. 2000, Ivković et al. 2002, Apiolaza 2009, Apiolaza et al. 2011, Guller et al. 2011). Estimates of heritabilities of some relevant traits are presented in Table 2.2. Heritability of wood density is generally found to be higher than those of growth traits in forest trees. Published heritability of density in pines varies from 0.40-0.85, compared to the usual range of 0.15-0.25 for many growth traits (Zobel and Jett 1995, Guller et al. 2011). This indicates that genetic manipulation of wood density can result in good gains.

Table 2.2 Heritability estimates of some traits of interest in fast grown plantation trees in five references

Trait	Cornelius 1994	Gapare et al. 2012	Kennedy et al. 2013	Hong et al. 2014	Steffenrem et al. 2016
Growth traits					
DBH	0.23	0.13	0.29	0.24	0.09
HGT	0.28	-	-	0.27	0.13
Vol	0.21	-	-	0.24	-
Wood quality traits					
DEN	0.50	0.64	0.71	0.42	0.44
MoE	-	0.47	0.52	0.45	-
MoR	-	-	0.62	-	-
MFA	-	0.49	0.52	0.52	-

DBH: diameter at breast height; HGT: height; Vol: volume; DEN: density; MoE: modulus of elasticity; MoR: modulus of rupture; MFA: microfibril angle

2.5.2 Genetic correlation

Some genes influence more than one trait. These traits are correlated genetically and selection for one will cause change in the other. However, the environment also can cause traits to be correlated (Falconer and Mackay 1996). These associations are known as phenotypic correlations. For example, increased stem volume is often associated with increased tree diameter (Zobel and Jett 1995). The total phenotypic relationship is due to both genetic and environmental factors that affect both traits.

Associations resulting from environmental factors are referred to as environmental correlations. Correlations due to genes that affect both traits are called genetic correlations (Falconer and Mackay 1996). Genetic correlations are of importance to tree breeders because they are correlations between breeding values of two traits. Genetic correlations can range from -1.0 to +1.0. Correlations may be classified in three ways: strength, sign, and whether they are favorable or unfavourable. Strength of correlation is indicated by the value itself. Correlations near –1 or 1 indicate a strong relationship. Correlations near 0 indicate a weak relationship. The sign is an indication of direction of change. A negative correlation means that as one trait increases the other decreases. A positive correlation means that the two traits tend to change in the same direction. The sign of the genetic correlation does not indicate whether the relationship between traits is favourable, only the statistical relationship (Cassady and Robinson 2002). For example, the genetic correlation between wood density and MFA is negative (Hong et al. 2014). Because fast gains in wood density tend to be associated with low MFA, this illustrates a negative statistical relationship, but favourable economic relationship.

A genetic correlation between traits will result in a correlated response to selection. A favourable correlation results in selection for one trait improving another. An unfavourable correlation between traits increases the difficulty of making simultaneous improvement in both traits. Different results on genetic correlation between wood quality traits and growth traits on conifers have been reported. Most researchers (Wu et al. 2008, Hong et al. 2014) found unfavourable genetic correlation between wood quality traits and growth traits in *Pinus radiata* and Scots pine, respectively. The adverse genetic correlations could be due to genetic and environmental causes (Hong et al. 2014). On the other hand, Fukatsu et al. (2015) reported a positive genetic correlation between wood properties and growth traits in Japanese larch (*Larix kaempferi* Lamb. Carrière). Based on these reports, the genetic correlations between wood properties and growth traits depend on species. Knowledge of heritability, breeding values and genetic correlations of traits of interest is used to calculate selection indexes.

2.6 Selection index

Selection index is a technology to maximize genetic improvement in a specified objective (MacNeil et al. 1997). Under this method individual’s trees are ranked according to their index values and selection based on these rankings. The use of selection index which incorporates many traits is increasingly gaining importance in tree improvement programmes. For example, Zhang et al. (2011) reported that for improving leaf biomass and oil content in Tea-tree (*Melaleuca alternifolia* (Maiden and Betche) Cheel) breeding programme in Australia, selection index comprising leaf biomass, oil content, height, leafiness, 1,8-cineole, terpinen-4-ol was 99% efficient. Selection on leaf biomass and oil content was 24% less efficient in improving leaf biomass and oil content compared with selection using an index of all six traits. Park et al. (1989) found that selection for height, diameter, volume, stem straightness, branch characteristics and wood density improved efficiency of response in the aggregate genotype by 46% over selection for diameter alone. Apiolaza and Garrick (2001) reported that for improving pulp yield, selection index comprising volume and wood density was 96% efficient. Selection on volume alone was 35% less efficient in improving pulp yield compared with selection using an index of all two traits.

The theory of selection index was first developed by Smith (1936) and later by Hazel and Lush (1942). The selection index (I) is defined as:

$$I = \hat{a} = \beta_1 P_1 + \beta_2 P_2 + \ldots + \beta_m P_m$$

where P_1 to P_m are phenotypic measurements of m traits on which selection is to be based, and β_1 to β_m are the corresponding factors by which each measurement is weighted or the partial regression coefficients of the individual trait breeding value on each measurement. Selection based on multi-trait selection index is aimed at improving the aggregate breeding value, which is defined as:

$$H = a_1 A_1 + a_2 A_2 + \ldots + a_n A_n$$

where the **A**'s are breeding values for the *n* traits to be improved, and the **a**'s are the weighting factors which express the relative importance attached by the breeder to each trait.

The set of equations, for multi-trait selection, whose solutions gives the β values are: -

$$\beta_1 P_{11} + \beta_2 P_{12} + \ldots + \beta_m P_{1m} = a_1 A_{11} + a_2 A_{12} + \ldots + a_n A_{1n}$$

$$\beta_1 P_{21} + \beta_2 P_{22} + \ldots + \beta_m P_{2m} = a_1 A_{21} + a_2 A_{22} + \ldots + a_n A_{2n}$$

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$$\beta_1 P_{m1} + \beta_2 P_{m2} + \ldots + \beta_m P_{mm} = a_1 A_{m1} + a_2 A_{m2} + \ldots + a_n A_{mn}$$

where $\mathbf{P_{ii}}$ and $\mathbf{A_{ii}}$ are the respective phenotypic and genetic variances for individual traits and $\mathbf{P_{ij}}$ and $\mathbf{A_{ij}}$ are the phenotypic and genetic covariance's respectively between traits ***i*** and ***j***. The variances and covariances can be expressed in terms of the heritability of the traits and the correlations among the traits as follows:

$$P_{ii} = \sigma^2_i;$$

$A_{ii} = h^2{}_i\sigma^2{}_i$;

$P_{ij} = r_p\sigma_i\sigma_j$; and

$A_{ij} = r_A h_i h_j \sigma_i \sigma_j$.

where σ^2 is the phenotypic variance, h^2 is heritability, r_p is the phenotypic correlation and r_A is genetic correlation.

The correlation (r_{HI}) between the index and the aggregate genotype provides a criterion for choice among the indexes. Therefore, the accuracy of the index is calculated as:

$$r_{HI}^2 = \frac{\sigma_I^2}{\sigma_H^2} \qquad (2.1)$$

where: σ_I^2 and σ_H^2 are the variances of the index and the aggregate genotype, respectively. These variances are calculated using the following equations:

$$\sigma_I^2 = b'Ga \qquad (2.2)$$

$$\sigma_H^2 = a'Ga \qquad (2.3)$$

where: b' is the vector of selection index weight values and a' is the vector of economic weight values.

The expected genetic change (ΔG) each trait after one generation of selection on the indexes is estimated by solving the following equation:

$$\Delta G = \frac{b'Gi}{\sigma_I} \qquad (2.4)$$

where: i is the selection intensity, σ_I is the standard deviation of index and G is the genetic variances (cov.) matrix. Genetic gain is often referred as the amount of increase in performance that is achieved through artificial genetic improvement programmes. This is usually used to refer to the increase after one generation has passed (Baker 1986).

2.7 Conclusion of literature review

The review has revealed that in conifers tracheid length increases with an increase of growth rings, reaches a maximum in a certain year and then gradually increase or level off. The boundary between juvenile wood and mature wood can be well defined by the variation of tracheid length. Juvenile wood is defined as the zone where the length of fusiform initial (cambial cell) increases rapidly with cambial age, while mature wood is defined as the zone where the length of cambial cell is stable. Wood density and mechanical properties increases from pith to bark and decreases from butt upwards. Heritability for wood quality traits are found to be high genetic control than growth traits in forest trees. Indicating that higher genetic gains can be obtained by direct selection of wood quality traits. The genetic correlation between wood properties and growth traits are favourable in some conifers and unfavourable in others. Signifying that genetic correlations between wood properties and growth traits in forest trees depend on species. However, for unfavourable correlations, there is potential for simultaneous improvement of wood properties and growth traits through multi-trait selection index.

CHAPTER 3

Radial Variation in Tracheid Length and Growth Ring Width of *Pinus kesiya* Royle ex Gordon in Malawi

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3.1 Abstract

Wood anatomical features measured in tree-rings are useful indicators of environmental change and wood quality. This study was conducted to investigate the radial variation in tracheid length and growth ring width and to demarcate the boundary between juvenile wood and mature wood of *Pinus kesiya* Royle ex Gordon planted in Malawi. A total of 90 discs were collected from six families at breast height (1.3 m above the ground) and were measured for tracheid length and growth ring width. The results show that there were statistical significant ($P<0.001$) differences on tracheid length and growth ring width among the ring numbers in juvenile wood. Tracheid length at first increased rapidly from pith to bark and thereafter increased gradually or remains more or less constant, while growth ring width decreased. However, there were no significant ($P>0.05$) differences on tracheid length and growth ring width among families across the radius. On the basis of radial variation of tracheid length, the boundary between juvenile wood and mature wood could be marked at ring number 10 from the pith. This should be taken into account when planning for forest management and product manufacturing using *Pinus kesiya* planted in Malawi.

Keywords: Tracheid length, growth ring width, juvenile wood, mature wood, wood quality.

3.2 Introduction

Pinus kesiya Royle ex Gordon is one of the most valuable timbers in international trade and an important species for tropical forestry (Gogoi et al. 2014). This species generally grows well at altitudes ranging from 300 to 2700 m above the sea level. The trees usually grow up to 45m tall with straight cylindrical trunk and a bole free of branches up to 20m. *Pinus kesiya* grows on a range of soil types, but prefers well-drained, neutral to acid soils. Once established the tree is fairly resistant to drought and frost. *Pinus kesiya* grows naturally in Himalaya region of Asia, which includes: China, India, Laos, Myanmar, Philippines, Thailand, Tibet, and Vietnam (Missio et al. 2005). It has also been introduced in many tropical countries, for instance, South Africa in 1906 from Assam and 1915 from Phillipines, Zimbabwe in 1935 from Phillipines, Kenya, Zambia, Tanzania and Malawi (Dowse and Wessels 2013).

Pinus kesiya is one of the major exotic tree species in Malawi. Its success as an exotic is due to its fast growth rate and wide adaptability. It provides high class value of timber. The wood is essentially used for paneling, construction, cabinet work, joinery and sometimes poles (Eerikainen 2003, Nyunai 2008, Missanjo and Mwale 2014). The species was first introduced in Malawi in 1935. Then, large scale plantings were done with seeds from Zimbabwe and South Africa in 1950's. In 1970's and 1980's seed orchards were established with the aim of creating owned seed sources of improved traits (FRIM 1989). There is a general agreement in literature that *Pinus kesiya* growth varies according to location (Diaz et al. 2007, Gogoi et al. 2014), but most of the available data comes from Asian countries, especially in India (Downes et al. 2002, Seth et al. 2005, Gogoi et al. 2014). Anatomical properties such as tracheid length, and growth characteristics such as growth ring width are one of the most essential tools for understanding tree growth and its reaction to varying climatic settings (Bhat et al. 2001, Tian et al. 2009). They form the basis for wood anatomy, dendroclimatology, dendrochronology and dendroecology (Pant 2003, Sousa et al. 2012). They are valuable instruments in forest management as well as in product manufacturing as they are closely connected with tree growth rate and wood properties (Alteyrac et al. 2006, Gogoi et al. 2014). This is an indication that information on radial variation pattern of ring width and tracheid length can facilitate tree growth and wood quality in forest management and wood utilization (Saravanan et al. 2013, Sharma et al. 2013b, Anoop et al. 2014).

Despite these facts no information is available on radial variation pattern in growth ring width and tracheid length of *Pinus kesiya* in Malawi. Thus no effort has been made to investigate the radial variation pattern of growth ring width and tracheid length in this species. Reports from different research has shown that radial variation in anatomical properties and growth characteristics are caused by both specific environmental factors, forest management practices and within controlled genetic factors (Downes et al. 2002, Pant 2003, Alteyrac et al. 2006, Diaz et al. 2007, Mmolotsi et al. 2013). Therefore, the purpose of this study was to investigate the radial variation in growth ring width and tracheid length and to demarcate the boundary between juvenile wood and mature wood for *Pinus kesiya* in Malawi. The knowledge on radial variation pattern in tracheid length and growth ring width and the boundary between juvenile wood and mature wood would be incorporated into decision support system in Malawi to assist the forestry industry in planning and developing tree improvement programmes and wood utilization for *Pinus kesiya* and thus anticipating the impacts.

3.3 Materials and methods

3.3.1 Study site

The study was conducted in Malawi located in Southern Africa in the tropical savannah region at Chongoni Forest Plantation in Dedza (Figure 3.1). Chongoni is located between latitudes 14^{o}10’S and 14^{o}21’S and longitudes 34^{o}09’E and 34^{o}17’E and between 1570 m and 1690 m above the sea level. It receives about 1200 to 1800 mm rainfall per annum, with a mean annual temperature ranging from 7 to 25 ^{o}C. It is situated about 85 km southeast of the capital Lilongwe.

3.3.2 Plant material and sampling

The materials for the study were collected from a *Pinus kesiya* seed orchard which was planted in 1984 with 18 families in a completely randomized design in four replicates. Trees were planted at a spacing of 2.75m x 2.75m with seed source from Zimbabwe. All the silvicultural treatments (weeding, slashing, pruning and thinning) were done on the instruction of the breeder (Ingram and Chipompha 1987). The stand density when the samples were collected, in the year 2014, was about 875 stems per hectare.

In May 2014, six of the eighteen families were choosen and a total of ninety straight boled trees (15 trees from each family) with no major defects were randomly selected. The following growth traits were measured: diameter at breast height (DBH) using a caliper; total height using a vertex with a transponder; and merchantable height (height at 15 cm top diameter) using a linear tape after felling. The growth data are presented in Table 3.1. The north side of each tree was marked before felling. The cross-sectional discs of 10 cm thickness were taken at breast height (1.3 m above the ground).

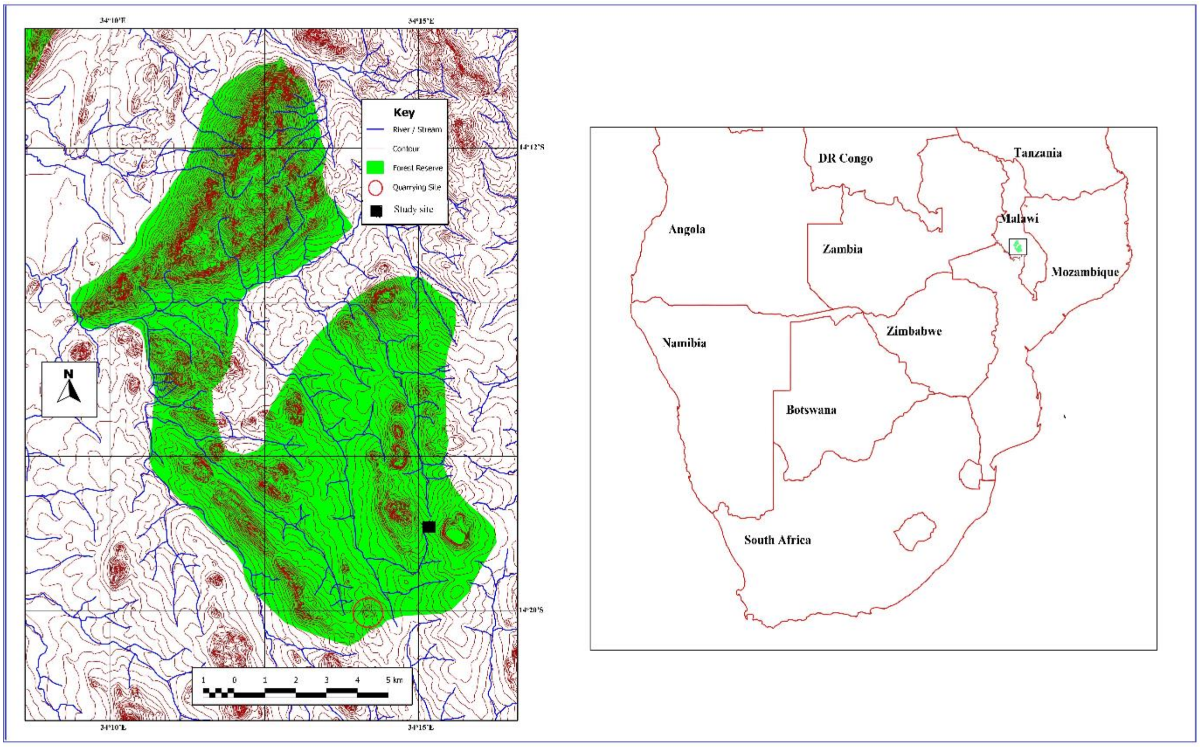

Figure 3.1 Location of Chongoni Forest Plantation in Southern Africa

Table 3.1 Characteristics of growth data set

Family	Variable	Mean	Minimum	Maximum	SD
n = 15 trees per family					
A	Diameter at breast height (cm)	36.1	32.0	39.0	2.22
	Total height (m)	29.3	24.6	34.2	2.55
	Merchantable height (m)	24.3	20.4	27.4	1.92
B	Diameter at breast height (cm)	28.0	23.0	32.0	2.51
	Total height (m)	24.3	19.8	28.3	2.25
	Merchantable height (m)	18.4	16.3	21.8	1.60
C	Diameter at breast height (cm)	34.6	29.0	38.0	2.75
	Total height (m)	27.5	24.7	29.5	1.62
	Merchantable height (m)	21.0	19.2	23.8	1.41
D	Diameter at breast height (cm)	33.0	28.0	38.0	2.70
	Total height (m)	25.3	23.1	29.8	2.04
	Merchantable height (m)	20.0	17.2	22.6	1.58
E	Diameter at breast height (cm)	31.0	26.0	36.0	2.51
	Total height (m)	24.5	21.4	27.4	1.97
	Merchantable height (m)	19.3	16.5	22.3	1.70
F	Diameter at breast height (cm)	29.1	24.0	34.0	3.45
	Total height (m)	24.7	19.6	26.9	2.37
	Merchantable height (m)	18.9	16.2	21.4	1.42

Note: Merchantable height is the height of the tree at 15 cm top diameter, SD: Standard deviation.

3.3.3 Sample processing measurement

Each cross-sectional disc was smoothened to the end grain by a sand paper. Radial strips from the north side were cut from bark to pith and air-dried. Growth ring width from pith to bark were measured in these strips by using ocular micrometer in one of the eye piece of a stereomicroscope at 20x. A total of 28 growth rings were observed for each disc.

Every third ring from the pith to the bark was carefully split from the strips and the latewood were macerated. Maceration were prepared by dipping the wood pieces in a 1:1 solution of 65% nitric acid (HNO_3) and distilled water (H_2O) plus potassium chlorate ($KCIO_3$) (3g/100 ml solution) for 5 days. After maceration the elements were rinsed with distilled water thrice, stained with safranin, and then mounted on a glass slide and a cover-slip was placed over the specimen. Lengths of thirty randomly selected tracheids were measured using a Nikon V-12 profile projector at a fifty-fold magnification.

2.3.4 Statistical analysis

Data obtained on growth ring width and tracheid length were tested for normality and homogeneity with Kolmogorov-Smirnov D and normal probability plot tests using Statistical Analysis of Systems software version 9.1.3 (SAS 2004). After the two criteria were met the data were subjected to analysis of variance (ANOVA) using the same Statistical Analysis of Systems software with family and ring number as fixed factors. Differences between treatments means were separated using Fischer’s least significant difference (LSD) at the 0.05 level. Graphs were plotted using Microsoft Excel 13.

3.4 Results and discussion

3.4.1 Radial variation in tracheid length and growth ring width

The length of tracheids in wood is an important determinant of the use to which that wood is put. The quality of both lumber and pulp is determined, in part, by the length of tracheids in the wood. Long fibres give lumber greater strength and papers produced from pulp of long fibres are of more strength and fold-resistance (Sharma et al. 2014). The variation in patterns of tracheid length and growth ring width as a function of ring number from pith to bark are given in Table 3.2 and Figures 3.2 and 3.3, respectively.

The results presented in Table 3.2 indicates that there were statistical significant ($P<0.001$) differences on tracheid length and growth ring width among the ring numbers from pith to bark. Tracheid length at first increased rapidly from pith to bark, then more slowly, while annual ring width decreased. Radial increase in tracheid length from pith to bark is due to increase in length with cambial age (Chalk 1930). The average growth ring of *Pinus kesiya* for the present study has been found to be 4.28±0.18 mm, which is higher than the mean growth ring width for *Pinus kesiya* (3.81 mm) reported by Gogoi et al (2014) and lower than those of *Pinus eldarica* (4.95 mm) (Reza et al. 2002). This difference may be attributed to initial plant spacing. There is acceleration of growth for widely spaced trees than crowded trees, because widely spaced trees do not compete for growth elements such as nutrients, water and sunlight, hence they tend to have wider growth ring width (Zhu et al. 2000). In the present study, trees were planted at a spacing of 2.75 m x 2.75 m, which was wider than for Gogoi et al. (2014) which were planted at a spacing of 1.8 m x 1.8 m, while for Reza et al. (2002) trees were planted at a spacing of 3.0 m x 3.0 m.

Table 3.2 Mean values of tracheid length and growth ring width of *Pinus kesiya* at different ring number

Ring number from pith to bark	**Tracheid length (mm)**	**Growth ring width (mm)**
3	1.62±0.08 ^{d}	13.84±0.18 ^{a}
6	2.36±0.08 ^{c}	9.41±0.18 ^{b}
9	3.01±0.08 ^{b}	5.33±0.18 ^{c}
12	3.93±0.08 ^{a}	2.02±0.18 ^{d}
15	3.97±0.08 ^{a}	1.71±0.18 ^{d}
18	4.02±0.08 ^{a}	1.66±0.18 ^{d}
21	4.14±0.08 ^{a}	1.60±0.18 ^{d}
24	4.29±0.08 ^{a}	1.52±0.18 ^{d}
27	4.36±0.08^{a}	1.44±0.18 ^{d}
CV (%)	5.6	8.2
R^2	0.97	0.95

Note: ^{a,b,c,d} means with different superscript within a column significantly differ (P<0.001)

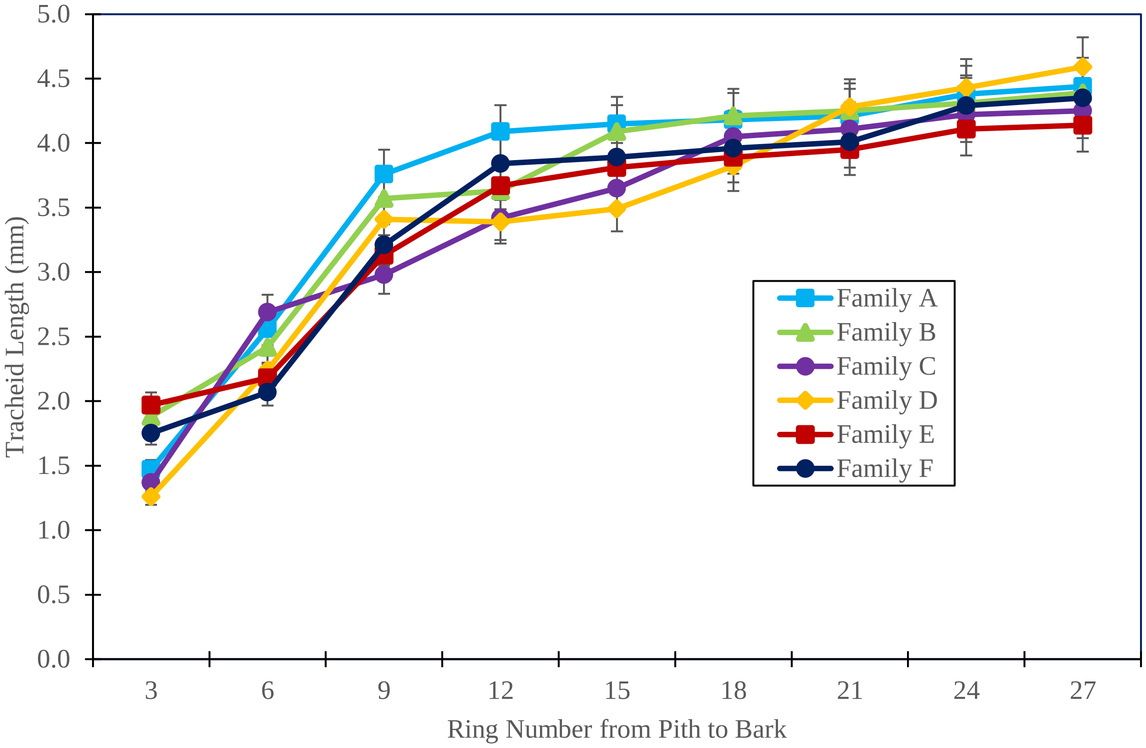

Figure 3.2 Radial variation of tracheid length for different six families of *Pinus kesiya*

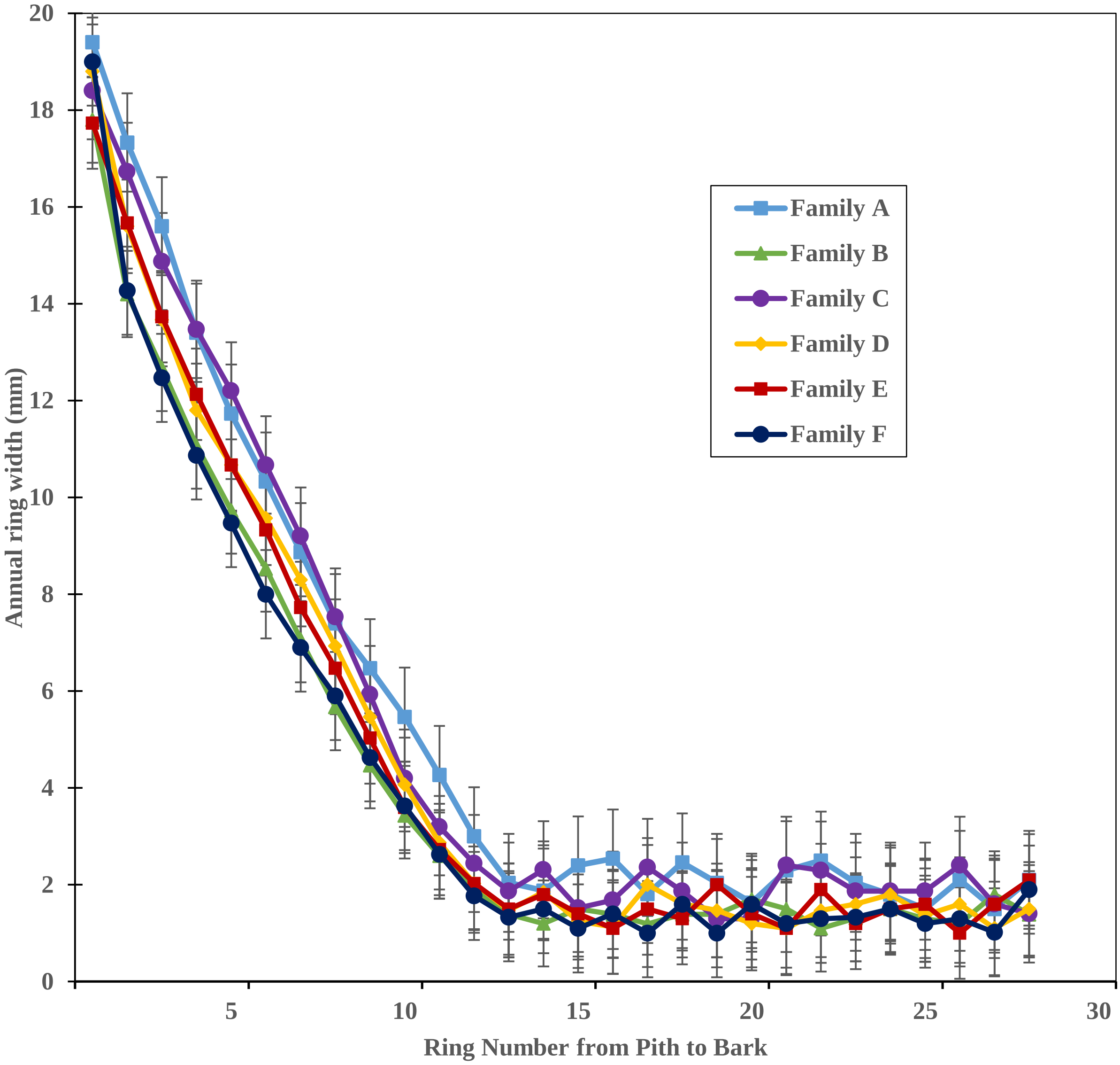

Figure 3.3 Radial variation of growth ring width for different six families of *Pinus kesiya*

There were no significant ($P>0.05$) differences on tracheid length and growth ring width among families across the radius. Thus, the pattern of variation was the same (Figures 3.2 and 3.3). This is an indication that any tree among the families can be selected for tree improvement programs if tracheid length is considered as a variable.

3.4.2 Juvenile and mature woods boundary

Radial variation in anatomical properties are greatly essential to observe the degree of variation from pith to bark and to demarcate the boundary between juvenile wood and mature wood (Ishiguri et al. 2007, Sharma et al. 2013a, Sharma et al. 2014). Juvenile wood is a term derived to clarify why growth rings close to the pith have certainly different wood properties (Seth et al. 2005). The concept of juvenile wood is an important consideration in relation to wood properties and explains why upper logs in mature stands have juvenile characteristics. In comparison to mature wood, juvenile wood is characterized by disadvantageous traits reducing its quality, thus limiting their potential processability (Nawrot et al. 2012). Therefore, demarcation of the boundary between juvenile wood and mature wood is essential for the optimization of timber utilization, quality and value of final products (Alteyrac et al. 2006, Nawrot et al. 2012). Juvenile wood tends to have higher microfibril angles, lower wood density, thinner cell walls, shorter tracheid lengths, greater spiral grain, lower cellulose to lignin ratio, higher longitudinal shrinkage, lower latewood percentage and higher growth ring width (Pant 2003, Tian et al. 2009).

Basing on these parameters, various methods have been used to demarcate the boundary between juvenile wood and mature wood. The simplest graphic method has been used by few researchers (Adamopoulos and Voulgaridis 2002), while linear regression model, non-linear and polynomial models were opted by other researchers (Zhu et al. 2000, Mutz et al. 2004, Koubbaa et al. 2005). The present study used Yang et al. (1986) method and logarithm regression model for latewood tracheid length to demarcate the boundary between juvenile wood and mature wood. For the Yang et al. (1986) method, two linear regression models, one for the juvenile wood and one for mature wood were used. Juvenile wood was defined as the zone where the length of fusiform initial (cambial cell) increased rapidly with cambial age, while the mature wood was defined as the zone where the length of cambial cell was stable. The intersection between the two graphs was taken as the demarcation point between juvenile and mature woods.

Figure 3.4 shows that the intersection between the two linear graphs was at ring number 10 from the pith and Figure 3.5 shows lower tracheid length near the pith and then increased rapidly and nonlinearly up to ring number 10, which is the main characteristics of juvenile wood (Pant 2003, Tian et al. 2009). Beyond ring number 10 and near the bark there was a gradual increase and stable pattern in tracheid length. Basing on these results, the boundary between juvenile and mature woods can be marked at ring number 10 from pith. Hence, rings 1–10 can be regarded as juvenile wood and ring 11 to bark as mature wood. This indicates that efficiency of selection in tree breeding program based on the inner wood for tracheid length would generally be lower than selection based on outer wood. This should be taken into account when planning for forest management and product manufacturing using *Pinus kesiya* grown in Malawi. The present results are in agreement to those in literature (Gogoi et al. 2014, Kamala et al. 2014).

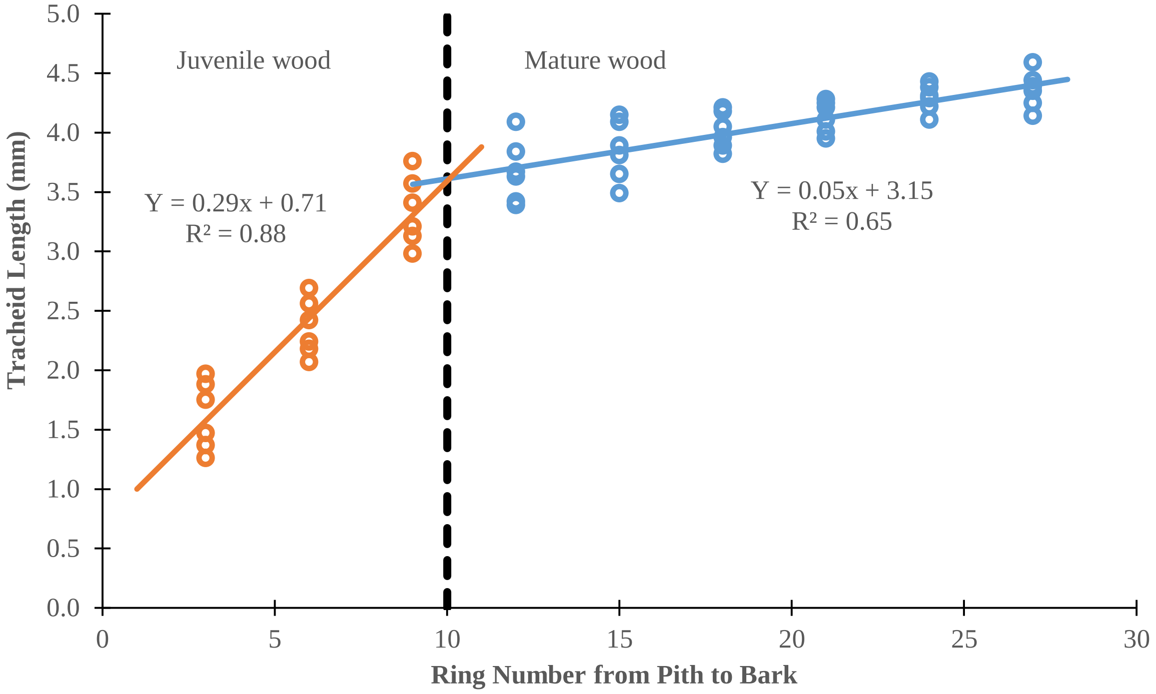

Figure 3.4 The boundary between juvenile wood and mature wood in *Pinus kesiya*

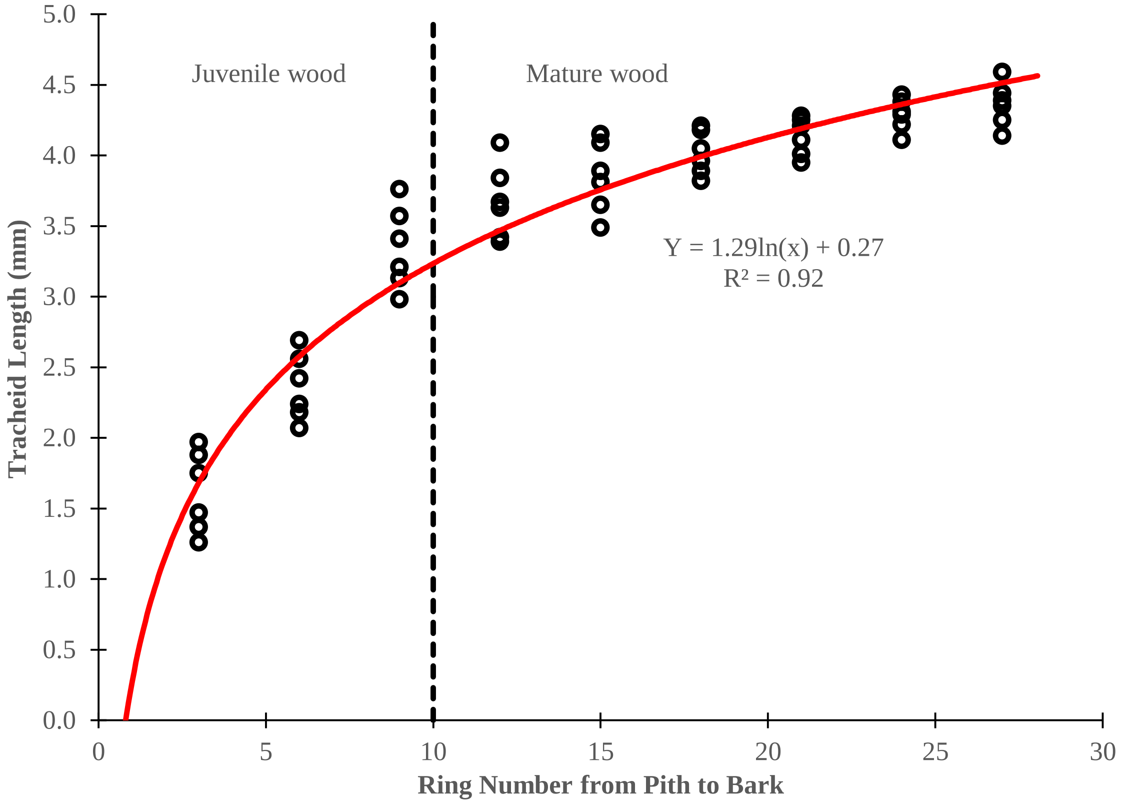

Figure 3.5 Predictive model for tracheid length based on ring number from pith to bark

3.5 Conclusion

The study has revealed that there were statistical significant differences on tracheid length and growth ring width among the ring numbers in juvenile wood. Tracheid length at first increased rapidly from pith to bark and thereafter increased gradually or remains more or less constant, while growth ring width decreased. However, there were no significant differences on tracheid length and growth ring width among families across the radius. This is an indication that any tree among the families can be selected for tree improvement programs if tracheid length is considered as a variable. On the basis of radial variation of tracheid length, the boundary between juvenile wood and mature wood could be marked at ring number 10 from the pith. This should be taken into account when planning for forest management and product manufacturing using *Pinus kesiya* grown in Malawi.

CHAPTER 4

Wood Density and Mechanical Properties of *Pinus kesiya* Royle ex Gordon in Malawi

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4.1 Abstract

Successful development of an appropriate tree breeding strategy and wood utilization requires information on wood properties. This study was therefore conducted to assess wood density and mechanical properties of *Pinus kesiya* Royle ex Gordon grown in Malawi. Wood samples from six families of *P. kesiya* at the age of 30 years were used for the study. The estimated mean wood density, Modulus of Elasticity (MoE), Modulus of Rupture (MoR) and moisture content were 0.593 ± 0.001 g/cm^3, 13.46 ± 0.07 GPa, 113.67 ± 0.57 MPa and 12.08% ± 0.03%, respectively. There were statistically significant (P<0.001) differences in wood density and mechanical properties along the radial direction and stem height. Wood density and mechanical properties increased from pith to bark and decreased from the butt upwards. There were no significant (P>0.05) differences in wood density and mechanical properties among the families. This is an indication that any tree among the families can be selected for tree improvement programs if density is considered as a variable. Wood density had a strong positive significant linear relationship with both MoE (r = 0.790; P<0.001) and MoR (r = 0.793; P<0.001). This suggests that it has the potential to simultaneously improve the wood density and mechanical properties of this species. Therefore, controlling wood density for the tree improvement program of *P. kesiya* in Malawi would have a positive impact on mechanical properties.

Keywords: *Pinus kesiya*, modulus of elasticity, modulus of rupture, wood density, tree improvement

4.2 Introduction

Pinus kesiya Royle ex Gordon is a softwood tree species of the family Pinaceae. It is one of the most valuable tree timber species in the tropics. Its world-wide demand is attributed to its high quality timber on account of the durability of the wood it produces (Gogoi et al. 2014). *Pinus kesiya* is native to the Himalaya region (Asian): China, India, Laos, Myanmar, Philippines, Thailand, Tibet, and Vietnam and it grows well at altitudes from 300 to 2700 m above the sea level (Missio et al. 2005). It has been successfully established as exotic in many countries of the world including Malawi, where it is raised as one of the fastest timber species. The tree grows to a height about 45 m with a straight, cylindrical trunk. It has a thick, reticulate and deeply fissured bark and pruinose branchlets with a waxy bloom (Gogoi et al. 2014).

It is vital to record the wood parameters prior to large scale expansion of plantations outside its natural range. The information on wood parameters can facilitate tree growth and wood quality in forest management and wood utilization. Wood quality assessment involves the consideration of wood density and mechanical properties (Anoop et al. 2014). Certain wood properties are reported to be good indicators of timber properties and uses. Modulus of Elasticity (MoE) and Modulus of Rupture (MoR) are important properties for the use of wood as structural material. MoE is an indication of stiffness of board or structural member while MoR is an indication of strength (Johnson & Gartner 2006). Reports from several researchers indicate that wood density is the most important property controlling MoE and MoR (Zobel and van Buijtenen 1989, Steffenrem et al. 2007, Kord et al. 2010). Therefore, the determination of MoE and MoR together with wood density is important to understand their relationships. The relationship among these properties are species specific (Shmulsky and Jones 2011); for instance, other researchers (Stanger 2003, Kamala et al. 2014) reported a strong relationship between wood density and mechanical properties in *Pinus patula*. On the other hand, other researchers (Deresse 1998) reported a weak relationship between wood density and mechanical properties in *Pinus resinosa* and there was no relationship between wood density and stiffness in *Pinus radiata* (Cave and Walker 1994). The relationships are of great importance in machine stress grading (placement of pieces of lumber of similar mechanical properties into different categories) and in tree breeding programs. They are used to predict the outcome of one parameter when the corresponding parameter has been improved (Zhang 1995).

Pinus kesiya plantations were established in Malawi in order to provide raw materials for sawn timber and to reduce pressure on tree species from the natural forest. Regardless of the establishment of these fast growing *Pinus kesiya* plantations adequate information about its wood density and mechanical properties are necessary for the foresters to make wise management decision and grow trees of high quality wood that can lead to greater profitability for the forestry industry (Harris et al. 2002). Despite these facts, no information is available on wood density and mechanical properties for *Pinus kesiya* grown in Malawi. Just like many other species, research on *Pinus kesiya* has concentrated on growth variables like height, diameter and volume (Missanjo et al. 2013, Missanjo and Kamanga-Thole 2014). Therefore, the main objective of this study was to assess wood density and mechanical properties of *Pinus kesiya* grown in Malawi. Specifically, the study aimed at: estimating and determining the variation of wood density and mechanical properties along the radial direction and stem height, determining the relationship between wood density and mechanical properties, and assessing the quality of timber produced from *Pinus kesiya* in Malawi based on their mechanical properties for grading purpose. The study provides information to wood industry experts on the potential use and sustainable use of the species when processing logs for timber. It also provides information to tree breeders to establish and refine breeding and deployment programs of the species. Finally, the study provides foundation for machine grading of *Pinus kesiya* timber in Malawi.

4.3 Materials and methods

4.3.1 Study area

The study was conducted in Chongoni Forest Plantation in Dedza, Malawi (Figure 3.1). It is situated about 85 km southeast of the capital, Lilongwe and lies on latitudes 14^{0}10’S and 14^{0}21’S and longitudes 34^{0}09’ E and 34^{0}17’E. It is located between 1570 m and 1690 m above the sea level and receives about 1200 to 1800 mm rainfall per annum, with a mean annual temperature ranging from 7 ^{0}C to 25^{0}C.

4.3.2 Plant material and sampling

The materials for the study were collected from a *Pinus kesiya* seed orchard which was planted in 1984 at a spacing of 2.75 m x 2.75 m with seed source from Zimbabwe. The orchard consisted of 18 families which was planted in a completely randomized design in four replicates. All the silvicultural treatments (weeding, slashing, pruning and thinning) were done on the instruction of the breeder (Ingram and Chipompha 1987).

Six of the 18 families were chosen and a total of ninety straight boled trees (15 trees from each family) with no major defects were randomly selected. Logs of 50 cm length were cut at 1.3 m, 3.3 m, 5.3 m and 7.3 m above the ground per tree. The logs were further cut into 20 mm x 20 mm x 320 mm small wood specimens. A total of 1080 small wood specimens were collected, three specimens per log (inner, middle, and outer). A lot of care was taken to avoid any defects of the specimens. The average height and diameter at breast height of the trees expressed with standard deviations were 25.9 ± 2.8 m and 32.0 ± 3.9 cm, respectively. The north side of each tree was marked before felling. The trees were harvested in May 2014.

4.3.3 Sample processing and measurement

The specimens were conditioned to about 12% moisture content in the laboratory by oven-drying at 105 °C to constant weight. Wood density (ρ) was calculated using Equation (4.1):

$$\rho = \frac{m_{od}}{V_o} \tag{4.1}$$

where, m_{od} is the oven dry mass (g) and V_o is the wood oven dry volume, obtained by displacement method by immersing the specimen in a beaker. Then the specimens were subjected to bending test using Instron Tester over a span length of 300 mm. Load was applied to the center of the specimen at a constant speed of 0.11mm/s. Load of the force plate and the corresponding deflection was recorded from the dial gauge for each sample (the recording was continued until it failed to support one tenth of the maximum load or deflected by more than 60mm). MoR and MoE were calculated as:

$$MoR = \frac{3PL}{2bh^2} \tag{4.2}$$

$$MoE = \frac{P_1L^3}{4d_1bh^3} \tag{4.3}$$

where P is maximum load (N), P_1 is Load at the limit of proportionality (N), L is Span length (mm), b is width of the specimen, h is thickness of the specimen, and d_1 is the deflection at the limit of proportionality (mm). The average moisture content of the specimens at bending test was about 12%.

4.3.4 Statistical analysis

Wood density, MoE and MoR data were tested for normality and homogeneity with Kolmogorov-Smirnov D and normal probability plot tests in SAS software version 9.1.3 (SAS 2004). After the two criteria were met the data were subjected to analysis of variance (ANOVA) using the same SAS software version 9.1.3 (SAS 2004) with stem height and radial direction as fixed factors and family as random effect factor. Differences between treatments means were separated using Fischer's least significant difference (LSD) at the 0.05 level. Regression analysis was performed to determine the relationship between wood density and the mechanical properties.

Based on previous research (Missanjo and Matsumura 2016a), the boundary between juvenile wood and mature wood for *Pinus kesiya* grown in Malawi is ring number 10 from the pith. Therefore, data for juvenile wood and mature wood was subjected to analysis of variance, using SAS PROC GLM type 3 method, to find out if the variation of the mechanical properties were significantly different or not. Differences between treatment means were also separated using Fisher's least significant difference at the 0.05 level.

Grade yield for the specimens were checked using the grading standard of mechanical properties of timbers from South African standard for pine, South East Asia and Pacific Regions for softwood species, and the European standard for softwood species (Table 4.1).

Table 4.1 Mechanical grades of timber for South African Pine, South East Asia and Pacific Regions softwood species, and European Standard for softwood species

Grading Standard	Grade	MoE (GPa)	MoR (MPa)
South African standard for pine	xxx	<7.8	
	S5	7.8 – 9.5	
	S7	9.6 – 11.9	
	S10	≥12.0	
South East Asia and Pacific Regions standard for softwood species	I	<7.45	<58.9
	II	7.45 – 10.3	58.9 – 82.4
	III	10.4 – 13.2	82.5 – 107.0
	IV	13.3 – 16.2	107.1 – 130.9
	V	≥16.3	≥131.0
European standard for softwood species	C14	7	
	C16	8	
	C18	9	
	C20	9.5	
	C22	10	
	C24	11	
	C27	11.5	
	C30	12	
	C35	13	
	C40	14	
	C45	15	
	C50	16	

Adapted from (ES-EN338 2003, SANS 2003, Kamala et al. 2014)

4.4 Results and discussion

4.4.1 Wood density, modulus of elasticity and modulus of rupture

A summary of the results on wood density, MoE and MoR along the radial direction and stem height are presented in Tables 4.2 and 4.3. The results indicate that there were statistically significant ($P<0.001$) differences in wood density, MoE and MoR along the radial direction. Wood density, MoE and MoR increased from pith to bark. The increase in wood density from the pith to bark is due to the increasing age of the cambium (Akachuku 1984). The present results are in agreement with previous researches (Akachuku 1984, Fuwape and Fabiyi 2003, Izekor et al. 2010, Kord et al. 2010, Anoop et al. 2014). Variation along the radial direction is the most studied within tree variability in wood, which is usually reflected as radial pattern of change in wood characteristic of juvenile and mature wood. The radial change in wood properties varies in magnitude and type in different species (Ishiguri et al. 2009, 2011, Uetimane and Ali 2011). The present study also confirms that the magnitude of wood density and mechanical properties varied from pith to bark.

The results also show that there were statistically significant ($P<0.001$) differences in wood density, MoE and MoR along the stem height. There was a decrease in wood density, MoE and MoR from base to top. However, there were not statistically significant ($P>0.05$) differences in wood density, MoE and MoR up to 6m height. This indicates that for uniformity of density and mechanical properties in processed lumber of *P. kesiya* in Malawi, logs of 6 m long or less must be used. According to other researchers (Getahun et al. 2014) juvenility increases from bottom to top and as juvenility increases, density decreases. Due to maturity of wood tissues in the bottom portion, density showed a decreasing trend towards the top portion. This implies that the high-density wood from butt end logs should be used for structural purposes where high strength is required.

Table 4.2 Variation of wood density, MoE and MoR among the families, along the stem height and along the radial direction with standard errors

Variable	Description	n	Density (g/cm^3)	MoE (GPa)	MoR (MPa)
Family	A (ZW701)	180	0.590 ± 0.044^{a}	13.81 ± 0.20^{a}	118.25 ± 1.77^{a}
	B (ZW703)	180	0.593 ± 0.003^{a}	13.53 ± 0.20^{a}	114.40 ± 1.35^{a}
	C (ZW705)	180	0.580 ± 0.003^{a}	13.20 ± 0.18^{a}	110.03 ± 1.30^{a}
	D (ZW709)	180	0.599 ± 0.003^{a}	13.27 ± 0.12^{a}	112.76 ± 1.28^{a}
	E (ZW712)	180	0.592 ± 0.002^{a}	13.45 ± 0.15^{a}	113.72 ± 1.37^{a}
	F (ZW716)	180	0.602 ± 0.003^{a}	13.49 ± 0.13^{a}	112.89 ± 1.14^{a}
Stem height (m) above the ground	1.3	270	0.597 ± 0.002^{a}	13.74 ± 0.14^{a}	116.93 ± 1.21^{a}
	3.3	270	0.594 ± 0.002^{ab}	13.56 ± 0.13^{ab}	115.05 ± 1.14^{ab}
	5.3	270	0.591 ± 0.003^{ab}	13.43 ± 0.15^{ab}	113.94 ± 1.09^{ab}
	7.3	270	0.587 ± 0.003^{b}	13.12 ± 0.13^{b}	108.77 ± 1.05^{b}
Radial direction	Inner (Ring 1-5)	360	0.574 ± 0.002^{b}	11.80 ± 0.12^{b}	106.32 ± 0.90^{b}
	Middle (Ring 12-18)	360	0.593 ± 0.002^{a}	14.19 ± 0.12^{a}	115.99 ± 0.99^{a}
	Outer (Ring 21-28)	360	0.601 ± 0.002^{a}	14.39 ± 0.12^{a}	118.70 ± 1.03^{a}
	Mean		0.593±0.001	13.46±0.07	113.67±0.57
	CV%		6.57	6.35	5.95
	R^2		0.869	0.837	0.863

Note: n=sample size (number of wood specimen); ^{a,b} Means with different superscript within a column in the same variable significantly differ ($P<0.001$); CV=coefficient of variation; R^2=coefficient of determination.

Table 4.3 Variation of wood density, stiffness and strength in juvenile wood and mature wood along the stem height

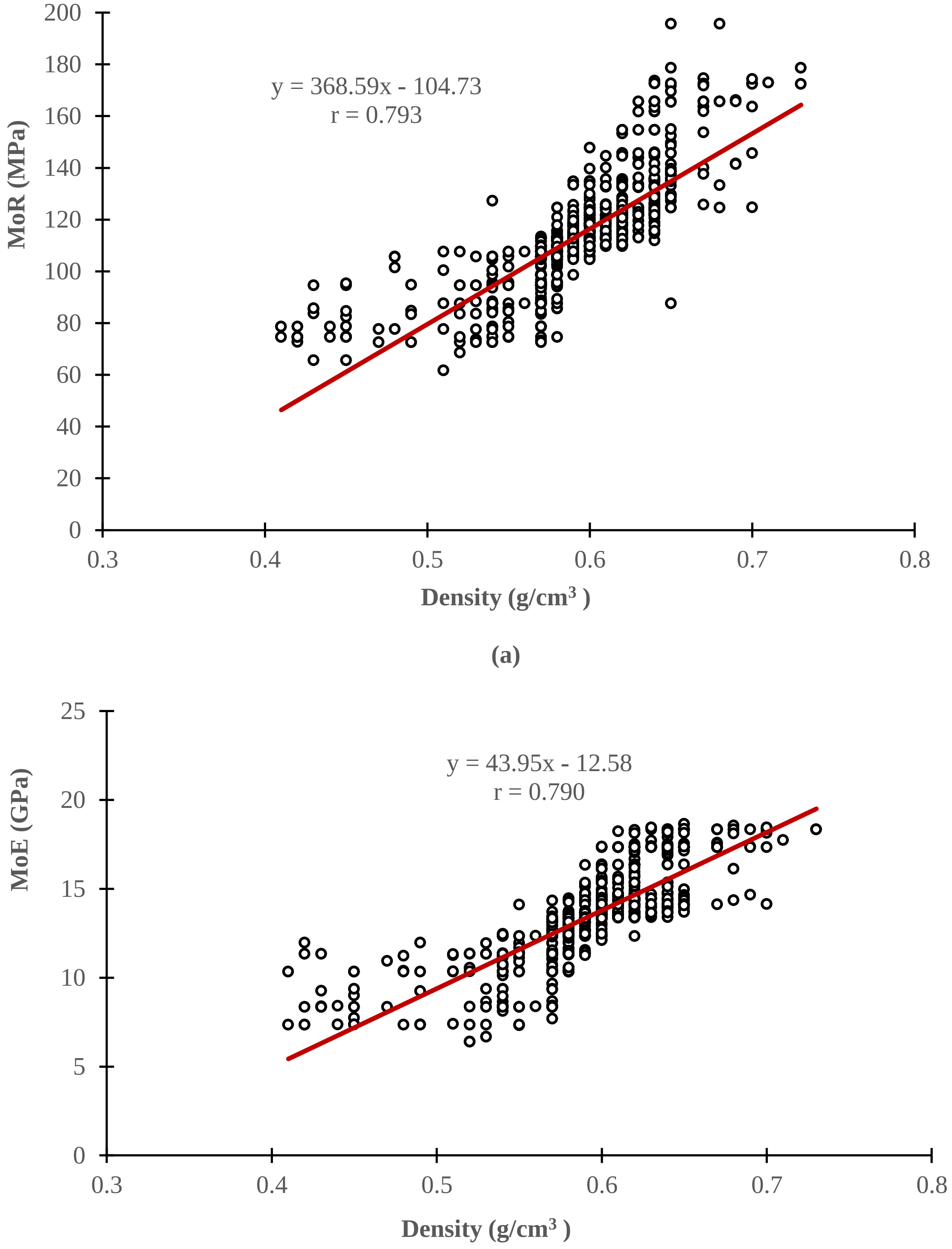
Stem height (m)	Density (g/cm^3)		MoE (GPa)		MoR (MPa)	
	Juvenile wood	**Mature wood**	**Juvenile wood**	**Mature wood**	**Juvenile wood**	**Mature wood**
7.3	0.579±0.005^a	0.593±0.003^b	11.60±0.24^a	13.80±0.15^b	103.19±1.73^a	112.06±1.31^b
5.3	0.582±0.004^a	0.596±0.003^{ab}	11.74±0.25^a	14.30±0.18^{ab}	104.28±1.63^a	117.27±1.37^{ab}
3.3	0.586±0.004^a	0.598±0.003^{ab}	11.87±0.22^a	14.41±0.15^{ab}	107.99±1.76^a	119.08±1.46^{ab}
1.3	0.589±0.003^a	0.601±0.003^a	11.99±0.23^a	14.65±0.18^a	109.82±2.04^a	120.99±1.49^a
Mean	0.584±0.002	0.597±0.001	11.80±0.12	14.29±0.12	106.32±0.96	117.35±0.68

Note: Mean values are followed by standard errors; ^{a,b} Means with different superscript within a column in the same variable significantly differ *(P*<0.001).

The present results are comparable with those reported by Izekor et al. (2010) and Ogunsanwo and Akinlade (2011), working with *Tectona grandi*s and *Gmelina arborea* respectively. Other researchers (Kord et al. 2010, Fuwape and Fabiyi 2003) also reported similar observation for *Populus euramericana* and *Nauclea diderichii* wood plantations, respectively. The observed decrease in wood density from bottom to top agrees with the auxin gradient theory (Larson 1969). According to the theory, the endogenous auxin arising in the apical region of growing shoots stimulates cambial division and xylem differentiation. Therefore, high production of early wood near the crown contributes significantly to low wood density at the top. There were no significant ($P>0.05$) differences in wood density, MoE and MoR among families. This is an indication that any tree among the families can be selected for tree improvement programmes of pine if wood density, MoE or MoR are considered as variables.

4.4.2 The relationship between wood density and mechanical properties

Correlation, graphical representation and regression equations results of wood density and mechanical properties are presented in Figure 4.1. The results show that wood density had a strong significant linear relationship with MoE ($r = 0.790$, $P<0.001$) and MoR ($r = 0.793$, $P<0.001$). This implies that wood density can be used as a parameter for predicting mechanical properties. In other words, this shows that wood density is a good indicator of mechanical properties of wood; therefore, controlling density would have a positive impact on mechanical properties. The present results are in line with those of other researchers (Izekor et al. 2010, Wahab et al. 2013) who reported a strong positive relationship between wood density and mechanical properties in *T. grandis* and *Gigantochloa levis*, respectively. The positive relationship between wood density and mechanical properties in *E. tereticornis* (Sharma et al. 2005) also support the findings of the present study.



(a)

(b)

Figure 4.1 Relationship between (**a**) wood density and MoR; and (**b**) wood density and MoE.

4.4.3 Grade yield of juvenile wood and mature wood

Summary results for the mechanical properties and grade yields for juvenile wood and mature wood are presented in Table 4.4 and Figure 4.2, respectively. The results show that there were statistically significant (P<0.001) differences between mature wood and juvenile wood in mechanical properties. Mature wood had higher values in mechanical properties than juvenile wood. This indicates that mature wood is superior in stiffness and strength than juvenile wood. Similar results were reported by other researchers Kamala et al. (2014) working with *Pinus patula* grown in Malawi.

Figure 4.2 shows grade yield for both juvenile wood and mature wood according to MoE and MoR using grading standard of mechanical properties of timbers from South African standard for pine, South East Asia and Pacific regions, and the European standard for softwood species. The results clearly show that mature wood yielded more grades with higher values of MoE and MoR than juvenile wood. This implies that mature wood and juvenile wood should be used for different purposes to avoid underutilization. According to other researchers Kamala et al. (2014), uniform use of juvenile wood and mature wood for structural purposes would be potentially dangerous because juvenile wood has inferior mechanical performance. Therefore, lumber strength can be improved by processing logs of old trees and minimize the use of the interior portion of the log.

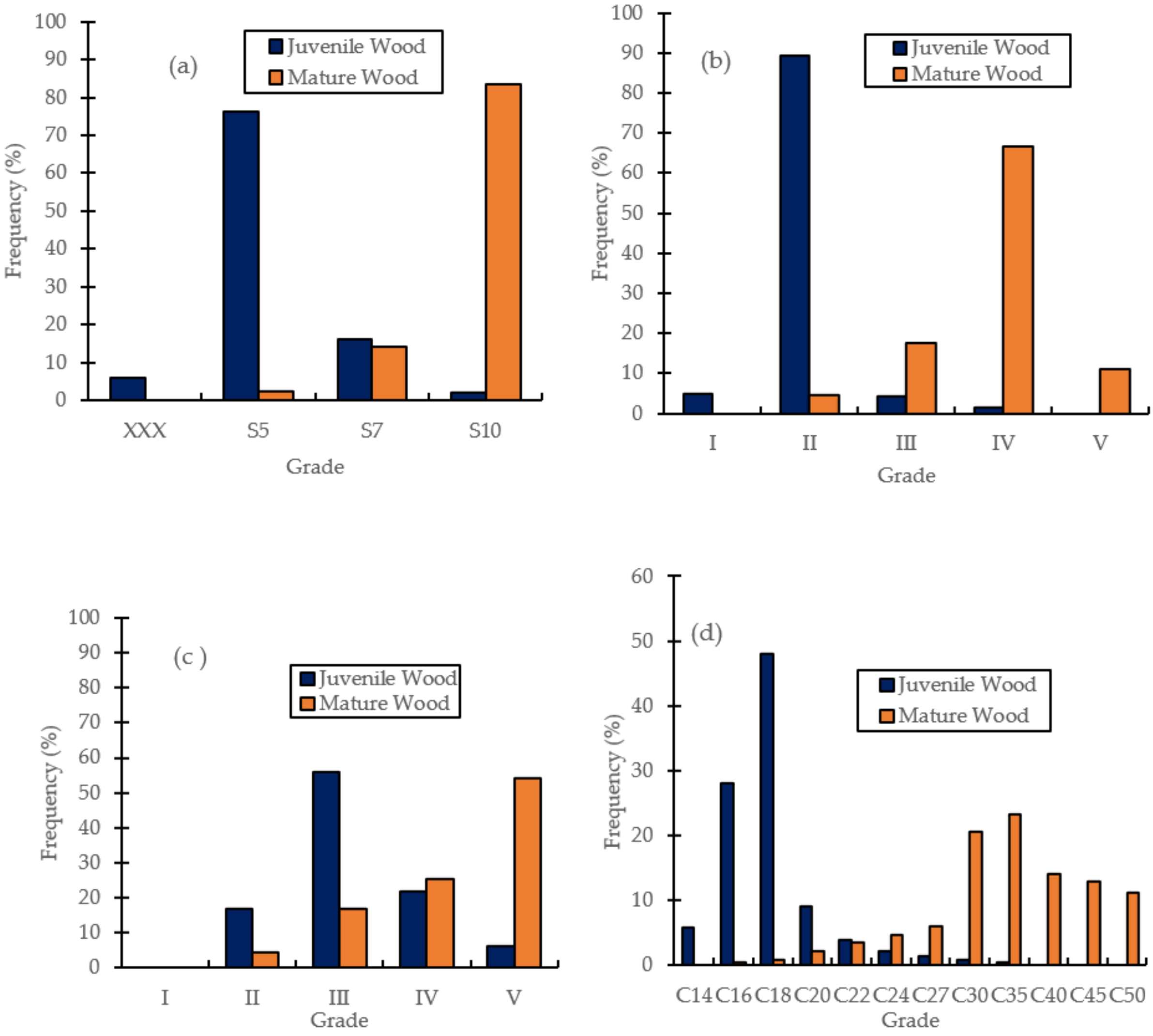


Figure 4.2 Specimen grade allocation for Juvenile wood and Mature wood in terms of (**a**) MoE for South African Standard for Pine; (**b**) MoE and (**c**) MoR according to South East Asia and Pacific Regions; (**d**) MoE according to European Standard for softwood species.

Table 4.4 Mechanical properties of juvenile and mature woods of *P. kesiya* specimens in Malawi.

Description	**MoE (GPa)**	**MoR (MPa)**
Juvenile Wood	11.80 ± 0.12 ^{b}	106.32 ± 1.0 ^{b}
Mature Wood	14.29 ± 0.12 ^{a}	117.35 ± 1.0 ^{a}
Mean	13.46 ± 0.12	113.67 ± 1.0
CV (%)	6.46	6.28
R^2	0.813	0.816

$^{a,\ b}$ Means with different superscript within a column significantly differ ($P<0.001$); CV = coefficient of variation; R^2 = coefficient of determination.

Based on the results in Table 4.4, mature wood for *Pinus kesiya* grown in Malawi can be allocated into grades S10, IV and C40, while juvenile wood can be allocated into grades S7, III and C27 using grading standard of mechanical properties of timbers from South African standard for pine, South East Asia and Pacific regions, and the European standard for softwood species, respectively. This indicates that wood products from *P. kesiya* grown in Malawi such as lumber, composite panels and structural composite lumber products can compete successfully with same products in the huge construction markets of Southern Africa, Asia and Europe.

The procedure in establishment of grades of lumber are: testing of small wood specimens according to the guidelines, establishing strength values and allowable properties, establishing visual grades rules, and, lastly, verifying grades using in-grade testing (Ridley-Ellis 2011, Kamala et al. 2014). This research has clarified the variation of mechanical properties, and thus has established the first step in assigning allowable mechanical properties for *P. kesiya* grown in Malawi. Therefore, testing using the "in grade approach" (use of full size lumber samples) is recommended to compare the results. This will help in assignment of standard grades that will ensure the efficient utilization of *P. kesiya* structural lumber in Malawi.

4.5 Conclusion

The study has shown that there were statistically significant differences in wood density and mechanical properties (MoR and MoE) along the radial direction and stem height. Wood density and mechanical properties increased from the pith to the bark and decreased from the butt upwards. Therefore, for uniformity of density and mechanical properties in processed lumber of *P. kesiya* in Malawi, logs of 6 m long or less must be used. There were no significant differences in wood density and mechanical properties among families. This is an indication that any tree among the families can be selected for tree improvement programs if density is considered as a variable. There were statistically significant differences between mature wood and juvenile wood in mechanical properties. Mature wood had higher superior mechanical performance than juvenile wood. Wood density had a strong positive significant linear relationship with mechanical properties. This suggests that it is potentially possible to simultaneously improve wood density and mechanical properties of *P. kesiya* in Malawi. Therefore, controlling wood density would have a positive impact on mechanical properties. Furthermore, the present results are a foundation that will provide a technical basis for the machine grading of *P. kesiya* structural lumber in Malawi.

CHAPTER 5

Genetic Improvement of Wood Properties in *Pinus kesiya* Royle ex Gordon for Sawn Timber Production in Malawi

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5.1 Abstract

Accurate prediction of genetic potential and response to selection in breeding requires knowledge of genetic parameters for important selection traits. In this study, we estimated genetic parameters for wood properties in Khasi pine (*Pinus kesiya* Royle ex Gordon) grown in Malawi. Data on wood properties and growth traits were collected from six families of *Pinus kesiya* at the age of 30. The results show that wood density had a higher genetic control (h^2 = 0.595 ± 0.055) than wood stiffness (h^2 = 0.559 ± 0.038) and wood strength (h^2 = 0.542 ± 0.091). The genetic correlation among wood quality traits was significantly moderate (0.464 ± 0.061) to high (0.735 ± 0.025). The predicted genetic response indicated that selection for wood density at 10% selection intensity would increase stiffness and strength by 12.6% and 8.85%, respectively. The genetic correlations between growth and wood quality traits were moderately unfavourable. However, sufficient variation exists within the breeding population to select individuals with both good growth rate and high wood quality traits. It is therefore suggested that all trees with both diameters at breast height (DBH) greater than 32.0 cm and density greater than 0.593 g/cm^3 must be selected in order to increase the efficiency of the breeding programme. However, in the long term, it is recommended that the best selection strategy would be to develop a multiple-trait selection index. The selection index should be developed using optimal index weights for the advanced *Pinus kesiya* breeding programme in Malawi.

Keywords: *Pinus kesiya*, wood properties, heritability, genetic correlation, correlated response

5.2 Introduction

Khasi pine (*Pinus kesiya* Royle ex Gordon) is a tree that can grow up to 45 m in height and over 100 cm in diameter (Gogoi et al. 2014). It is naturally distributed in the Himalayan region of Asia, which includes: China, India, Laos, Myanmar, Philippines, Thailand, Tibet, and Vietnam. The species has a large ecological adaptability and growing performance and can be found in a variety of different locations from 300 to 2700 m above the sea level (Missio et al. 2005). The most efficient way to meet the increasing global wood demand is to establish plantations with genetically improved seeds. The relative fast growth and wide geographical distribution of the species led to the establishment of a breeding programme in Malawi in the 1970s with seed sources from South Africa and Zimbabwe (Missanjo and Kamanga-Thole 2014). The timber of this species is easily sawn and suitable for paneling, cabinet work, joinery, poles and general construction (Missio et al. 2005, Missanjo and Mwale 2014).

Modulus of elasticity (MoE) and Modulus of Rupture (MoR) are important traits associated with structural quality. MoE is an indication of wood stiffness while MoR is an indication of wood strength (Johnson and Gartner 2006). These traits must be considered as composite traits that depend on physical, chemical and anatomical properties of wood. According to reports from different researchers (Zobel and van Buijtenen 1989, Steffenrem et al. 2007), wood density is the most important trait controlling wood stiffness and strength. It has a strong positive correlation with both tensile and compression strength (Kollmann and Cote 1968). Therefore, improved wood density trait is expected to meet a wide range of demands and potential for future utilization. Current studies (Hannrup et al. 2000, Ivković et al. 2002, Apiolaza 2009, Apiolaza et al. 2011, Guller et al. 2011) have indicated that wood density, with high heritability and large economic gain from selection, is an ideal selection criterion for tree breeding programmes because of its strong effect on wood quality. Heritability of wood density is generally found to be higher than those of growth traits in forest trees. Published heritability of density in pines varies from 0.40–0.85, compared to the usual range of 0.15 to 0.25 for many growth traits (Zobel and Jett 1995, Guller et al. 2011). This indicates that genetic manipulation of wood density can result in good gains.

The main limitation to the effective breeding programme of *Pinus kesiya* in Malawi has been lack of genetic parameter information on wood properties. The information helps to guide decisions on the most appropriate breeding strategy and to monitor genetic progress. Most of the genetic variation studies in Malawi have focused on growth traits (Missio et al. 2005). However, faster growth is generally negatively correlated with important wood quality traits (Lenz et al. 2010, 2013). Therefore, there is a need to include wood quality traits in tree selection programmes to ensure future wood supplies have the appropriate mechanical properties for structural applications and other end uses.

In this paper, genetic parameters for wood quality traits, namely wood density, stiffness and strength, were estimated. Genetic parameters for growth traits (DBH, height and volume) were also estimated to provide an indication of the genetic control and relationship between wood properties and growth traits. The objectives in this study were to: (1) estimate heritability and genetic gains in wood density, stiffness and strength; (2) determine the genetic control in wood properties along the radial direction and stem height; (3) estimate genetic correlations among the wood properties; (4) determine the genetic correlation between wood properties and growth traits; and (5) estimate the correlated responses for the target traits. These parameters are important to estimate the direct and indirect responses from selection and to guide the establishment and refinement of the *Pinus kesiya* breeding programme in Malawi.

5.3 Materials and methods

5.3.1 Study area and genetic materials

The study was undertaken using an open pollinated Pinus kesiya orchard located in Chongoni Forest Plantation in Dedza, Malawi. It is situated about 85 km southeast of the capital, Lilongwe, and lies on latitudes $14^0$10’S and $14^0$21’S and longitudes $34^0$09’ E and $34^0$17’E. The orchard was established in a ferruginous soil in 1984 with an 18-family seed source from Zimbabwe. Ten tree plots laid out in a completely randomized design in four replicates were planted at a spacing of 2.75 m x 2.75 m. All the silvicultural treatments were performed on the instruction of the breeder. In May 2014, six families were chosen based on straightness. A total of ninety trees (15 trees from each family) with no major defects were randomly selected for the study.

5.3.2 Growth data

The sample trees were measured for diameter at breast height (DBH) (1.3 m above the ground level) using a caliper, and total height was measured using a vertex with a transponder. Stem volume (Vol, m^3) was calculated as a function of diameter at breast height (DBH, cm) and total height (HGT, m) was calculated according to the following equation (Ingram and Chipompha 1987):

$$\text{Vol} = 3.6128 \times 10^{-5} \times [DBH]^2 \times HGT \qquad (5.1)$$

The average height, diameter at breast height and volume of the trees expressed with standard deviations were 25.9 ± 2.8 m, 32.0 ± 3.9 cm and 0.989 ± 0.319 m^3, respectively.

5.3.3 Wood sample processing and measurement

Wood sample processing and measurement was conducted as outlined by Missanjo and Matsumura (2016b). Briefly, a total of 1080 wood specimens, measuring 20 mm × 20 mm × 320 mm, were collected from innerwood, middlewood and outerwood at 1.3 m, 3.3 m, 5.3 m and 7.3 m tree height. The specimens were conditioned to 12% moisture content in the laboratory by oven-drying at 105 °C to constant weight. Wood density was calculated as dry mass divided by dry volume, where volume was obtained by the displacement method. The samples were then subjected to bending test using an Instron Tester over a span length of 300 mm. The estimated mean wood density, Modulus of Elasticity (MoE) and Modulus of Rupture (MoR) with standard deviations were 0.593 ± 0.033 g/cm^3, 13.5 ± 2.3 GPa and 114 ± 19 MPa, respectively.

5.3.4 Statistical analysis

Data on wood properties (Wood density, MoE and MoR) and growth (DBH, height and volume) were tested for normality and homogeneity with Kolmogorov-Smirnov D and normal probability plot tests in SAS software version 9.1.3 (SAS, 2004). In a few marginal cases, a graphic residual analysis was also performed; however, no data transformation was deemed necessary. Variance components and covariances were estimated using Mixed procedure and PROC VARCOMP in SAS. Data on wood properties (density, MoE and MoR) were subjected to the following linear mixed model:

$$\mathrm{Y}_{ijkl} = \mu + \mathrm{H}_i + \mathrm{R}_j + \mathrm{F}_k + T_l(F_k) + (HR)_{ij} + (HF)_{ik} + (RF)_{jk} + HT(F_k)_{il} + RT(F_k)_{jl} + (HRF)_{ijk} + \mathrm{e}_{ijl(k)} \quad (5.2)$$

where: Y_{ijkl} is the observation in the $ijkl^{\mathrm{th}}$ tree; μ is the overall mean; H_i and R_j are fixed effects of stem height and stem radial position, respectively; F_k is the random effect of family; $\mathrm{T}_l(\mathrm{F}_k)$ is the tree-within-family effect; $(\mathrm{HR})_{ij}$ is the interaction between stem height and stem radial position effect; $(\mathrm{RF})_{jk}$ is the interaction between stem radial position and family effect; $\mathrm{HT}(\mathrm{F}_k)_{il}$ is the interaction between stem height and tree-within-family effect; $\mathrm{RT}(\mathrm{F}_k)_{jl}$ is the interaction between stem radial position and tree-within-family effect; $(\mathrm{HRF})_{ijk}$ is the interaction between stem height, stem radial position and family effect; and $\mathrm{e}_{ijl(k)}$ is the random error term.

A X^2 test was performed on the difference in the −2 residual log likelihood of the model to select the best model. All the interactions between parameters were removed from the analysis because their contribution to the total variance was negligible. Furthermore, the variance component for these terms could not be estimated or was otherwise insignificant. Equation (5.2) was therefore reduced to:

$$\mathrm{Y}_{ijkl} = \mu + \mathrm{H}_i + \mathrm{R}_j + \mathrm{F}_k + T_l(F_k) + \mathrm{e}_{ijl(\mathrm{k})} \quad (5.3)$$

Growth data were subjected to a linear mixed model with replicate as a fixed factor and family as a random effect factor.

Family mean heritability and individual heritability were calculated using Equations (5.4) and (5.5), respectively (Falconer and Mackay 1996):

$$h_a^2 = \frac{\sigma_f^2}{\sigma_f^2 + \frac{\sigma_e^2}{bn}} \tag{5.4}$$

$$h_w^2 = \frac{3\sigma_f^2}{\sigma_e^2} \tag{5.5}$$

where h_a^2 and h_w^2 are heritability among and within families, respectively; σ_f^2 is family variance; σ_e^2 is residual error variance; *b* is number of positions in the stem height where specimens were collected per tree for specimen-level analysis, while for tree-level analysis, it is the number of replicates; and *n* is the number of positions in the radial direction where specimens were collected per log for specimen-level analysis, while for tree-level analysis, it is the number of trees per replicate. The within-family heritability estimate was one third due to the mixed mating that is expected in *Pinus* species (Apiolaza et al 2011), rather than one quarter as is appropriate for true half-sibs (Falconer and Mackay 1996). Standard errors of heritabilities were estimated by the Delta method and PROC IML in SAS.

Genetic correlations (r_A) between traits were estimated using the following formula (Falconer and Mackay 1996):

$$r_A = \frac{COV_a(x, y)}{\sqrt{\sigma_{ax}^2 . \sigma_{ay}^2}} \tag{5.6}$$

where the numerator is the additive genetic covariance between traits *X* and *Y*; σ_{ax}^2 and σ_{ay}^2 are the additive variance components for traits *X* and *Y*, respectively. Standard errors associated with genetic correlation were calculated using the following equation (Falconer and Mackay 1996):

$$SE(r_A) = \frac{1 - r_A^2}{\sqrt{2}} . \sqrt{\frac{SE(h_x^2).SE(h_y^2)}{h_x^2 . h_y^2}} \tag{5.7}$$

where r_A is the genetic correlation between the traits; h_x^2 and h_y^2 are heritability for traits X and Y, respectively; $SE(h_x^2)$ and $SE\left(h_y^2\right)$ are standard errors for heritability traits X and Y, respectively. Residual correlations (r_E) between traits were calculated using the same formula as for genetic correlation. However, residual variance components were used. Phenotypic correlations were calculated as Pearson product moment correlations (r_P) using the CORR procedure in SAS.

In most tree breeding programmes, stem wood quality (stiffness and strength) and volume are the most important breeding objective traits (Hong et al. 2014). Therefore, genetic gains and correlated response were calculated to improve these three traits (MoE, MoR and Volume) by direct selection and indirect selection using correlated traits. Genetic gains (G_x) and correlated response (CR_x), expressed in percentage, were calculated using the following formulas (Falconer and Mackay 1996):

$$G_x = i.h_x^2.\mathrm{CV}_{\mathrm{p}x} \tag{5.8}$$

$$CR_x = i.h_x.h_y.r_A.\mathrm{CV}_{\mathrm{p}x} \tag{5.9}$$

where i is the selection intensity; h_x^2 is the heritability of the objective trait; r_A is the genetic correlation between the traits; h_x and h_y are square roots of the heritability for the objective and selected traits, respectively; CV_{px} is the coefficient of phenotypic variance for the objective trait, expressed as:

$$CV_{px} = \frac{\sigma_{px}}{\mu} \times 100 \tag{5.10}$$

where σ_{px} is the phenotypic standard deviation for the objective trait; μ is the phenotypic mean value of the objective trait.

5.4 Results and discussion

5.4.1 Heritability and genetic gains

Heritability and genetic gains for wood properties were relatively higher than those for growth traits, except the genetic gain for volume among the family (Table 5.1). Heritability for wood properties among the family indicated high genetic control, while heritability for growth traits indicated moderate genetic control. This suggests that there is a substantial degree of genetic control and strong potential gains in wood properties compared with growth traits. Therefore, important genetic progress can be achieved using a combined selection from among and within the families. Wood density had higher heritability and genetic gain, indicating that this trait is easier to select, and higher genetic gains can be obtained by direct selection of this trait.

Heritability is an important parameter for economical and biological success of plantation forestry, monitoring genetic progress and developing breeding strategies (Falconer and Mackay 1996, Hong et al. 2014). High heritability for MoE ($h^2 = 0.559 \pm 0.038$) observed in this study is very encouraging. High MoE increases the recovery rate of structural and appearance-grade products, which resulted in a higher economic return (Hong et al. 2014). The present results are consistent with those in the literature (Cornelius 1994). On the other hand, the present findings are higher than those observed by other researchers (Yildirim et al. 2006) working with Turkish pine (*Pinus brutia* Ten.). This confirms the promising genetic control of the traits as well as the high potential of the population for selection in the present study.

Table 5.1 Heritability (h^2) and genetic gains (G_S) for wood properties and growth traits.

Traits	**Among Families**		**Within Families**	
	h^2 (s.e.)	**G_s (%)**	**h^2 (s.e.)**	**G_s (%)**
Wood Properties				
Density (g/cm^3)	0.595(0.055)	22.6	0.367(0.100)	13.2
MoE (GPa)	0.559(0.038)	16.7	0.317(0.095)	9.01
MoR (MPa)	0.542(0.091)	15.8	0.295(0.092)	8.20
Growth Traits				
Total height (m)	0.469(0.048)	7.11	0.177(0.078)	2.42
DBH (cm)	0.400(0.042)	6.05	0.133(0.073)	1.63
Volume (m^3)	0.483(0.053)	19.4	0.187(0.079)	7.55

Note: MoE = modulus of Elasticity; MoR = modulus of rupture; DBH = diameter at breast height; s.e. = standard error, Genetic gains (Gs) at 10% selection intensity (i.e., $i = 1.76$).

5.4.2 Genetic control of wood properties along the radial direction and stem height

Trends in heritability from pith to bark and along the stem height were also investigated for wood density, MoE and MoR (Figure 5.1). The results show that the heritability for wood density, MoE and MoR increased from pith to bark and decreased from the butt upwards. This suggests that efficiency of selection based on the outer wood for wood density, MoE and MoR would generally be higher than selection based on inner wood. The heritability ranged from 0.409 ± 0.048 (MoR) to 0.606 ± 0.052 (wood density) along the radial direction and 0.619 ± 0.055 (wood density) to 0.405 ± 0.047 (MoR) along the stem height. This indicates that the traits (wood density, MoE and MoR) are under moderate to high genetic control along the radial direction and stem height. Therefore, genetic progress can be achieved through indirect selection of these wood properties (wood density, MoR and MoR). The present results are consistent with the findings of other researchers (Vargas-Hernandez and Adams 1992, Hylen 1999, Li and Wu 2005, Gaspar et al. 2008) in different species.

The increase in heritability for wood density from pith to bark is not surprising since genes may change with age (Moura and Dvorak 2001). Phenotypic variances for wood density decrease with age (Gaspar et al. 2008), hence strong genetic control for wood density increases from pith to bark. However, the present results are in conflict with those reported by other researchers (Nicholls et al. 1980, Hodge and Purnell 1993, Louzada and Fonseca 2002, Kumar et al. 2006) for different species. Hodge and Purnell (1993) and Nicholls et al. (1980) reported a decrease in heritability of wood density from pith to bark in slash pine (*Pinus elliottii* Engelm.) and radiata pine (*Pinus radiata* D. Don), while other researchers (Louzada and Fonseca 2002, Kumar et al. 2006) found an increase in heritability followed by a decrease from pith to bark of wood density in maritime pine (*Pinus pinaster* Aiton) and *Pinus radiata*.

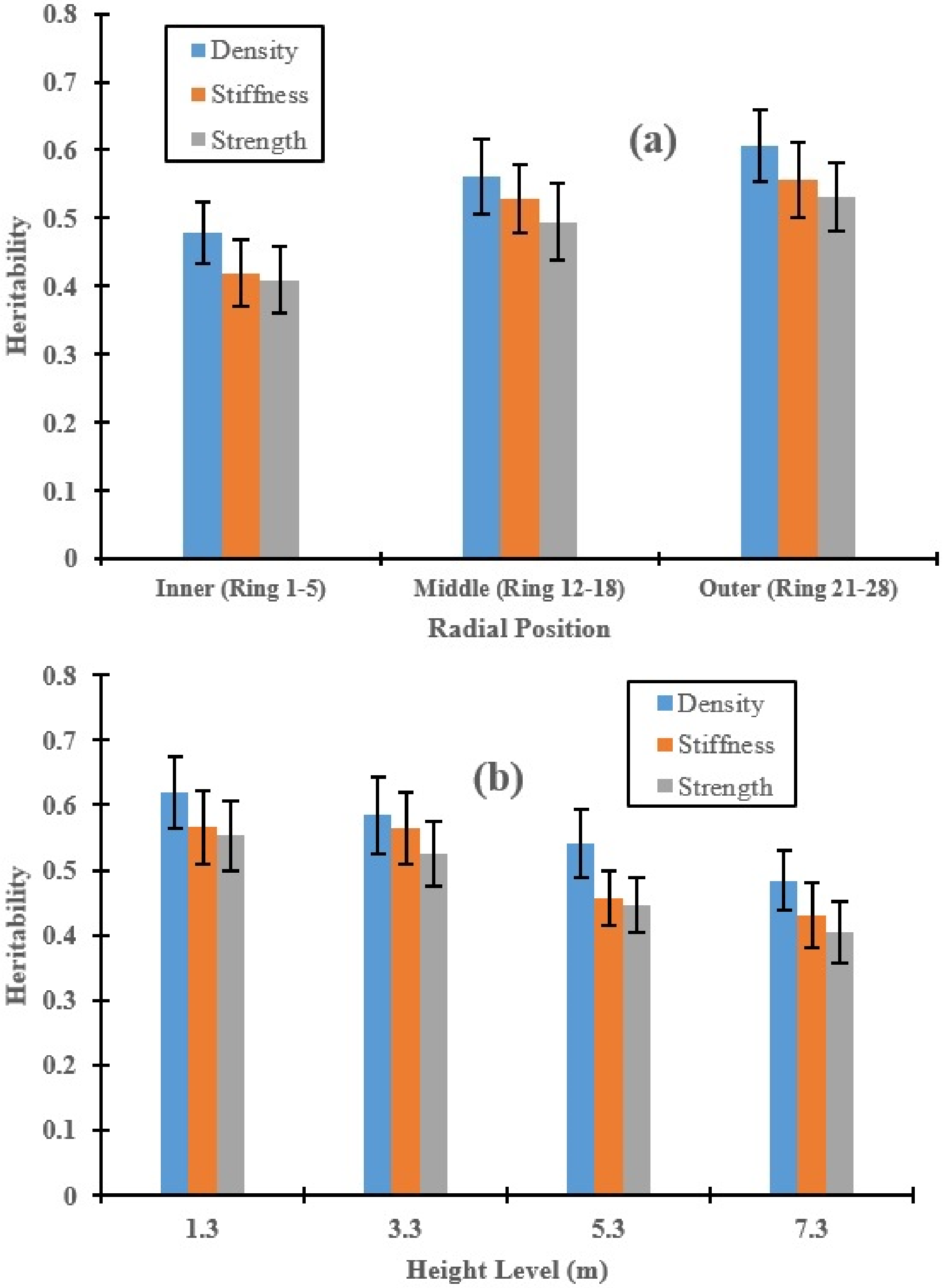

Figure 5.1 Radial (**a**) and axial (**b**) genetic control of wood density, stiffness and strength.

The reason behind these difference in results may be that the estimates of genetic parameters in the previous studies could have been affected by different factors such as site conditions, genetic material, experimental and measurement procedures for wood density and other factors (Wright 1976, Zobel and Sprague 1998, Gaspar et al. 2008). For example, in measurement procedures, wood density in *Pinus pinaster* (Louzada and Fonseca 2002) was measured using ring-by-ring measurements, while in the present study, wood density was the mean of rings 1–5 for inner wood, rings 12–18 for middle wood and rings 21–28 for outer wood.

5.4.3 Genetic correlation among wood properties

The genetic correlations are summarized in Table 5.2. High positive genetic correlation was observed between wood density and MoE (r_A = 0.735 ± 0.025). Strength showed a positive moderate genetic correlation with wood density (r_A = 0.539 ± 0.060) and stiffness (r_A = 0.464 ± 0.061). The corresponding phenotypic relationships are plotted in Figure 5.2 and summarized in Table 5.2. The phenotypic correlations among the wood properties were highly significant (P<0.001) and ranged from r_p = 0.790 ± 0.019 (wood density and MoE) to r_p = 0.818 ± 0.018 (MoR and MoE). However, the residual correlations ranged from weak (r_E = 0.213 ± 0.053; wood density and MoE) to moderate (r_E = 0.521 ± 0.061; wood density and MoR) (Table 5.2).

The phenotypic correlation between traits is a complex of genetic and non-genetic factors. The decomposition of phenotypic correlation into genetic and other correlations is essential to improve understanding of the relationships among the traits (Fukatsu et al. 2015). The genetic correlation between wood density and stiffness was very strong in the present study, but their corresponding residual correlations were weak. This implies that the phenotypic relationship between wood density and stiffness mainly depends on the genetic relationship.

Table 5.2 Phenotypic, genetic and residual correlations between and among growth traits and wood properties.

Traits	Correlation (Standard Error)		
	Phenotypic	**Genetic**	**Residual**
Between Growth Traits and Wood Properties			
Height vs. Density	−0.248 (0.010) *	−0.386(0.057)	−0.052 (0.006)
Height vs. MoE	−0.013 (0.001) ^{ns}	−0.309(0.056)	−0.036 (0.002)
Height vs. MoR	0.041 (0.003) ^{ns}	−0.366(0.082)	−0.019 (0.009)
DBH vs. Density	−0.338 (0.011) *	−0.496(0.049)	−0.097 (0.004)
DBH vs. MoE	−0.112 (0.006) ^{ns}	−0.473(0.046)	−0.298 (0.083)
DBH vs. MoR	−0.093 (0.004) ^{ns}	−0.468(0.071)	−0.149 (0.089)
Volume vs. Density	−0.358 (0.010) *	−0.458(0.052)	−0.290 (0.061)
Volume vs. MoE	0.099 (0.002) ^{ns}	−0.399(0.051)	−0.224 (0.058)
Volume vs. MoR	−0.056 (0.005) ^{ns}	−0.488(0.071)	−0.272 (0.086)
Among Growth Traits			
Height vs. DBH	0.688 (0.077) **	0.935 (0.009)	0.545 (0.052)
Height vs. Volume	0.850 (0.056) **	0.684 (0.040)	0.550 (0.052)
DBH vs. Volume	0.955 (0.031) **	0.987 (0.002)	0.921 (0.011)
Among Wood Properties			
Density vs MoE	0.790 (0.019) **	0.735 (0.025)	0.213 (0.053)
Density vs MoR	0.793 (0.019) **	0.539 (0.060)	0.521 (0.061)
MoE vs MoR	0.818 (0.018) **	0.464 (0.061)	0.475 (0.060)

Note: DBH = diameter at breast height, MoE = modulus of elasticity; MoR = modulus of rapture; Standard errors are given in parenthesis. **correlation estimates significantly different from zero (*P*<0.001); *correlation estimates significantly different from zero (*P*<0.05); ^{ns} = correlation estimates not significantly different from zero (*P*>0.05).

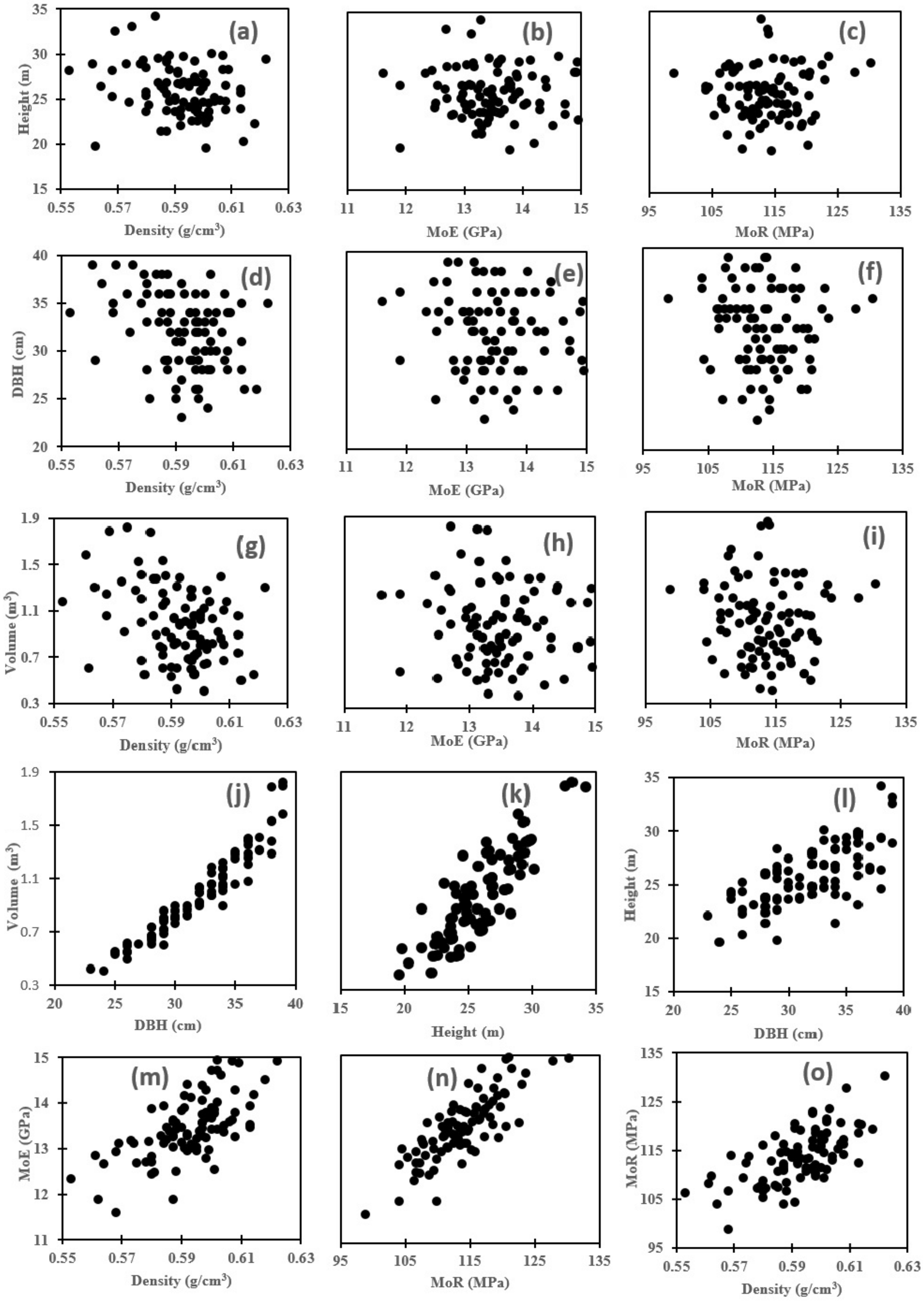

Figure 5.2 Phenotypic relationship between growth traits and wood properties (**a**–**i**); among growth traits (**j**–**l**); and among wood properties (**m**–**o**).

Genetic correlations are useful to make inferences about indirect responses of one trait from the selection of others. Wood density is of particular importance because it can have strong impact on wood stiffness and strength (Panshin and Zeeuw 1980, Hung et al. 2015). The present study found that the genetic correlations between wood density and mechanical properties (MoE and MoR) were favourable. Therefore, selection based solely on wood density, which is easily measurable, could result in improvements in both wood stiffness and strength. Similar favourable genetic correlations among wood properties (wood density, stiffness and strength) have been reported in previous studies (Kumar et al. 2002, Hai 2009, Guller et al. 2011).

Wood density and microfibril angle (MFA) are both regarded as important factors for the prediction of stiffness (Hong et al. 2014). However, in the present study, only density was considered. This is because MFA affects both density and stiffness (Hong et al. 2014). The genetic correlation between density and stiffness was favourable in the present study, suggesting that the genetic correlation between MFA and stiffness is also likely to be favourable. Thus, wood with high stiffness has high density and small MFA (Panshin and Zeeuw 1980, Walker and Butterfield 1995, Hung et al. 2015). However, further research may be required to confirm the correlation between MFA and stiffness.

5.4.4 Genetic correlation between wood properties and growth traits

Genetic and phenotypic correlations between wood properties (wood density, MoE and MoR) and growth traits (DBH, height and volume) are summarized in Table 5.2. Weak negative phenotypic correlations between most wood properties and growth traits were observed. Most of the phenotypic correlations between growth traits and wood properties were non-significant with the exception of wood density. The genetic correlations between wood properties and growth traits were unfavourable. The negative correlation between wood properties and growth traits could be due to genetic and environmental causes (Hong et al. 2014). The adverse genetic correlations between wood properties and growth traits ranged from $r_A = -0.309 \pm 0.056$ (height and MoE) to $r_A = -0.496 \pm 0.049$ (height and wood density). Such unfavourable genetic correlations between wood properties and growth traits were reported in many other conifers (Wu et al. 2008, Hong et al. 2014). On the other hand, other researchers (Fukatsu et al. 2015) reported a positive genetic correction between wood properties and growth traits in Japanese larch (*Larix kaempferi* Lamb. Carrière). Based on the present results and previous reports, the genetic correlations between wood properties and growth traits depend on species.

Stiffness is usually a breeding objective trait to increase recovery rate for sawn timber (Hong et al. 2014), and the adverse genetic correlations between growth traits and stiffness indicate proper index weights should be estimated in future studies (Ivković et al. 2006).

5.4.5 Correlated response

Correlated response is often used as a measure of the increase or decrease in performance after indirect selection (Hong et al. 2014). A summary of the results on correlated responses for three breeding objectives traits (MoE, MoR and volume) are presented in Table 5.3. Correlated responses were assessed under a standardized scenario ($i = 1.76$ in Equation (5.9), which means that about 10% of individuals are retained during selection). The results indicate that selection for wood density had a major impact on wood stiffness and strength. Thus, selection for wood density would increase stiffness and strength by 12.6% and 8.85%, respectively, and decrease volume by 9.78%.

Table 5.3 Correlated genetic responses for three breeding target traits with 10% selection intensity.

Selection Traits	**Correlated Response (%) for Target Traits**		
	MoE	**MoR**	**Volume**
Wood properties			
Density	12.6	8.85	−9.78
MoE	16.7*	7.43	−8.30
MoR	7.62	15.8*	−9.96
Growth traits			
DBH	−6.68	−6.32	17.3
Height	−4.74	−5.37	13.0
Volume	−6.18	−7.23	19.4*

Note: DBH=diameter at breast height, MoE=modulus of elasticity; MoR= modulus of rapture; * = Genetic gain.

Generally, selection for growth traits (DBH, height) generated a positive correlated response for volume. On the other hand, selection for wood property traits generated negative correlated response for volume. Similarly, selection for growth traits (DBH, height and volume) generated negative correlated response for stiffness and strength. For example, selection for DBH alone would decrease stiffness and strength by 6.68% and 6.32%, respectively. The negative correlated responses between growth traits and wood quality traits were reported in other pine species (Wu et al. 2008, Hong et al. 2014). Such negative correlated response between growth and wood quality traits indicate the need for a multiple-trait selection index (Hong et al. 2014).

5.4.6 Implication of tree improvement of *Pinus kesiya* in Malawi

The adverse genetic correlations between wood properties and growth traits of *P. kesiya* trees were moderate. This suggests that there may be some genotypes with both high growth performance and high wood density, stiffness and strength. Therefore, the adverse genetic correlation between wood properties and growth traits may not entirely prohibit the improvements of both wood quality and growth traits (Gapare et al. 2009). In the short term, it is possible to achieve significant gains in both density and DBH by selecting families or individuals from the top right quadrant (individuals with both high wood density and DBH) (Figure 5.3). Therefore, all trees with both DBH greater than 32.0 cm and density greater than 0.593 g/cm^3 must be selected in order to increase the efficiency of the breeding programme. This will result in simultaneous increases in wood stiffness, strength and volume. On the other hand, a long-term strategy would require a larger sample data set to develop a multiple-trait selection index. It is recommended that a multiple-trait selection index should be developed using optimal index weights for the advanced breeding programme of *Pinus kesiya* in Malawi.

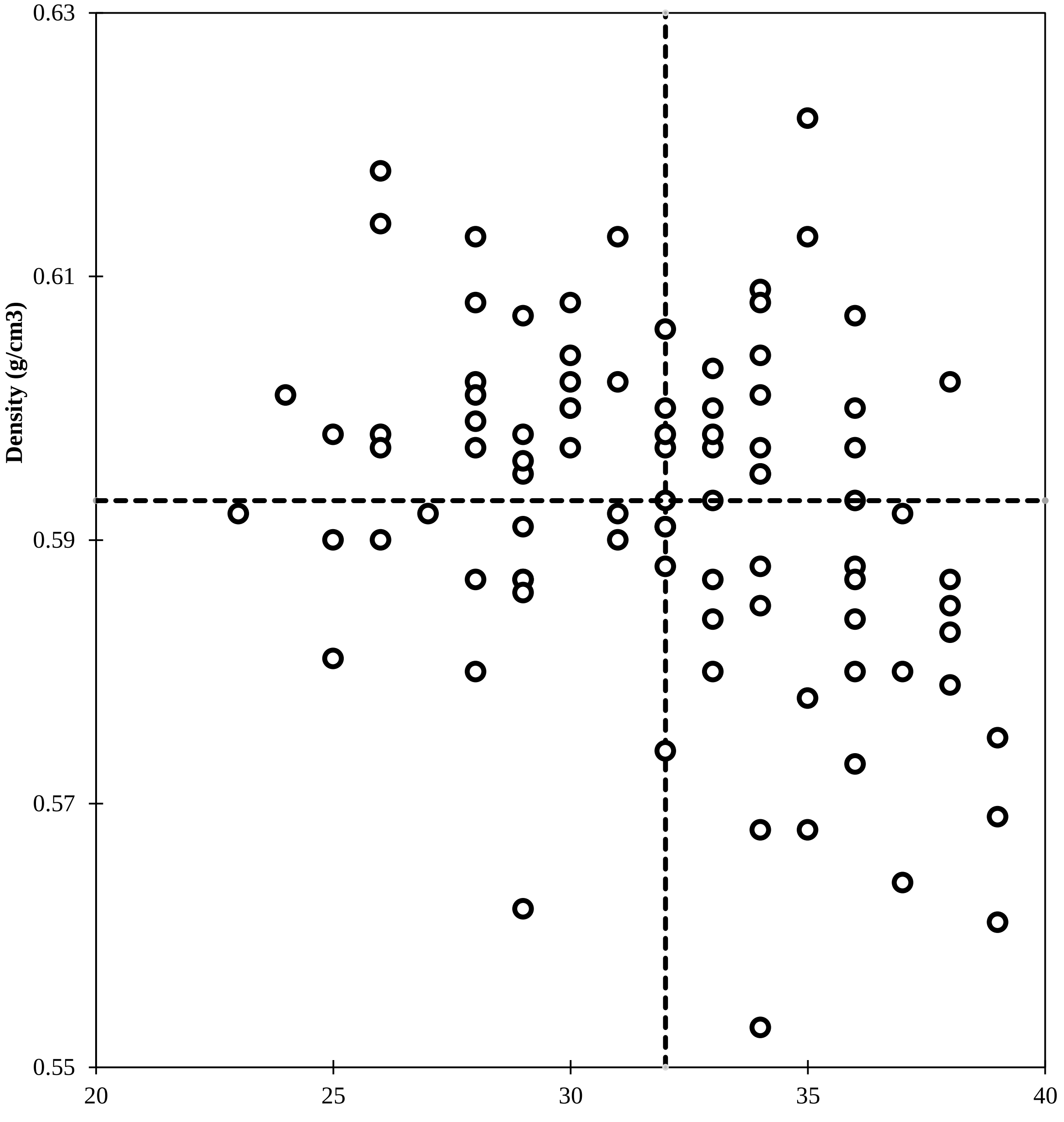

Figure 5.3 Selection strategy using individuals with both high density and DBH. Dotted lines are current family means for density and DBH acting as a base (control).

5.5 Conclusion

The study has revealed that wood density has a higher genetic control than mechanical properties (MoE and MoR) and growth traits (DBH, height and volume). The genetic correlation and correlated response among wood properties and growth traits were favourable. Selection for wood density would have a major impact on wood stiffness and strength. On the other hand, the genetic correlation and correlated response between growth and wood quality traits were moderately unfavourable. However, sufficient variation exists within the breeding population to select individuals with both good growth rate and high wood quality traits. It is therefore suggested that all trees with both DBH greater than 32.0 cm and density greater than 0.593 g/cm^3 must be selected in order to increase the efficiency of the breeding programme. However, in the long term, it is recommended that the best selection strategy would be to develop a multiple-trait selection index. The selection index should be developed using optimal index weights for the advanced *Pinus kesiya* breeding programme in Malawi.

CHAPTER 6

Multiple Trait Selection Index for Simultaneous Improvement of Wood Properties and Growth Traits in *Pinus kesiya* Royle ex Gordon in Malawi

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6.1 Abstract

Tree breeders face a problem of negative correlations between wood properties and growth traits. It is necessary to overcome this difficulty in order to obtain promising genotypes. Selection Index is one of the helpful tools in this process, because it allows multiple features of interest to be selected. In this study, a multiple trait selection index for Khasi pine (*Pinus kesiya* Royle ex Gordon) planted in Malawi was developed. Data on wood properties and growth traits were collected from six families of *P. kesiya* at the age of 30. The breeding objective was defined in terms of wood stiffness, wood strength and volume. Selection traits included in the index were: wood stiffness (MoE), wood strength (MoR), volume (Vol), wood density (WD), and diameter at breast height (DBH). The index was termed as $I_T = -80.36MoE - 14.60MoR + 132.07Vol + 4858.09WD - 7.56DBH$. The accuracy of the index was 98.8% and the correlation between the index and the aggregate breeding objective was 0.994. A genetic gain of 16.7% for volume, 14.8% for wood stiffness and 13.2% for wood strength would be expected from a standardized 10% selection intensity. Therefore, application of the developed selection index is necessary in order to increase the efficiency of *Pinus kesiya* breeding programme in Malawi.

Keywords: *Pinus kesiya*, selection index, wood properties, growth traits, breeding objective

6.2 Introduction

Breeding programmes are designed to identify superior genotypes for different traits of economic interest. This is based on the performance information of individual trees or families for dissemination of their genes in the population (Baker 1986, Ivković et al. 2006). However, one of the major difficulties faced by tree breeders is the negative correlation between wood properties and growth traits. It is necessary to overcome this difficulty to obtain promising genotypes. Literature shows that the selection index is one of the helpful tools in this process, because it allows multiple features of interest to be selected simultaneously (Baker 1986, Vieira et al. 2016).

Selection indexes have frequently been used for selection in recurrent selection programmes for various plant species (Martin et al. 1982, Sanhueza et al. 2002, Sharma and Duveiller 2003, Vieira et al. 2016). These indexes have been robust in their application. Although the theory of selection indexes was introduced into plant breeding more than 70 years ago (Hazel 1943) and is highly developed in various forms, its application in the forest tree breeding sector is still not very extensive. Possible explanations for this are (i) the complexity of the forest production system; (ii) difficulties in determining the relationship between wood properties and final product quantity and quality; and (iii) uncertainty about the future use of trees due to long rotational age (Berlin 2009). Furthermore, the optimal selection index may not be extensively used due to difficulties in the derivation of relative economic values as well as the scarcity of information on the relationships among the traits (Ivković et al. 2006).

Khasi pine (*Pinus kesiya* Royle ex Gordon) is one of the major exotic plantation tree species grown in Malawi. It is mainly used for sawn timber production. Its morphology, uses and application in Malawi have been well explained by other researchers (Missanjo and Matsumura 2016b, 2016c). The breeding programme for this species in Malawi started in early 1970s with the aim of improving growth characteristics and tree stem form (Missanjo and Matsumura 2016b). The selection of the second generation trees and evaluation of the wood properties of the first generation plus-tree clones are currently being undertaken (Missanjo and Matsumura 2016c).

Genetic parameters and genetic correlations among traits are essential in the establishment and refinement of tree breeding programmes (Hong et al. 2014, Fukatsu et al. 2015, Hung et al. 2015). Missanjo and Matsumura (2016c) identified high heritabilities in the wood properties (0.542 to 0.595) (density, stiffness and strength) and growth traits (0.400 to 0.483) (volume, height and diameter) of *Pinus kesiya* in Malawi. This indicates that it is possible to improve these traits through selection. On the other hand, Missanjo and Matsumura (2016c) reported an adverse genetic correlation (−0.309 to −0.496) between the wood properties and growth traits of *Pinus kesiya*. This shows that selection for wood properties would result in a decrease in growth traits and vice versa. Such a negatively correlated response between wood properties and growth traits, indicates the need of a multiple-trait selection index.

The objective of this study was to investigate the potential of simultaneous genetic improvement of wood properties and growth traits through a multiple-trait selection index and also to estimate the genetic gains from various selection intensities. The selection index would help to guide the establishment and refinement of the *Pinus kesiya* breeding programme in Malawi.

6.3 Materials and methods

6.3.1 Study area, genetic materials and assessment

The study used an open pollinated progeny trial of *P. kesiya* at 30 years of age that was established in a ferruginous soil in Chongoni Forest Plantation in Dedza, Malawi, in 1984. It is located about 85 km southeast of the capital, Lilongwe and lies on latitudes 14°10′ S and 14°21′ S and longitudes 34°09′ E and 34°17′ E. The progeny trial comprised 18 families with seed source from Zimbabwe. The test stand was established using ten-tree plots laid out in a completely randomized design in four replicates. The initial planting density was 1320 stems/ha, and all the silvicultural treatments were done on the instruction of the breeder (Ingram and Chipompha 1987).

In May 2014, six families were chosen based on straightness. A sample of 15 trees from each family (a total of ninety trees) with no major defects were randomly selected for the study. The mean height, diameter at breast height (DBH), and volume of the trees expressed with standard deviations during sampling were 25.9 ± 2.8 m, 32.0 ± 3.9 cm and 0.989 ± 0.319 m^3, respectively. Wood sample processing and measurement was conducted as outlined by Missanjo and Matsumura (2016b). Briefly, a total of 1080 wood specimens, measured 20 mm × 20 mm × 320 mm, were collected from innerwood, middlewood and outerwood at 1.3 m, 3.3 m, 5.3 m and 7.3 m of the stem height. The estimated mean wood density, Modulus of Elasticity (MoE) and Modulus of Rupture (MoR) with standard deviations were 0.593 ± 0.033 g/cm^3, 13.5 ± 2.3 GPa and 114 ± 19 MPa, respectively.

6.3.2 Statistical analysis

Genetic parameters that were used in the construction of the selection index were those obtained in our previous study (Missanjo and Matsumura 2016c) (Table 6.1). The genetic parameters for the wood quality traits (density, MoE and MoR) were estimated using a linear mixed model with stem height, stem radial position and replicate as fixed effects, and family as a random effect. However, replicate was removed from the analysis because its contribution to the total variance was negligible. On the other hand, genetic parameters for growth traits (DBH and volume) were estimated using a linear mixed model with replicate as a fixed factor and family as a random effect factor. The statistical analysis was done using SAS Mixed procedure and PROC VARCOMP in SAS software version 9.1.3 (SAS Institute Inc., Cary, NC, USA) (SAS 2004).

The selection index was constructed using the following equation given in matrix expression according to Lee (1999):

$$Pb = Ga \tag{6.1}$$

where P is the phenotypic variances (cov.) matrix; G is the genetic variances (cov.) matrix; a is the economic weights column vector; and b is the weighting factors column vector. In this study, the economic weights were not in monetary values, but were the mean annual increment (MAI) of the studied traits for a rotation period of 30 years. The economic weights of the studied traits are presented in Table 6.1. The objective traits were MoE, MoR and volume, while the other traits included in the construction of the index were wood density and DBH.

Table 6.1 Heritability (bold and diagonal), Genetic correlations (above diagonal), Phenotypic correlations (below diagonal), Means, Phenotypic standard deviation (σ_p), Genetic standard deviation (σ_A), Economic weights (a) and Estimated Breeding Values (EBV) used to construct the Selection Index

Traits	Density (g/cm^3)	MoE (GPa)	MoR (MPa)	DBH (cm)	Volume (m^3)
Density	**0.595(0.055)**	0.735(0.025)	0.539(0.060)	-0.496(0.049)	-0.458(0.052)
MoE	0.790(0.019)**	**0.559(0.038)**	0.464(0.061)	-0.473(0.046)	-0.399(0.051)
MoR	0.793(0.019)**	0.818(0.018)**	**0.542(0.091)**	-0.468(0.071)	-0.488(0.071)
DBH	-0.338(0.011)*	-0.112(0.006)^{ns}	-0.093(0.004)^{ns}	**0.400(0.042)**	0.987(0.002)
Volume	-0.358(0.010)*	0.099(0.002)^{ns}	-0.056(0.005)^{ns}	0.955(0.031)**	**0.483(0.053)**
Means	0.593(0.001)	13.5(0.1)	114(1)	32.0(0.4)	0.989(0.034)
σ_p	0.128	2.28	18.8	2.75	0.225
σ_A	0.085	1.41	11.3	1.13	0.109
a	0.020	0.449	3.79	1.07	0.033
EBV		3.69	6.95		3.76

Note: MoE=modulus of Elasticity; MoR=modulus of rupture; DBH=diameter at breast height; values in parenthesis are standard errors; **correlation estimates significantly different from zero (*P*<0.001); *correlation estimates significantly different from zero (*P*<0.05); ^{ns} correlation estimates not significantly different from zero (*P*>0.05).

The selection index weights were then calculated as:

$$b = P^{-1}Ga \tag{6.2}$$

The accuracy of the selection index, which is defined as the function of the correlation (r_{HI}) between the index and the aggregate genotype (breeding objective variance) (Calus et al. 2008) was calculated as:

$$r_{HI}^2 = \frac{\sigma_I^2}{\sigma_H^2} \tag{6.3}$$

where: σ_I^2 and σ_H^2 are the variances of the index and the aggregate genotype, respectively. These variances were calculated using the following equations according to Lee (1999):

$$\sigma_I^2 = b'Ga \tag{6.4}$$

$$\sigma_H^2 = a'Ga \tag{6.5}$$

where: b'=(b_1, b_2 … b_n) is the vector of selection index weight values and a'=(a_1, a_2 … a_n) is the vector of economic weight values.

The expected genetic change (ΔG) and the standard deviation (σ) for each trait after one generation of selection on the indexes were estimated by solving the following equations (Falconer and Mackay 1996):

$$\Delta G = \frac{b'Gi}{\sigma_I} \tag{6.6}$$

$$\sigma = \sqrt{\frac{\sum(x-\mu)^2}{n-1}} \tag{6.7}$$

where *i* is the selection intensity, σ_I is the standard deviation of the index, b' and G are as explained earlier, *x* is individual observations, μ is the overall mean, and *n* is the number of observations. Genetic gain is often referred to as the amount of increase in performance that is achieved through artificial genetic improvement programmes. This is usually used to refer to the increase after one generation has passed (Baker 1986). Data obtained on expected genetic change was subjected to one-way analysis of variance (ANOVA) using SAS software version 9.1.3 (SAS 2004). Differences between means were separated using Fischer's least significant difference (LSD) at 0.05 level.

6.4 Results and discussion

6.4.1 Selection index

The selection indexes constructed are presented in Table 6.2. Three selection indexes (I_1, I_2 and I_T) were constructed according to three strategies with the aim to improve the objective traits (MoE, MoR and volume). The first strategy was indirect selection, which involved selecting the density and DBH. The second strategy was direct selection, while the third strategy was the combination of indirect and direct selection. Wood density and DBH were selected because they are positively genetically correlated with mechanical properties (MoE, MoR) and volume, respectively.

The comparisons of the three selection indexes indicate that the selection index, I_T, which incorporated MoE, MoR, density, DBH and volume is the most efficient ($r_{HI}^2 = 98.8\%$) compared to $I_2(r_{HI}^2 = 79.4\%)$ and $I_1(r_{HI}^2 = 70.4\%)$. This means that the selection index, I_T, is recommended for improving the objective traits (MoE, MoR and volume) in *Pinus kesiya* in Malawi. Thus, individual trees can be ranked according to their index values and selection based on these rankings.

Table 6.2 Index weights (b-values), Index variance (σ_I^2) and Index Accuracy (r_{HI}^2) to improve wood quality and growth traits in *Pinus kesiya*

Selection Index	**Selection Traits**	**b-values**	$\boldsymbol{\sigma_I^2}$	$\boldsymbol{r_{HI}^2}$(%)
I_1	WD	20.93	19.79	70.4
	DBH	0.2306		
I_2	MoE	44.63	22.32	79.4
	MoR	-2.790		
	Vol	-243.5		
I_T	MoE	-80.36	27.75	98.8
	MoR	-14.60		
	Vol	132.07		
	WD	4858.09		
	DBH	-7.56		

Note: MoE=modulus of Elasticity; MoR=modulus of rupture; DBH=diameter at breast height; WD=wood density; Vol=volume

The results revealed that omitting density and DBH as selection traits reduced the index accuracy by 19.4%. It is also clear from the results that the index not including MoE, MoR and volume as selection traits, showed a reduction in index accuracy of 28.4%. As in many other studies (Park et al. 1989, Lee 1999, Sanhueza et al. 2002, Zhang et al. 2011, Stephens et al. 2012), the present study suggests that the accuracy of the index is influenced by which traits are included in the index.

6.4.2 Expected genetic gain

A summary of the results on expected genetic gains after one generation for the traits studied under different selection indexes is presented in Table 6.3. The expected genetic gains were assessed under a standardized scenario (i = 1.76 in Equation 6.6, which means that about 10% of individuals are retained during selection). The results show that when the accuracy of the index increased, the expected genetic gains for all incorporated traits significantly increased. For instance, when the accuracy of the index increased from 70.4% for I_1 to 79.4% for I_2, the mean expected genetic gain for all the traits increased from 5.73% to 8.75%. MoR had the largest expected genetic gain increase (2.59% to 8.55%). Similarly, when the accuracy of the index increased from 79.4% for I_2, to 98.8% for I_T, the mean expected genetic gain for all the traits increased from 8.75% to 13.68%. Volume had the largest expected genetic gain increase (9.37% to 16.7%).

Table 6.3 Expected genetic gains per generation when using Indexes to improve Wood quality and growth traits in *Pinus kesiya* with 10% selection intensity (*i*=1.76)

Traits	**Expected Genetic Gain (%) under different selection indexes**		
	I_1	I_2	I_T
MoE	5.93 (1.30)^c	10.4 (1.5)^b	14.8 (1.5)^a
MoR	2.59 (0.11)^c	8.55 (1.11)^b	13.2 (1.4)^a
Vol	7.46 (0.78)^c	9.37 (1.03)^b	16.7 (2.2)^a
WD	9.72 (1.05)^c	12.1 (1.1)^b	18.5 (2.7)^a
DBH	2.96 (0.13)^c	3.34 (0.16)^b	5.21 (1.02)^a

Note: MoE=modulus of Elasticity; MoR=modulus of rupture; DBH=diameter at breast height; WD=wood density; Vol=volume; values in parenthesis are standard deviations. Mean values followed by different superscripts within a row significantly differ ($p < 0.001$)

The present findings indicate that the rates of genetic gain would be affected by the accuracy of the selection index. Thus, increasing the accuracy of the selection index results in increasing the expected genetic gain. The present findings are in agreement to those in the literature (Sanhueza et al. 2002, Zhang et al. 2011). Zhang et al (2011) reported that when the selection accuracy increased, a corresponding increase was also noticed in genetic gain for a breeding programme of tea-tree (*Melaleuca alternifolia* (Maiden and Betche) Cheel) in Australia. Similarly, Sanhueza et al. (2002) observed an increase in expected genetic gain when the accuracy of the index increased for a breeding programme of Tasmanian blue gum (*Eucalyptus globulus* Labill.) in Chile. In contrast, Lee (1999) and Park et al. (1989) reported a constant expected genetic gain for the objective traits when the selection accuracy increased for breeding programmes of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Scotland and Jack pine (*Pinus banksiana* Lamb.) in Canada, respectively. The differences in the results could be attributed to the genotype of the species (Zhang et al. 2011).

Other factors such as heritability, selection intensity and generation interval between parents and progeny could also affect genetic gain (Lee 1999). Hong et al. (2014) investigated the performance of Scots pine under single trait selection and found that a large increase of genetic gain could be achieved for the high heritable traits. In contrast, the present study revealed that a larger genetic gain increase was achieved for the trait with moderate heritability (volume, in our case) under multi-trait selection. This is likely due to the high emphasis on the simultaneous improvement of wood quality and growth traits in the present study.

The number of families used in the present study is limited (six families); further studies incorporating all the eighteen families may be required to confirm the present findings. However, the selection index, I_T, constructed, is reliable because of its high accuracy. Therefore, application of the developed selection index, I_T, is necessary in order to increase the efficiency of the *Pinus kesiya* breeding programme in Malawi.

6.5 Conclusion

The study has revealed that there is potential for simultaneous genetic improvement of the wood properties (density, MoE, MoR) and growth traits (DBH, volume) of *Pinus kesiya* in Malawi through a multiple-trait selection index. The selection index developed showed high accuracy. High expected genetic gains of the traits incorporated in the index were also obtained. The expected genetic gains increased with an increase of selection accuracy. Therefore, application of the developed selection index is necessary in order to increase the efficiency of the *Pinus kesiya* breeding programme in Malawi.

CHAPTER 7

General Discussion, Conclusions and Recommendations

7.1 General discussion

The goal of any tree improvement programme is to obtain populations of superior genetic value that can lead to the establishment of a more valuable plantations. To achieve this, it is then vital to clearly define the objectives, to identify the characteristics that affect the final objective and to assess their genetic control (Gaspar 2009). When this information is at hand, deployment strategies can then be chosen. For example, in a tree breeding programme that aims to produce material for wood processing industry, it is important to consider wood properties as potential selection criteria (Zobel and Jett 1995, Gaspar 2009).

The overall objective of the study was to contribute to the *Pinus kesiya* improvement programme in Malawi with information regarding radial variation in tracheid length and growth ring width, variation in wood density and mechanical properties along radial direction and stem height, genetic control of wood quality and growth traits, and determine how wood quality traits interact between themselves and with growth traits. The study was also aimed at development of a selection index to simultaneously improve wood properties and growth traits important for sawn timber production of *Pinus kesiya*.

In Chapter 3, the radial variation in tracheid length and growth ring width was studied and the boundary between juvenile wood and mature wood was identified. The results indicate that there were statistically significant differences on tracheid length and growth ring width among the ring numbers from pith to bark. Tracheid length at first increased rapidly from pith to bark, then more slowly, while the growth ring width decreased. Radial increase in tracheid length from pith to bark is due to increase in length of fusiform initial with cambial age (Chalk 1930). There were no significant differences on tracheid length and growth ring width among families across the radius. This is an indication that any tree among the families can be selected for tree improvement programmes if tracheid length is considered as a variable. The demarcation of the boundary between juvenile wood and mature wood is essential for the optimization of timber utilization, quality and value of final products (Nawrot et al. 2012). Mature wood tends to have high strength and stiffness, therefore lumber from mature wood can be used for structural purposes. On other hand, juvenile wood tends to have higher microfibril angles, lower wood density, thinner cell walls, shorter tracheid lengths, greater spiral grain, lower cellulose to lignin ratio, higher longitudinal shrinkage, lower latewood percentage and higher growth ring width, hence low strength and stiffness (Bao et al. 2001, Nawrot et al. 2014). On the basis of radial variation of tracheid length, the boundary between juvenile wood and mature wood could be marked at ring number 10 from the pith. This suggest that when processing logs of *Pinus kesiya* trees in Malawi, lumber from ring number 10 from pith to bark should be used for structural purposes. Furthermore, the results suggest that efficiency of selection in tree breeding programme based on the inner wood for tracheid length would generally be lower than selection based on outer wood.

Wood quality assessment involves the consideration of wood density and mechanical properties (modulus of elasticity-MoE and modulus of rupture-MoR) (Anoop et al. 2014). MoE and MoR are important properties for the use of wood as structural material. MoE is an indication of stiffness of board or structural member while MoR is an indication of strength (Johnson and Gartner 2006). Wood density is the most frequently studied among the desirable wood quality properties to breed for (Zobel and Van Buijtenen 1989), since it is widely recognized as the most important property controlling MoE and MoR (Steffenrem et al. 2007, Kiaei 2011). Therefore, in Chapter 4 wood density and mechanical properties of *Pinus kesiya* were assessed. Wood density and mechanical properties significantly increased from pith to bark and significantly decreased from the butt upwards. However, there were no significant differences on wood density and mechanical properties for juvenile wood from butt upwards. This implies that the high density mature wood from the butt end logs should be used for structural purposes where high strength and stiffness is required. Similarly, there were no significant differences in wood density and mechanical properties up to 6 m stem height for mature wood. This indicates that for uniformity of density and mechanical properties in processed lumber for mature wood of *Pinus kesiya* in Malawi, logs of 6 m long or less must be used. Wood density had a strong significant linear relationship with MoE and MoR. This shows that wood density is a good indicator of mechanical properties of wood, therefore, controlling wood density would have a positive impact on mechanical properties.

To use timber reliably for structural purposes, it is important that the strength properties of any member fall within certain limit. Mechanical stress grading is a form of testing that allows timber to be sorted into strength classes, also enabling timber unsuitable for construction to be rejected. Timber for non-structural uses, such as furniture or flooring may also be sorted to meet certain appearance grades (Holland and Reynolds 2005). Grading acts as a value adding process for timber. Properly graded timber gives a value of worthiness and satisfaction to the customers and are sold at higher prices than ungraded timber (Kamala 2012). In Malawi, timber is mostly sold and used without proper grading. Thus, it is basically sold and used on the basis of dimension size. Timber is also sold to other countries within Africa. Without grading, timber is sold at low prices. This means that the forestry and wood industry as well as the county is on loss as a business entity. Grading would enable maximization of the timber value. In Chapter 4 grade yield for the specimens were checked using the grading standard of mechanical properties of timber from three different regions (Table 4.1). The results indicate that timber from mature wood for *Pinus kesiya* grown in Malawi can be allocated into grades S10, IV and C40, while timber from juvenile wood can be allocated into grades S7, III and C27 using grading standard of mechanical properties of timber from South African standard for pine, South East Asia and Pacific Regions for softwood species, and the European standard for softwood species, respectively. This indicates that wood products from *Pinus kesiya* grown in Malawi such as lumber, composite panels and structural composite lumber products can compete successfully with same products in the huge construction markets of Southern Africa, Asia and Europe. However, this study has only established the first step in assigning allowable mechanical properties of *Pinus kesiya* grown in Malawi. Therefore, testing using the "in grade approach" (use of full size lumber samples) is recommended to compare the results. This will help to establish national timber grading standard that will ensure the efficient utilization of *Pinus kesiya* structural lumber in Malawi.

Genetic control of wood density and mechanical properties has not been well documented, compared with growth traits. In Chapter 5 the genetic variation in radial and stem height of wood density, MoE and MoR were analysed. Correlation patterns among these traits were also assessed. Both wood density and mechanical properties are subject to high genetic control ($0.542<h^2<0.595$). Wood density had a higher genetic control ($h^2=0.595$), indicating that high genetic gains can be obtained by direct selection of this trait. Heritability for wood density and mechanical properties increased from pith to bark and decreased from butt upwards. This suggests that efficiency of selection based on outer wood for wood density and mechanical properties would generally be higher than selection based on inner wood. Furthermore, the results showed high phenotypic and genetic correlations between wood density and mechanical properties, indicating that these traits are at least for large part controlled by the same set of genes (Gaspar 2009) and that indirect selection procedures could be carried out on these traits. Selection for wood density, at 10% selection intensity, would increase MoE and MoR by 12.6% and 8.85%, respectively.

The high heritability values obtained for wood quality traits (wood density, MoE and MoR) suggests that large gains can be obtained by selection for these traits, in the absence of adverse genetic correlations with other traits. Therefore, in Chapter 5 genetic and phenotypic correlations between wood properties and growth traits were assessed. Weak negative phenotypic correlations between most wood properties and growth traits were observed. Most of the phenotypic correlations between growth traits and wood properties were non-significant with the exception of wood density. The genetic correlations between wood properties and growth traits were unfavourable. Selection for wood density, at 10% selection intensity, would decrease volume by 9.78%, while selection for DBH, at 10% selection intensity, would decrease MoE and MoR by 6.68% and 6.32%, respectively.

Tree improvement programmes aim to simultaneously improve more than one trait. Selection index presents tree breeders with the attractive option of combining information from several traits (Cotterill and Dean 1990, Gaspar 2009). Knowledge of all genetic parameters enables the application of multi-trait selection index, which combines all information on phenotypic performance and genetic structure (Gaspar 2009). In order to explore the potential of simultaneous genetic improvement of wood properties and growth traits in *Pinus kesiya*, a multi-trait selection index was developed and the expected genetic gains were estimated (Chapter 6). The breeding objective of the selection index was defined in terms of wood stiffness, wood strength and volume. Selection traits included in the index were: wood stiffness (MoE), wood strength (MoR), volume (Vol), wood density (WD), and diameter at breast height (DBH). The index was termed as $I_T = -80.36MoE - 14.60MoR + 132.07Vol + 4858.09WD - 7.56DBH$. The accuracy of the index was 98.8% and the correlation between the index and the aggregate breeding objective was 0.994. A genetic gain of 16.7% for volume, 14.8% for wood stiffness and 13.2% for wood strength would be expected from a standardized 10% selection intensity. So individual trees can then be ranked according to their index values and selection based on these rankings. Therefore, application of the developed selection index is necessary in order to increase the efficiency of *Pinus kesiya* breeding programme in Malawi. In a small country with limited financial resources like Malawi, the optimization of resources with a multi-option use in a breeding programme such as Malawi *Pinus kesiya* improvement programme is extremely essential.

7.2 Conclusion

The study has revealed that tracheid length at first increased rapidly from pith to bark and thereafter increased gradually or remains more or less constant, while growth ring width decreased. On the basis of radial variation of tracheid length, the boundary between juvenile wood and mature wood could be marked at ring number 10 from the pith. This suggest that when processing logs of *Pinus kesiya* trees in Malawi, lumber from ring number 10 from pith to bark should be used for structural purposes. High wood density and mechanical properties values were observed, indicating that wood from *P. kesiya* can be used for structural purposes. Wood density and mechanical properties significantly increased from pith to bark and significantly decreased from the butt upwards. Wood density had a higher genetic control than the other studied traits. The genetic correlations between growth and wood quality traits were unfavourable. However, there is potential for simultaneous genetic improvement of wood properties (density, MoE, MoR) and growth traits (DBH, volume) of *Pinus kesiya* in Malawi through multiple-trait selection index. The selection index developed showed a high accuracy. High expected genetic gains of the traits incorporated in the index were also obtained. The expected genetic gains increased with an increase of selection accuracy.

7.3 Recommendations

Wood industry experts should use the information obtained on this study on the potential use and sustainable use of the species when processing logs for timber.

Timber grading acts as a value adding process for timber. Properly graded timber is sold at high prices. The present study has initiated the first step to establish national timber grading standards in Malawi. Therefore, it is highly recommended that some effort should be made to come up with a timber grading system for the species in Malawi.

The findings of the study are of great importance for the continued development of *Pinus kesiya* breeding programme in Malawi to guide future generation. Therefore, tree breeders should use the information on genetic parameters obtained in this study to establish and refine breeding and deployment programmes of the species.

The number of families used in the present study is limited (six families), further studies incorporating all the eighteen families may be required to confirm the present findings. However, the selection index, I_T constructed is reliable because of its high accuracy. Therefore, application of the developed selection index, I_T is necessary in order to increase the efficiency of *Pinus kesiya* breeding programme in Malawi.

References

1. Adenaiya AO. & Ogunsanwo OY. (2016). Radial Variation in Selected Physical and Anatomical Properties Within and Between Trees of 31-Year-Old *Pinus caribaea* (Morelet) Grown in Plantation in Nigeria. *South-east European Forestry*, 7(1), 49-55.

2. Adamopoulos S. & Voulgaridis E. (2002). Within tree variation in growth rate and cell dimensions in the wood of black locust (*Robinia pseudoacacia*). *IAWA Journal*, 23(2), 191-199.

3. Air Asia Survey (AAS). (2012). Forest resource mapping project under the Japanese grant for the forest preservation programme to Republic of Malawi: Final report for implementation phase. Department of Forestry, Malawi.

4. Akachuku AE. (1984). The possibility of tree selection and breeding for genetic improvement of wood property of *Gmelina arborea. Forest Science,* 30, 275–283.

5. Alteyrac J., Cloutier A., Ung CH. & Zhang SY. (2006). Mechanical properties in relation to selected wood characteristics of black spruce. *Wood and Fiber Science,* 38(2), 229 – 237.

6. Anoop EV., Jijeesh CM., Sindhumathi CR. & Jayasree CE. (2014). Wood physical, anatomical and mechanical properties of big leaf Mahogany (*Swietenia macrophylla* Roxb) a potential exotic for South India. *Research Journal of Agriculture and Forestry Sciences*, 2(8), 7 – 13.

7. Apiolaza LA. (2009). Very early selection for wood quality: Screening for early winners. *Annals of Forest Science*, 66, 601–610.

8. Apiolaza LA & Garrick DJ. (2001). Breeding objectives for three silvicultural regimes of radiata pine. *Canadian Journal of Forest Research,* 31, 654 – 662.

9. Apiolaza LA., Shakti SC. & Walker JCF. (2011). Genetic control of very early compression and opposite wood in *Pinus radiata* and its implications for selection. *Tree Genetics and Genomes,* 7, 563–571.

10. Atmer B. & Thornqvist T. (1982). The properties of tracheids in spruce (*Picea abies* Karst.) and pine (*Pinus sylvestris* L.). Department of Forest Products, Swedish University of Agricultural Sciences, Uppsala, Sweden, Rep. 134.

11. Baker R. (1986). *Selection indices in plant breeding.* CRC Press, Boca Raton.

12. Bao FC., Jiang ZH., Jiang XM., Lu XX., Luo XQ. & Zhang SY. (2001). Differences in wood properties between juvenile wood and mature wood in 10 species grown in China. *Wood Science and Technology,* 35(4), 363 – 375.

13. Barner H., Ditlevsen B. & Olesen K. (1992). Introduction to Tree Improvement. Danida Forest Seed Center (Lecture Note D-1).

14. Beaulieu J. (2003). Genetic variation in tracheid length and relationships with growth and wood traits in eastern white spruce (*Picea glauca*). *Wood Fiber Science*, 35, 609–616.

15. Bendtsen BA. & Senft J. (1986). Mechanical and anatomical properties in individual growth rings of plantation-growth eastern cottonwood and loblolly pine. *Wood and Fiber Science*, 18(1), 23-38.

16. Berlin M. (2009). Development of Economic Forest Tree Breeding Objectives. PhD Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden, September 2009.

17. Bhat KM., Priya PB. & Rugmini P. (2001). Characterization of juvenile wood in teak. *Wood Science and Technology*, 34(6), 517 – 534.

18. Bisset IJW., Dadswell HE. & Wardrop AB. (1951). Factors influencing tracheid length in conifer stems. *Australian Forestry*, 15(1), 17 – 30.

19. Buksnowitz CH., Teischinger A. & Grabner M. (2010). Tracheid length in Norway spruce (*Picea abies* (L.) Karst.) analysis of three databases regarding tree age, cambial age, tree height, inter-annual variation, radial distance to pith log qualities. *Wood Research,* 55(4), 1 – 14.

20. Calus MPL., Meuwissen THE., de Roos APW. & Veerkamp RF. (2008). Accuracy of genomic selection using different methods to define haplotypes. *Genetics*, 178(1), 553 – 561.

21. Campelo F., Nabais C. Freitas H. & Gutierrez E. (2006). Climatic significance of tree-ring width and intra-annual density fluctuations in *Pinus pinea* from a dry Mediterranean area in Portugal. *Annals of Forest Science,* 64, 229 – 238.

22. Carlquist S. (1988). Comparative Wood Anatomy: Systematic, Ecological and Evolutionary Aspects of Dicotyledon Wood. Springer-Verlag, Berlin.

23. Cassady J. & Robinson W. (2002). Genetic parameters and their use in breeding. NSIF-FS3, North Carolina State University, USA.

24. Cave ID. & Walker JCF. (1994). Stiffness of wood in fast-grown plantation softwoods: The influence of microfibril angle. *Journal of Natural Products,* 44, 43–48.

25. Chalk L. (1930). Tracheid length with special reference to Sitka spruce (*Picea sitchensis Carr*). *Forestry*, 4, 7-14.

26. Cornelius J. (1994). Heritabilities and additive genetic coefficients of variations in forest trees. *Canadian Journal of Forest Research*, 24, 372–379.

27. Cotterill PP. & Dean CA. (1990). *Successful tree breeding with index selection*. CSIRO Australia, Victoria.

28. Cown DJ. (1992). Corewood (juvenile wood) in *Pinus radiata* – Should we be concerned? *New Zealand Journal of Forestry,* 22(1), 87 – 95.

29. Cown DJ. & McConchie DL. (1981). Effects of thinning and fertilizer application on wood properties of *Pinus radiata*. *New Zealand Journal of Forestry,* 22(2), 79 – 91.

30. Cown DJ. & McConchie DL. (1982). Rotation age and silvicultural effects on wood properties of four stands of *Pinus radiata*. *New Zealand Journal of Forestry*, 22(1), 71 – 85.

31. Creber GT. & Chaloner WG. (1984). Influence of environmental factors on the wood structure of living and fossil trees. *Botanical Review,* 50, 357–448.

32. Deresse T. (1998). *The Influence of Age and Growth Rate on Selected Properties of Maine-Grown Red Pine*. PhD Thesis, University of Maine, Orono, ME, USA.

33. Deresse T., Shepard R. & Shaler S. (2003). Microfibril angle variation in red pine (*Pinus resinosa* Ait.) and its relation to the strength and stiffness of early juvenile wood. *Forest Products Journal*, 53(7/8), 34 – 40.

34. Diaz R., Zas R. & Fernandez-Lopez J. (2007). Genetic variation of *Prunus avium* in susceptibility to cherry leaf spot (*Blumeriella jaapii*) in spatially heterogeneous infected seed orchards. *Annals of Forest Science,* 64(1), 21 – 30.

35. Dinwoodie JM. (1961). Tracheid and Fiber-Length in Timber. A Review of Literature. *Forestry*, 34, 124-144.

36. Dinwoodie JM. (1963). Variation in Tracheid length in *Picea sitchensis* Carr. Forest Product Research Laboratory, Special Report No. 16. HMSO, London.

37. Domec JC. & Gartner BL. (2002). How do water transport and water storage differ in coniferous earlywood and latewood? *Journal of Experimental Botany*, 53, 2369–2379.

38. Downes GM., Wimmer R. & Evans R. (2002). Understanding wood formation. Gains to commercial forestry through tree ring research. *Dendrochronologia*, 201(2), 37 – 51.

39. Dowse GP. & Wessels CB. (2013). Selected mechanical proper and the structural grading of young *Pinus patula* sawn timber. *Southern Forests: Journal of Forest Science*, 75(1), 7 – 17.

40. Eerikainen K. (2003). Predicting the height-diameter pattern of planted *Pinus kesiya* stands in Zambia and Zimbabwe. *Forest Ecology and Management*, 175(1-3), 355 – 366.

41. Erickson HD. & Harrison T. (1974). Douglas-fir wood quality studies. Part I: effects of age and stimulated growth on wood density and anatomy. *Wood Science and Technology*, 8, 207–226.

42. ES EN 338. (2003). *European Standard. Structural Timber–Strength Classes*; CEN, Brussels.

43. Evans R., Downes GM., Menz DNJ. & Stringer SL. (1995). Rapid measurement of variation in tracheid transverse dimensions in a radiata pine tree. *Appita Journal*, 48, 134–138.

44. Evans R. & Ilic J. (2001). Rapid prediction of wood stiffness from microfibril, angle and density. *Forest Products Journal*, 51(3), 53–57.

45. Fabisiak E., Mania P. & Kudela J. (2014). Variation in tracheid lengths in resonance wood of spruce (*Picea abies* L.). Annals of Warsaw University of Life Sciences, SGGW, *Forestry and Wood Technology,* 86, 104 – 108.

46. Fabisiak E. & Moliński W. (2002). Variability of wood basic density and length of tracheids in 45-year larch-fir stand (*Larix decidua* Mill.): In: Wood structure and properties '02. (Eds. J. Kudela and S. Kurjatko), Zvolen, Arbora Publishers 2002, pp. 25 – 28.

47. Falconer DS. & Mackay TFC. (1996). *Introduction to Quantitative Genetics, 4th ed.*; Longman Group Ltd, Essex, England.

48. FRIM (Forestry Research Institute of Malawi). (1989). Annual Report. Zomba, Malawi.

49. Fritts HC., Smith DG., Cardis JW. & Budelsky CA. (1965). Tree-ring characteristics along a vegetation gradient in Northern Arizona. *Ecology*, 46, 393–401.

50. Fukatsu E., Hiraoka Y., Matsunaga K., Tsubomura M. & Nakada R. (2015). Genetic relationship between wood properties and growth traits in *Larix kaempferi* obtained from a diallel mating test. *Journal of Wood Science,* 61, 10-18.

51. Fukatsu E., Tsubomura M., Fujisawa Y. & Nakada R. (2013). Genetic improvement of wood density and radial growth in *Larix kaempferi*: results from a diallel mating test. *Annals of Forest Science,* 70, 451 – 459.

52. Fuwape JA. & Fabiyi JS. (2003). Variations in strength properties of plantation grown *Nauclea diderichii* wood. *Journal of Tropical Forest Products,* 9, 45–53.

53. Gapare WJ., Baltunis BS., Ivković M. & Wu HX. (2009). Genetic correlations among juvenile wood quality and growth traits and implication for selection strategy in *Pinus radiata* D. Don. *Annals of Forest Science,* 66(6), 606. doi:10.1051/forest/2009044

54. Gapare WJ., Ivković M. Dillon SK., Chen F., Evans R. & Wu HX. (2012). Genetic parameters and provenance variation of *Pinus radiata* D. Don. ‘Eldridge collection’ in Australia 2: wood properties. *Tree Genetics and Genomes,* 8, 895 – 910.

55. Gaspar M. (2009). Genetic Control of Wood Quality and Growth Traits of *Pinus pinaster* Ait. in Portugal. PhD thesis, University of Trás-os-Montes and Alto Douro, Portugal, September 2009.

56. Gaspar MJ., Louzada JL., Silva ME., Aguiar A. & Almeida MH. (2008). Age trends in genetic parameters of wood density components in 46 half-sibling families of *Pinus pinaster*. *Canadian Journal of Forest Research,* 38, 1470–1477.

57. Geimer R., Herian V. & Xu D. (1997). Influence of juvenile wood on dimensional stability and tensile properties of flake board. *Wood and Fiber Science*, 29 (2), 103 – 119.

58. Getahun Z., Poddar P. & Sahu O. (2014). The Influence of physical and mechanical properties on quality of wood produced from *Pinus patula* tree grown at Arsi Forest. *Advanced Research Journal of Plant and Animal Science,* 2, 32–41.

59. Gogoi BR., Sharma M. & Sharma CL. (2014). Ring width variations of Khasi pine (*Pinus kesiya* Royle ex Gordon) at breast height. *Journal of the Indian Academy of Wood Science*, 11(1), 87 – 92. doi:10.1007/s13196-014-0123-1

60. Goyal GC., Fisher JJ., Krohn MJ., Packwood RE. & Olson JR. (1999). Variability in pulping and fiber characteristics of hybrid poplar trees due to their genetic makeup, environmental factors, and tree age. *TAPPI,* 82(5), 141 – 147.

61. Green DW, Winandy JE. & Kretschmann DE. (1999). Mechanical properties of wood. In: USDA Forest Service FPL, editor. Wood handbook: wood as an engineering material, vol. 4. Madison WI, pp. 1–45.

62. Groom L., Shaler S. & Mott L. (2002). Mechanical properties of individual southern pine fibers. Part III. Global relationships between fiber properties and fiber location within an individual tree. *Wood and Fiber Science*, 34(2), 238 – 250.

63. Guan N., Luo XQ. & Zhang HS. (1997). Juvenile-mature differences in wood mechanical properties of 10 major afforestation species in China. *Journal of the Institute of Wood Science,* 14(4), 175 – 179.

64. Guilley E., Hervé J., Huber F. & Nepveu G. (1999). Modelling variability of within-ring density components in *Quercus petraea* Liebl. with mixed-effect models and simulating the influence of contrasting silvicultures on wood density. *Annals of Forest Science,* 56,449-458.

65. Guller B., Isik K. & Centinay S. (2011). Genetic variation in *Pinus brutia* Ten.: Wood density traits. *BioResources*, 6, 4012–4027.

66. Hai PH. (2009). Genetic improvement of plantation-grown *Acacia auriculiformis* for sawn timber production. Ph.D. Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden, September 2009.

67. Hannrup B., Ekberg I. & Persson A. (2000). Genetic correlation among wood, growth capacity and stem traits in *Pinus sylvestris*. *Scandinavian Journal of Forest Research,* 15, 161–170.

68. Harris JM. (1991). Structure of wood and bark. Chapter 2 In Properties and Uses of New Zealand Radiata Pine, Volume 1 – Wood Properties. Eds J.A. Kininmonth and I.J. Whitehouse. NZ Ministry of Forestry, Forest Research Institute.

69. Harris P., Petherick R. & Andrews M. (2002). Wood testing tool. In Proceeding of 13th International Symposium on non-destructive testing of wood, August 19–21, 2002, University of California Berkeley, California, CA, USA, 2003; pp. 195–201.

70. Hatton JV. (1993). Kraft pulping of second - growth jack pine. *TAPPI,* 76(5), 105 – 113.

71. Hatton JV. (1997). Pulping and papermaking properties of managed second - growth softwoods. *TAPPI,* 80(1), 178 – 184.

72. Hatton JV. & Gee WY. (1994). Kraft pulping of second - growth lodge pole pine. *TAPPI,* 77(6), 91 – 102.

73. Havimo M., Rikala J., Sirvio J. & Sipi M. (2009). Tracheid cross-sectional dimensions in Scots pine (*Pinus sylvestris*) – distributions and comparison with Norway spruce (*Picea abies*). *Silva Fennica,* 43, 681–688.

74. Hazel LN. (1943). The genetic basis for constructing of selection indexes. *Genetics,* 28, 476 – 490.

75. Hazel LN. & Lush JL. (1942). The efficiency of three methods of selection. *Journal of Heredity*, 33, 393 – 399.

76. Herman M., Dutilleul P. & Avella-Shaw T. (1998). Growth rate effects on temporal trajectories of ring width, wood density, and mean tracheid length in Norway spruce (*Picea abies* (L.) Karst.). *Wood Fiber Science*, 30, 6–17.

77. Hodge GR. & Purnell RC. (1993). Genetic parameter estimates for wood density, transition age, and radial growth in splash pine. *Canadian Journal of Forest Research,* 23, 1881–1891.

78. Holland C. & Reynolds T. (2005). Timber Grading and Scanning. BRE Bookshop, Garston, Watford, UK.

79. Hong Z., Fries A. & Wu HX. (2014). High negative genetic correlations between growth traits and wood properties suggest incorporating multiple traits selection including economic weights for the future Scots pine breeding programs. *Annals of Forest Science,* 71, 463 – 472. doi: 10.1007/s13595-014-0359-3

80. Hung TD., Brawner JT, Meder R., Lee DJ., Southerton S., Thinh HH. & Dieters MJ. (2015). Estimates of genetic parameters for growth and wood properties in *Eucalyptus pellita* F. Muell. to support tree breeding in Vietnam. *Annals of Forest Science,* 72, 205 – 217. doi: 10.1007/s13595-014-0426-9

81. Hylen G. (1999). Age trends in genetic parameters of wood density in young Norway spruce. *Canadian Journal of Forest Research*, 29, 135–143.

82. Ingram CL. & Chipompha NWS. (1987). *The Silvicultural Guide Book of Malawi*, 2nd ed.; FRIM, Zomba, Malawi.

83. Ishiguri F., Eizawa J., Saito Y., Iizuka K., Yokota S., Priadi D., Sumiasri N. & Yoshizawa N. (2007). Variation in the wood properties of *Paraserianthes falcataria* planted in Indonesia. IAWA Journal. 28(3), 339-348.

84. Ishiguri F., Hiraiwa T., Lizuka K., Yokota S., Priadi D., Sumiasri N. & Yoshizawa N. (2009). Radial variation of anatomical characteristics in *Paraseriantles falcataria* planted in Indonesia. *IAWA Journal*, 30, 343–352.

85. Ishiguri F., Wahyudi I., Takeuchi M., Takashima Y., Lizuka K., Yokota S. & Yoshizawa N. (2011). Wood properties of *Pericopsis mooniana* grown in a plantation in Indonesia. *Wood Science.* 57, 241–246.

86. Ivković M., Namkoong G. & Koshy M. (2002). Genetic variation in wood properties of interior spruce I growth, latewood percentage and wood density. *Canadian Journal of Forest Research*, 32, 2116–2127.

87. Ivković M., Wu HX., McRae TA. & Powell MB. (2006). Developing breeding objectives for radiata pine structural wood production I. Bioeconomic model and economic weights. *Canadian Journal of Forest Research*, 36, 2920–2931.

88. Izekor DN., Fuwape JA. & Oluyege AO. (2010). Effects of density on variations in the mechanical properties of plantation grown *Tectona grandis* wood. *Archives of Applied Science Research,* 2, 113–120.

89. Jaakkola T., Makinen H. & Saranpää P. (2007). Effects of thinning and fertilization on tracheid dimensions and lignin content of Norway spruce. *Holzforschung,* 61, 301–310.

90. Jaakkola T., Makinen H., Saren MP. & Saranpää P. (2005). Does thinning intensity affect the tracheid dimensions of Norway spruce? *Canadian Journal of Forestry Research*, 35, 2685–2697.

91. Jackson M. & Megraw RA. (1986). Impact of juvenile wood on pulp and paper products. In Juvenile Wood — What Does It Mean to Forest Management and Forest Products? Forest Products Research Society Proceedings 47309. Madison, WI: *Forest Products Research Society*.

92. Johnson GR. & Gartner BL. (2006). Genetic variation in basic density and modulus of elasticity of coastal Douglas-fir. *Tree Genetics and Genomes,* 3, 25–33.

93. Kafakoma R. & Mataya B. (2009). Timber value chain analysis for the Viphya plantations. Malawi Forest Governance Learning Group, London, UK.

94. Kamala FD. (2012). Study on Wood Properties Variation and Utilization of *Pinus patula* Families grown in Malawi. PhD thesis, Kyushu University, Japan, March 2012.

95. Kamala FD., Sakagami H. & Matsumura J. (2014). Mechanical properties of small clear wood specimens of *Pinus patula* planted in Malawi. *Open Journal of Forestry,* 4, 8–13.

96. Kellogg RM. & Kennedy RW. (1986). Practical applications of wood quality relative to end use. In Douglas - fir: Stand Management for the Future. C.D. Oliver, D. Hanley, and J. Johnson, *eds*. Tacoma, WA: *University of Washington*.

97. Kennedy SG., Cameron AD. & Lee SJ. (2013). Genetic relationships between wood quality traits and diameter growth of juvenile core wood in Sitka spruce. *Canadian Journal of Forest Research,* 43, 1 – 6.

98. Kiaei M. (2011). Anatomical, physical and mechanical properties of eldar pine (*Pinus eldarica* Medw.) grown in the Kelardasht region. *Turkish Journal of Agriculture and Forestry,* 35, 31 – 42.

99. Kollmann FFP. & Côté WA. Jr. (1968). *Principles of Wood Science and Technology I Solid Wood*; Springer-Verlag, Berlin, Germany.

100. Koubbaa A., Isbael N., Zheng SY., Bealieu J. & Bousquet J. (2005). Transition from juvenile to mature wood in black spruce (*Picea mariana* (Mill.) B.S.P.). *Wood and Fiber Science*, 37(3), 445-455.

101. Kozlowski TT., Kramer PJ. & Pallardy SG. (1991). The physiological ecology of woody plants, Academic Press, New York.

102. Krahmer RL. (1986). Fundamental anatomy of juvenile wood and mature wood. In Juvenile Wood — What Does It Mean to Forest Management and Forest Products? Forest Products Research Society Proceedings 47309. Madison, WI: *Forest Products Research Society*.

103. Kumar S., Dungey HS. & Matheson AC. (2006). Genetic parameters and strategies for genetic improvement of stiffness in Radiata pine. *Silvae Genetica,* 55, 77–84.

104. Kumar S., Jayawickrama KJS., Lee J. & Lausberg M. (2002). Direct and indirect measures of stiffness and strength show high heritability in a wind-pollinated radiata pine progeny test in New Zealand. *Silvae Genetica,* 51, 256–261.

105. Larson PR. (1969). *Wood Formation and the Concept of Wood Technology*: Volume 1. McGraw Hill, New York, NY, USA.

106. Larson PR. (1994). *The vascular cambium. Development and structure*. Springer-Verlag, Berlin.

107. Lasserre JP, Mason EG, Watt MS & Moore JR. (2009). Influence of initial planting spacing and genotype on microfibril angle, wood density, fibre properties and modulus of elasticity in *Pinus radiata* D. Don corewood. *Forest Ecology and Management*, 258, 1924–1931.

108. Lee SJ. (1999). Improving the timber quality of Sitka spruce through selection and breeding. *Forestry*, 72(2), 123 – 133.

109. Lenz P., Auty D., Achim A., Beaulieu J. & Mackay J. (2013). Genetic Improvement of White Spruce Mechanical Wood Traits—Early Screening by means of Acoustic Velocity. *Forests*, 4, 575–594.

110. Lenz P., Cloutier A., Mackay J. & Beaulieu J. (2010). Genetic control of wood properties in *Picea glauca*—An analysis of trends with cambial age. *Canadian Journal of Forest Research*, 40, 703–715.

111. Li B., McKeand S. & Weir R. (1999). Tree Improvement and Sustainable Forestry-Impact of two of Loblolly Pine Breeding in the USA. *Forest Genetics*, 6(4), 229 – 234.

112. Li L. & Wu HX. (2005). Efficiency of early selection for rotation-aged growth and wood density traits in *Pinus radiata*. *Canadian Journal of Forest Research*, 35, 2019–2029.

113. Lindström H. (1997). Fiber length, tracheid diameter, and latewood percentage in Norway spruce: development from pith outwards. *Wood Fiber Science*. 29, 21–34.

114. Louzada JLPC. & Fonseca FMA. (2002). The heritability of wood density components in *Pinus pinaster* Ait. and implications for tree breeding. *Annals of Forest Science*, 59, 867–873.

115. Luhanga J. (2009). Timber Trade in Malawi. *Resource Insight,* Issue 7. Accessed on www.sarwatch.org/publications/resource-insight/37-resources-insight

116. Machado JS. & Cruz HP. (2005). Within stem variation of Maritime Pine timber mechanical properties. *Holz Roh Werkst*, 63(2), 154–159.

117. Machado JS., Louzada JL., Santos AJA., Nunes L., Anjos O., Rodrigues J., Simões RMS., Pereira H. (2014). Variation of wood density and mechanical properties of blackwood (*Acacia melanoxylon* R. Br.). *Materials and Design,* 56, 975 – 980.

118. MacNeil MD., Nugent RA. & Snelling WM. (1997). Breeding for Profit: An Introduction to Selection Index Concept. *Genetics symposium*, Paper 142.

119. Makinen H. & Hynynen J. (2012). Predicting wood and tracheid properties of Scots pine. *Forest Ecology and Management,* 279, 11 – 20.

120. Makinen H. & Hynynen J. (2014). Wood density and tracheid properties of Scots pine: responses to repeated fertilization and timing of the first commercial thinning. *Forestry*, 87, 437 – 447.

121. Makinen H., Hynynen J. & Penttila T. (2015). Effect of thinning on wood density and tracheid properties of Scots pine on drained peatland stands. *Forestry,* 88, 359 – 367.

122. Martin SK., Loesch PJ., Demopulos-Rodriguez JT. & Wiser WJ. (1982). Selection indices for the improvement of opaque-2 maize. *Crop Science,* 22(3), 478 – 485. doi: 10.2135/cropsci1982.0011183X002200030010x

123. McAlister RH. & Clark A. (1992). Shrinkage of juvenile and mature wood of loblolly pine from three locations. *Forest Products Journal*, 42(7/8), 25 – 28.

124. McKinley RB. (1995). Factors affecting wood density of radiata pine – an update. Wood Quality Workshop i95. *Eds*. Klitscher, Crown, Donaldson, Rotorua, November 1998. FRI Bulletin No. 201: 83 pp.

125. Missanjo E. & Kamanga-Thole G. (2014). Impact of site disturbances from harvesting and logging on soil physical properties and *Pinus kesiya* tree growth. *International Scholarly Research Notices*, volume 2014, article ID 323626, doi:10.1155/2014/323626.

126. Missanjo E., Kamanga-Thole G. & Manda V. (2013). Estimation of genetic and phenotypic parameters for growth traits in a clonal seed orchard of *Pinus kesiya* in Malawi. *ISRN Forestry*, Volume 2013, Article ID 346982, doi:10.1155/2013/346982

127. Missanjo, E. & Matsumura J. (2016a). Radial variation in tracheid length and growth ring width of *Pinus kesiya* Royle ex Gordon in Malawi. *International Journal of Research in Agriculture and Forestry,* 3(1), 13–21.

128. Missanjo E. & Matsumura J. (2016b). Wood density and mechanical properties of *Pinus kesiya* Royle ex Gordon in Malawi. *Forests*, 7(7), 135. doi:10.3390/f7070135

129. Missanjo E. & Matsumura J. (2016c). Genetic Improvement of Wood Properties in *Pinus kesiya* Royle ex Gordon for Sawn Timber Production in Malawi. *Forests*, *7(11)*, 253. doi: 10.3390/f7110253

130. Missanjo E. & Mwale G. (2014). A mixed effect height-diameter model for *Pinus kesiya* in Malawi. *Journal of Biodiversity Management and Forestry*, 3(2). doi:10.4172/2327-4417.1000124

131. Missio RF., Silva AM., Dias LAS., Moraes MLT. & Resende MDV. (2005). Estimates of genetic parameters and prediction of additive genetic values in *Pinus kesiya* progenies. *Crop Breeding and Applied Biotechnology*, 5(4), 394 – 401. doi:10.12702/1984-7033.v05n04a04

132. Mmolotsi RM., Chisupo O., Mojeremane W., Rampart M., Kopong I. & Monekwe D. (2013). Dimensional relations and physical properties of wood of *Acacia saligna* an invasive tree species growing in Botswana. *Research Journal of Agriculture and Forestry Sciences*, 1(6), 2 – 15.

133. Moliński W., Fabisiak E. & Roszyk E. (2007). The propagation velocity of ultrasound waves along the grain in juvenile, mature and normal reaction of wood pine (*Pinus sylvestris* L.) Ann. Warsaw Agricultural University-SGGW. *Forest and Wood Technology,* 62, 200 – 206.

134. Moliński W., Roszyk E. & Puszyński J. (2014). Variation in Mechanical Properties within Individual Annual Rings of the Resonance Spruce Wood (Picea abies (L.) Karst.). *Drvna Industrija*, 65(3), 215-223.

135. Montes CS., Beaulieu J. & Hernández RE. (2007). Genetic variation in wood mechanical properties of *Calycophyllum spruceanum* at an early age in the Peruvian amazon. *Wood and Fiber Science,* 39(4), 578 – 590.

136. Moura VPG. & Dvorak WS. (2001). Provenance and family variation of *Pinus caribaea* var. *hondurensis* from Guatemala and Honduras grown in Brazil, Columbia and Venezuela. *Pesquisa Agropecuária Brasileira,* 36, 225–234.

137. Mutz R., Guilley E., Sauter UH. & Nepveu, G. (2004). Modelling juvenile-mature wood transition in scots pine (*Pinus sylvestris* L.) using non-linear mixed effect models. *Annals of Science,* 61, 831-841.

138. Mvolo CS., Koubaa A., Beaulieu J., Cloutier A. & Mazerolle ML. (2015b). Variation in wood quality in white spruce (*Picea glauca* (Moench) Voss.) Part I. Defining the juvenile – mature wood transition based on tracheid length. *Forests,* 6, 183 – 205.

139. Mvolo CS., Koubaa A., Defo M., Beaulieu J., Yemele MC. & Cloutier A. (2015a). Prediction of tracheid length and diameter in white spruce (*Picea glauca*). *IAWA Journal,* 36(2), 186 – 207.

140. Nakada R., Fujisawa Y. & Hirakawa Y. (2003). Effects of clonal selection by microfibril angle on the genetic improvement of stiffness in *Cryptomeria japonica* D. Don. *Holzforschung*, 57(5), 553–560.

141. Nawrot M., Pazdrowski W., Szymanski M. & Jedraszak A. (2012). Identification of juvenile and mature wood zones in stems of European Larch (*Larix decidua* Mill.) using a k-means algorithm. *Wood Research*, 57(4), 545 – 560.

142. Nawrot M., Pazdrowski W., Walkowiak R., Szymanski M. & Kazmierczak K. (2014). Analysis of coniferous species to identify and distinguish juvenile and mature wood. *Journal of Forest Science*, 60(4), 143 – 153.

143. Nicholls JW., Morris JD. & Pederick LA. (1980). Heritability estimates of density characteristics in juvenile *Pinus radiata* wood. *Silvae Genetica*, 29, 54–61.

144. Nyunai N., (2008). *Pinus kesiya* Royle ex Gordon, PROTA. Wageningen, Netherlands.

145. Ogunsanwo OY. & Akinlade AS. (2011). Effects of age and sampling position on wood property variations in Nigerian grown *Gmelina Arborea*. *Journal of Agricultural Research*, 11, 103–112.

146. Orwa C., Mutua A., Kindt R, Jamnadass R., & Anthony S. (2009) Agroforestry Tree Database: A tree reference and selection guide version 4.0. Available at (http://www.worldagroforestry.org/sites/treedbs/treedatabases.asp)

147. Panshin AJ. & de Zeeuw C. (1980). Text book of Wood Technology, Structure, Identification, Properties and Uses of the commercial wood of the United States and Canada. McGraw Hill Book Company, New York. 722 pp.

148. Pant GB. (2003). Long-term climate variability and change over monsoon Asia. *Journal of Indian Geophysical Union*, 7(3), 125 – 134.

149. Park YS., Simpson JD., Fowler DP. & Morgenstern EK. (1989). *A selection index with desired gains to rogue jack pine seedling seed orchards*, Information Report M-X-176, Department of Forest Resources, University of New Brunswick, Canada, 1989.

150. Plumptre RA. (1983). *Pinus caribaea* Vol II Wood properties. *Commonwealth Forest Institute*, Oxford University, *Tropical Forestry Paper No. 17*, 145 pp.

151. Priya PB. & Bhat KM. (1997). Wood anatomical changes associated with insect defoliation in juvenile teak. *IAWA Journal*, 18, 307-313.

152. Pugel A. & Shupe T. (2004). Composites from southern pine juvenile wood. Part III. *Forest Products Journal*, 54 (1), 47 – 52.

153. Pugel A., Price E. & Hse C. (1989). Composites from southern pine juvenile wood. Part I. *Forest Products Journal*, 40(1), 29 – 33.

154. Pugel A., Price E. & Hse C. (1990). Composites from southern pine juvenile wood. Part II. *Forest Products Journal*, 40(3), 57 – 61.

155. Rautiainen R. & Alen R. (2009). Variations in fibre length within a first-thinning Scots pine (*Pinus sylvestris*) stems. *Cellulose*, 16, 349–355.

156. Reza HM., Hosseinzadeh AAR., Johan LA., Familian H. & Hosseinkhani H. (2002). Investigation on trend of fiber variation of *Pinus eldarica*. *Iranian Journal of Wood and Paper Science Research*, 16, 73 – 93.

157. Ridley-Ellis D. (2011). *Introduction to Timber Grading: The European System of Machine Strength Grading*. Edinburgh Napier University, Edinburgh, UK.

158. Rollingson SW. (2012). Growth of a Pine tree. *The American Biology Teacher*, 74(9), 620 – 627.

159. Rozenberg P., Franc A., Mamdy C., Launay J., Schermann N. & Bastien JC. (1999). Genetic control of stiffness of standing Douglas fir from the standing stem to the standardized wood sample, relationships between modulus of elasticity and wood density parameters. Part II. *Annals of Forest Science*, 56(2), 145–154.

160. Sanhueza RP., White TL., Huber DA. & Griffin AR. (2002). Genetic parameter estimates, selection indices and predicted genetic gains from selection of *Eucalyptus globulus* in Chile. *Forest Genetics*, 9(1), 19 – 29.

161. Saranpää P. (1994). Basic density, longitudinal shrinkage and tracheid length of juvenile wood of *Picea abies*. *Scandinavian Journal of Forest Research,* 9, 64 – 78.

162. Saravanan V., Parthiban KT., Kumar P., Anbu PV. & Ganesh Pandian P. (2013). Evaluation of Fuel wood properties of *Melia dubia* at different age gradation. *Research Journal of Agriculture and Forestry Sciences*, 1(6), 8 – 11.

163. SAS 9.1.3. (2004). Qualification Tools User’s Guide. SAS Institute Inc. Cary, NC, USA.

164. Senft JF., Bendtsen BA. & Galligan WL. (1985). Weak wood: Fast grown trees make problem lumber. *Journal of Forest*, 83(8), 477 – 484.

165. Senft JF, Quanci MJ. & Bendtsen BA. (1986). Property profile of 60-year-old Douglas - fir. In Juvenile Wood — What Does It Mean to Forest Management and Forest Products? Forest Products Research Society Proceedings 47309. Madison, WI: *Forest Products Research Society*.

166. Seth MK., Thakur M. & Kapoor I. (2005). Circumferential and radial variation in ring width in west Himalayan Fir (*Abies pindrow* Royle). *Indian Forester,* 131(8), 1091 – 1100.

167. Sharma CL., Sharma M. & Carter MJ. (2013a). Radial variation in fibre length and wood density of *Melanorrhoea usitata* Wall. *The Indian Journal of Forestry,* 139(6), 518-520.

168. Sharma CL., Sharma M. & Jamir L. (2014). Radial variation in wood properties of plantation grown *Terminalia myriocarpa* Heurck and Muell-Arg in Nagaland, India. *Research Journal of Recent Sciences,* 3(ISC-2013), 9 – 14.

169. Sharma M., Sharma C.L. & Kumar YB. (2013b). Evaluation of Fiber characteristics in some weeds of Arunachal Pradesh, India for pulp and paper making. *Research Journal of Agriculture and Forestry Sciences,* 1(3), 5 – 21.

170. Sharma RC. & Duveiller E. (2003). Selection index for improving Helminthosporium leaf blight resistance, maturity and kernel weight in spring wheat. *Crop Science,* 43(6), 2031 – 2036. doi: 10.2135/cropsci2003.2031

171. Sharma SK., Rao RV., Shukla SR., Kumar P., Sudheendra R., Sujatha M. & Dubey YM. (2005). Wood quality of coppiced *Eucalyptus tereticornis* for value addition. *IAWA Journal,* 26, 137–147.

172. Shmulsky R. & Jones PD. (2011). *Forest Products and Wood Science, An Introduction*, 6th ed.; Wiley Blackwell, West Sussex, UK.

173. Smith HF. (1936). A discriminant function for plant selection. *Annals of Eugenics*, 7, 240 – 250.

174. Sotelo-Montes C., Beaulieu J. & Hernandez RE. (2007). Genetic variation in wood mechanical properties of *Calycophyllum spruceanum* at an early age in Peruvian Amazon. *Wood and Fiber Science*, 39, 578 – 590.

175. Sousa VB., Cardoso S., Quilhó T. & Pereira H. (2012). Growth rate and ring width variability of teak, *Tectona grandis* (Verbenaceae) in an unmanaged forest in East Timor. *International Journal of Tropical Biology*, 60(1), 483 – 494.

176. South African National Standard (SANS). (2003). *South African National Standard. The Structural Use of Timber. Part I. Limit States Design*; SABS Standards Division: Pretoria, South Africa.

177. Stanger TK. (2003). Variation and Genetic Control of Wood Properties in the Juvenile Core of *Pinus patula* Grown in South Africa. PhD Thesis, Department of Forestry, Graduate Faculty of North Carolina State University, Raleigh, NC, USA, May 2003.

178. Steffenrem A., Saranpää P., Lundqvistc S. & Skrøppa T. (2007). Variation in wood properties among five full-sib families of Norway spruce (*Picea abies*). *Annals of Forest Science*, 64, 799–806.

179. Steffenrem A., Solheim H. & Skrøppa T. (2016). Genetic parameters for wood quality traits and resistance to the pathogens *Heterobasidion parviporum* and *Endoconidiophora polonica* in a Norway spruce breeding population. *European Journal of Forest Research*, 135 (5), 815 – 825.

180. Stephens MJ., Alspach PA. & Beatson RA. (2012). Genetic parameters and development of a selection index for breeding Red raspberries for processing. *Journal of the American Society for Horticultural Science,* 137(4), 236 – 242.

181. Tasissa G. & Burkhart HE. (1998). Juvenile-mature wood demarcation in Loblolly pine trees. *Wood and Fiber Science,* 30, 119 – 127.

182. Tian Q., Gou X., Zang Y., Wang Y. & Fan Z. (2009). May-June temperature reconstruction over the past 300 years based on tree rings in the Qilian mountains of the Northeastern of the Tibetan Plateau. *IAWA Journal,* 30(4), 421 – 434.

183. Tirak-Hizal K. & Erdin N. (2016). Radial Variation of Annual Ring Width and Fiber Dimensions from Natural and Plantation Trees of Alder (*Alnus glutinosa* L. Gaertner) Wood. *Ormancilic Dergisi,* 12(2), 1 – 12.

184. Uetimane JE. & Ali AH. (2011). Relationship between mechanical properties and selected anatomical features of ntholo (*Pseudolachnostylis maprounaefolia*). *Journal of Tropical Forest Science,* 23, 166–176.

185. Vargas-Hernandez J. & Adams WT. (1992). Age-Age correlation and early selection for wood density in young coastal Douglas-fir. *Forest Science,* 38, 467–478.

186. Vavrčík H., Gryc V. & Koňas P. (2009). Comparison of wood density in relation to growth rings of English oak and Sessile oak. TRACE-Tree Rings in *Archaeology, Climatology and Ecology,* Vol. 8: Proceedings of the dendrosymposium 2009, April 16th – 19th 2009, Otočec, Slovenia. GFZ Potsdam, Scientific Technical Report STR 10/05, Potsdam, p. 157 - 163.

187. Vieira RA., Rocha R., Scapim A. Amaral Junior AT. & Vivas M. (2016). Selection index based on the relative importance of traits and possibilities in breeding popcorn. *Genetics and Molecular Research,* 15(2), 1 – 10. doi: 10.4238/grm.15027719

188. Wahab R., Mustafa TM., Amini M. & Rasat MSM. (2013). Anatomy and strength properties between tropical bamboo *Gigantochloa levis* and *G. scortechinii*. In Proceedings of the 2nd International Conference on Kenaf and Allied Fibres 2013 (ICKAF 2013), Selangor, Malaysia, 3–5 December 2013.

189. Walker JCF. & Butterfield BG. (1995). The importance of microfibril angle for the processing industries. *New Zealand Journal of Forestry*, 40(4), 35 – 40.

190. Wasniewski J. (1989). Evaluation of juvenile wood and its effect on Douglas - fir structural composite panels. Proceedings of the 23rd Particleboard and Composite Materials Symposium, Pullman, WA: *Washington State University*.

191. Wright JW. (1976). *Introduction to Forest Genetics*; Academic Press: New York, NY, USA.

192. Wu HX., Ivković M., Gapare WJ., Matheson AC., Baltunis BS., Powell MB. & McRae TA. (2008). Breeding for wood quality and profit in *Pinus radiata*: A review of genetic parameter estimates and implications for breeding and deployment. *New Zealand Journal of Forest Science,* 38, 56–87.

193. Yang JL. & Evans R. (2003). Prediction of MOE of eucalypt wood from microfibril angle and density. *Holz Roh Werkst,* 61(6), 449–52.

194. Yang KC., Benson CA. & Wong JK. (1986). Distribution of juvenile wood in two stems of *Larix laricina*. *Canadian Journal of Forest Research*, 16, 1041–1049.

195. Yang KC & Hazenberg G. (1994). Impact of spacing on tracheid length, relative density and growth rate of juvenile wood and mature wood in *Picea mariana*. *Canadian Journal of Forest Research*, 24(5), 996 – 1007.

196. Yildirim K., Ozturk H., Siklar S. & Kaya Z. (2006). Inheritance of wood specific gravity and its genetic correlation and its growth traits in young *Pinus brutia* progenies. In Proceedings of the IUFRO-Division 2 Joint Conference: Low Input Breeding and Genetic Conservation of Forest Tee species, Antalya, Turkey, 9-13 October 2006.

197. Zhang GJ., Ivković M., Prastyono & Doran JC. (2011). Development of an economic selection index for Australian tea tree. *Agroforestry Systems,* 82, 51 – 60. doi: 10.1007/s10457-010-9354-3

198. Zhang SY. (1995). Effect of growth rate on wood specific gravity and selected mechanical properties in individual species from distinct wood categories. *Wood Science and Technology,* 29, 451–465.

199. Zhu J., Nakano T. & Hirakawa Y. (2000). Effect of radial growth rate on selected indices for juvenile and mature wood of Japanese larch. *Journal of Wood Science,* 46(6), 417 – 422.

200. Zobel BJ. & Kellison RC. (1972). Short rotation forestry in the southeast. *TAPPI*, 55(8), 1205 – 1208.

201. Zobel BJ. & Jett JB. (1995). *Genetics of Wood Production*. Springer-Verlag, Berlin, Germany.

202. Zobel BJ. & Sprague JR. (1998). *Juvenile Wood in Forest Trees*. Springer-Verlag, Berlin, Germany.

203. Zobel BJ. & Talbert JT. (1984). *Applied Forest Tree Improvement*. 6th Edition. John Wiley and Sons Inc., New York.

204. Zobel BJ. & van Buijtenen JP. (1989). *Wood Variation: Its Causes and Control*; Springer-Verlag, Berlin, Germany.

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