ANATOMICAL AND PHYSICAL WOOD PROPERTY VARIATION AND JUVENILE WOOD DISTRIBUTION IN A SINGLE STEM OF TREMBLING ASPEN

by

Glen J. McDonald ©

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MAJOR ADVISOR'S COMMENTS

ABSTRACT

McDonald, G.J. 2003. Anatomical and physical wood property variation and juvenile wood distribution in a single stem of trembling aspen. Advisor: Dr. K.C. Yang.

Key woods: fibers, vessel elements, juvenile wood, mature wood, relative density, ring width, *Populus tremuloides*, trembling aspen.

The variation of fiber length, vessel element length, relative density, ring width and the distribution of juvenile wood within the stem of a 62-year-old trembling aspen (*Populus tremuloides* Michx.) were studied. Samples from the stem where acquired at 0.15 m, 1.3 m and then at every 2 m interval thereafter and examined in the east and west aspects. Radially, fibers and vessel elements both initially increased in length from the pith outwards and then remained relatively constant toward the bark. The vertical variation in cell length for both fibers and vessel elements was parabolic in shape. The ANOVA found that the three-way interaction aspect x zone x height was significant for both mean fiber and mean vessel element length. For both cell types, the juvenile wood zone had significantly shorter mean cell lengths than the mature wood zone in both aspects, when comparing means from the same height. Relative density did not have a radial variation common to all the heights. The vertical variation of relative density was eccentric. The ANOVA found that the two two-way interactions, zone x height and aspect x height, were significant. At heights where there was a significant difference, the mature wood zone had the significantly larger relative density. Ring width was found to generally increase from the pith outwards. The juvenile-mature wood boundary was demarcated using the radial variation of fiber length. The radial variation of vessel element length was tested as a criterion as well and found to be a viable criterion for demarcating the juvenile-mature wood boundary. Vertically, the width of the juvenile wood zone decreased with increasing height. The study tree consisted entirely of juvenile wood up to the age of 26. At age 62, the juvenile wood volume was 162 dm^3 which represented 28.0 percent of the total stem volume. The volume of mature wood exceeded the volume of juvenile wood at age 53. The relationship between the percentage of stem volume and percentage of basal area that is juvenile wood varied from linear to curvilinear depending on the height examined. From heights 0.15 m to 5.3 m, the relationship was curvilinear, while above 5.3 m the relationship was approximately linear. The width of the juvenile wood zone, expressed as number of rings, had a strong negative linear correlation with the interval age at the pith. The width of the juvenile wood zone decreased as the interval age at the pith increased, suggesting an ageing effect on the cambial initials influences the duration of juvenile wood production.

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ACKNOWLEDGEMENTS

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G.M.

INTRODUCTION

Historically viewed as a 'weed species' aspen, specifically trembling aspen (*Populus tremuloides* Michx.), has become an important fiber source as a result of new technologies in the pulping process and the development of wood composite materials. The high inherent brightness of aspen makes the fibers suitable for higher value paper and its relatively low density make aspen a preferred species for use in oriented strand board (OSB) (Forest Products Laboratory 1999). The production of OSB has increased dramatically and has largely replaced plywood as the sheeting material in building construction in North America (PCC 2000). Aspen is also processed for lumber, pallets, pulp, veneer, parallel strand lumber and particleboard. For many rural communities in Canada the use of aspen by the forest products industry has resulted in a new economic base (PCC 2000).

In Canada, there is an estimated standing volume of 1, 312 million m^3 of aspen in forest stands predominantly trembling aspen (PCC 2000). This represents approximately 80 percent of the total volume of the *Populus* species, found in *Populus* dominated stands. In stands were trembling aspen is not the predominant species, there is an additional 1, 614 million m^3 of trembling aspen in Canada. In Ontario, aspen has constituted the largest portion of the harvested hardwood volume reported in recent annual reports on forest management (Figure 1).

As trembling aspen continues to be a major fiber source, a comprehensive understanding of its wood properties would facilitate the manufacturing of consistently high quality wood products. An understanding of trembling aspens wood properties would also allow forest managers and tree breeders to manage trembling aspen for desirable qualities. The objectives of this study are to:

1. examine the variation of libriform fiber length, vessel element length, relative density and ring width,
2. quantitatively determine juvenile wood distribution,
3. examine the relationship between percentage of stem volume and percentage of basal area that is juvenile wood,
4. examine the relationship between interval age at pith and width of the juvenile wood zone.

Samples were obtained from specific heights in two cardinal aspects from one trembling aspen stem. Studying only one stem was done to provide a general overview of the wood properties in trembling aspen. In addition, one stem of trembling aspen was sampled due to the large number of measurements that led to time and financial restraints.

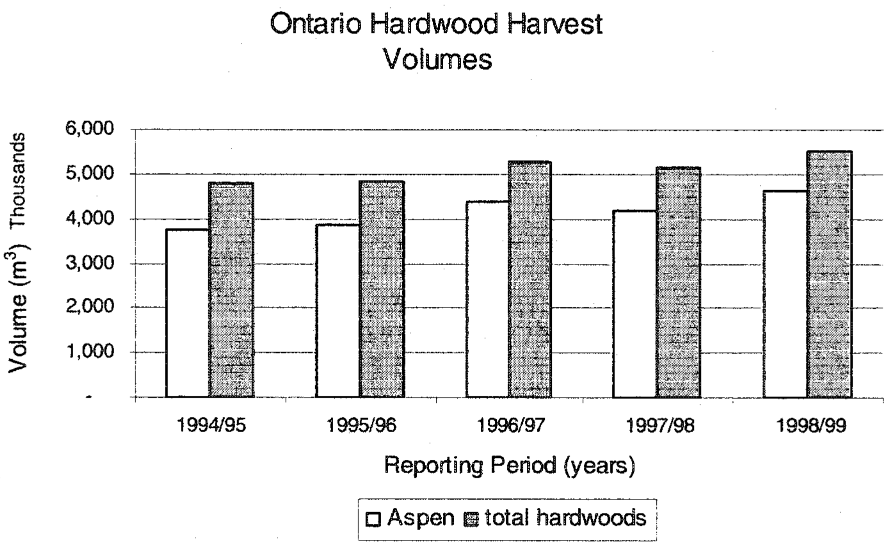


Figure 1. Ontario harvest volumes of aspen and all hardwoods. (OMNR 2000, 2001a, 2001b).

LITERATURE REVIEW

WOOD ANATOMY

The wood of hardwood species is composed of a variety of cell types that exhibit a large variation in size, shape, structure and arrangement depending on species (Jane 1956; Tsoumis 1968). Wood cells in hardwoods can be classified into three broad categories: vessel elements, fibers and parenchyma.

Fibers can be further subdivided into another two broad categories: hardwood tracheids and true fibers. There are two distinct hardwood tracheids that are recognized: vascular tracheids and vasicentric tracheids (Panshin and de Zeeuw 1980). There are two types of true fibers that are recognized in hardwoods: fiber tracheids and libriform fibers.

In hardwoods, parenchyma is the only cell type found in ray tissue (Panshin and de Zeeuw 1980; Kocurek and Stevens 1983). Parenchyma also occurs in non-ray xylem tissue. For this reason parenchyma is classified as either ray parenchyma or vertical parenchyma. There are three types of vertical parenchyma: strand parenchyma, fusiform parenchyma and epithelial parenchyma (Panshin and de Zeeuw 1980). There are two types of ray parenchyma: procumbent cells and upright cells.

Fibers, vessel elements and vertical parenchyma are all derived from the cambium fusiform initials (Jane 1956; Panshin and de Zeeuw 1980). Ray parenchyma is derived from ray initials (Jane 1956). The cambial fusiform initials and rays in trembling aspen are non-storied.

Not all hardwood species are composed of all the cell types. The cells that constitute the wood of trembling aspen are vessel elements, libriform fibers, strand parenchyma and procumbent ray parenchyma (Panshin and de Zeeuw 1980). A brief description of the characteristics of vessel elements and libriform fibers as found in trembling aspen is presented.

Libriform Fibers

Libriform fibers are thick walled and have pointed ends. The primary function of libriform fibers is to provide mechanical support for the tree (Jane 1956; Tsoumis 1968). Libriform fibers occupy approximately 56 to 79 percent of the cross-sectional surface area in trembling aspen (Kennedy 1968). The libriform fibers of trembling aspen are reported by Clayton (1968) as having an average diameter of 0.019 mm. Trembling aspen is reported by Panshin and de Zeeuw (1980) to have a mean fiber length of 1.32 mm with a standard deviation of 0.22. These values should be considered as general guidelines.

Vessel Elements

Vessel elements are dead, hollow and are perforated at their ends (Kocurek and Stevens 1983). In wood, vessel elements are connected end-to-end forming a pipe-like structure of indeterminate length called a vessel. The major function of vessels is to conduct water and nutrients from the roots upward. Vessel elements of trembling aspen have simple perforation plates, oblique end walls and do not have spiral thickening (Tsoumis 1968; Panshin and de Zeeuw 1980).

The arrangement of vessels, in the cross-sectional view, in trembling aspen wood is described primarily as diffuse porous with some occurrences of a semi-ring porous arrangement (Panshin and de Zeeuw 1980). The vessels of trembling aspen occur mostly in multiples, with a few being solitary. Vessels occupy approximately 20 to 33 percent of the cross-sectional surface area (Kennedy 1968). The largest vessel elements in trembling aspen are reported by Kennedy (1968) as having a tangential diameter between 0.05 mm – 0.10 mm. As a general guideline the mean vessel element length in trembling aspen is reported to be 0.67 mm with a standard deviation of 0.18 (Panshin and de Zeeuw 1980).

From here on libriform fibers will be referred to as ‘fibers’ and vessel elements will be referred to simply as ‘vessels’.

CELL LENGTH

The study of cell length variation within a tree was pioneered by Sanio. From his study of Scotch pine (*Pinus sylvestris* L.), Sanio developed a set of five conclusions about cell length variation which have been regarded as ‘Sanio’s Law’ (Spurr and Hyvarinen 1954). Sanio’s conclusion regarding radial variation was the concept that cell length generally increases from the pith through a number of growth rings, until a maximum length is reached, after which it remains constant for the remaining growth rings (Spurr and Hyvarinen 1954). Sanio’s conclusion regarding vertical variation was that cell length increases from the bottom up to a certain height, at which point a maximum length is reached and then decreases toward the crown. Subsequent research on the variation of cell lengths in different species and with larger sets of data have both supported and conflicted with these initial conclusions presented by Sanio.

Radial Variation

The radial variation of cell length can be usually divided into at least two zones, while in some species three zones are more appropriate. The initial zone of cell length radial variation is characterized by a rapid increase in cell length in the first ten to twenty growth rings from the pith. This zone is known as the juvenile wood zone. The duration of this zone is highly variable, depending on factors such as species and life span of the tree (Zobel and van Buijtenen 1989).

The second zone that is evident in some species is a transitional zone. The termination of the juvenile wood zone in some species is abrupt, but in most species there is a gradual transition between the first and what would be the third zone (Roos *et al.* 1990). During the transitional zone the rate of cell length increase is gradually reduced leading to the third zone. The duration of the transition zone is also highly variable.

The third zone is known as the mature wood zone. Extensive research on the radial variation of cell lengths has resulted in the acceptance of three cell length variations in the mature wood zone (Figure 2) (Panshin and de Zeeuw 1980):

1. Cell length continues to gradually increase, but at a much slower rate.
2. Cell length remains constant.
3. There is a gradual decrease in cell length, creating a curve that resembles a parabolic shape.

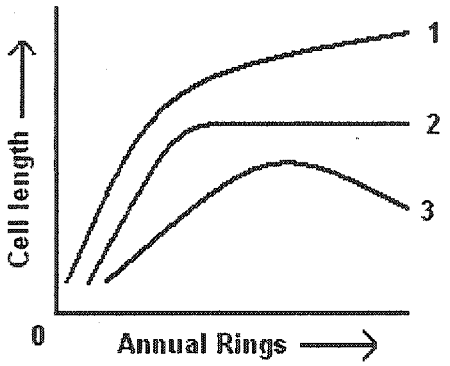


Figure 2. Typical curves (1, 2 and 3) for cell length radial variation from pith to bark (Adapted from Panshin and de Zeeuw 1980).

Cell length also exhibits a radial variation pattern within growth rings (intra-ring), as cell length increases from early-wood to late-wood (Chalk *et al.* 1955; Panshin and de Zeeuw 1980). Hejnowicz and Hejnowicz (1958) suggest that fibers are longer in the late-wood zone because the rate of intrusive growth changes during the growing season. The increase in fiber length from early-wood to late-wood can be as high as 100 percent for short-fibered hardwoods, while for long-fibered hardwoods the increase may be as low as 30 percent (Panshin and de Zeeuw 1980). Results of vessel length measurements in diffuse-porous wood indicate that there is only a slight increase in length within a growth ring (Panshin and de Zeeuw 1980). The longer length of vessels in late-wood has been attributed to the increase in the cambial fusiform initials with increasing age (Hejnowicz and Hejnowicz 1958; Panshin and de Zeeuw 1980).

Environmental conditions which increase ring width cause a larger late-wood zone, resulting in a larger volume of wood with longer fibers thus increasing the mean fiber length for the tree (Boyce and Kaeiser 1961). Hejnowicz and Hejnowicz (1958) found that the radial variation of cell length was similar regardless of whether the radial variation was expressed as number of rings or distance from the pith.

Fibers

Numerous studies on the radial variation of fiber length in *Populus* species have found that fiber length increases from the pith to the bark (Kennedy 1957; Boyce and Kaeiser 1961; Marton *et al.* 1968; Einspahr *et al.* 1972a; Holt and Murphey 1978; Yanchuk *et al.* 1984; DeBell *et al.* 1998; Fujiwara and Yang 2000). A study on the radial variation of fiber lengths in trembling aspen found that the rapid increase in cell length occurred in the first 22 years at a height of 1.3 m (Fujiwara and Yang 2000).

The increase in mean fiber length with increasing ring age was found by Murphey *et al.* (1979) to be statistically significantly different in poplar hybrids (*Populus* spp.). Mean fiber lengths of 0.59 mm, 0.66 mm and 0.72 mm for ages 2, 3 and 4, respectively where reported by Murphey *et al.* (1979). Marton *et al.* (1968) reported that mean fiber lengths from rings 1 to 3 were shorter than mean fiber lengths from rings 10 to 12 in poplar hybrids.

Snook *et al.* (1986) report a mean fiber length of 0.69 mm for three-year-old poplar hybrids grown on a good soil site and a mean fiber length of 0.63 mm for three-year-old hybrid poplars grown on a poor soil site. Fiber lengths from the two soil sites where statistically different.

A study of eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) found a non-significant difference in fiber length among three geographic locations, but a significant difference in fiber length within the geographic locations (Posey *et al.*1969). The fiber lengths were reported by Posey *et al.* (1969) to range from 0.88 mm to 1.42 mm, with a mean fiber length of all study trees of 1.07 mm, measured from wood samples obtained at breast height.

Yanchuk *et al.* (1984) found that mean fiber lengths for 15 trembling aspen clones had a large amount of variation. All the clones sampled were at least 36-years-old. The maximum mean fiber length was 0.97 mm and the minimum mean fiber length was 0.67 mm, at breast height. The fiber length radial variation reported by Yanchuk *et al.* (1984), started with short fibers at the pith, with lengths steadily increasing and then levelling off at approximately 4 to 5 cm from the pith.

Cech *et al.* (1960), studied one-year-old black cottonwood (*Populus trichocarpa* Torr. & Gray) shoots cultivated from cuttings or seeds and grown in a nursery. The mean fiber length of the shoots ranged from a minimum of 0.45 mm to a maximum of 0.81 mm.

Brown and Valentine (1963) studied trembling aspen that ranged in age from 6 to 36 years old from northern New York State. Sample trees where collected from four different groups of clones, from different locations in the state. Increment core samples were taken from the stem at three feet above the ground. Brown and Valentine (1963) found that distance from the pith had a highly significant effect on fiber length.

Hejnowicz and Hejnowicz (1958) studied the radial variation of fibers in a 53-year-old European aspen (*Populus tremula* L.) at various heights. The radial variation of fiber length exhibited the accepted general trend. At a height of 3.31 m, fiber lengths increased from approximately 0.40 mm near the pith to 1.25 mm near the bark.

The change in radial variation with increasing height was well illustrated by Panshin and de Zeeuw (1980) based on fiber length measurements done by Bisset and Dadswell (1949) in eucalyptus (*Eucalyptus regnans* F.v.M.) (Figure 3).

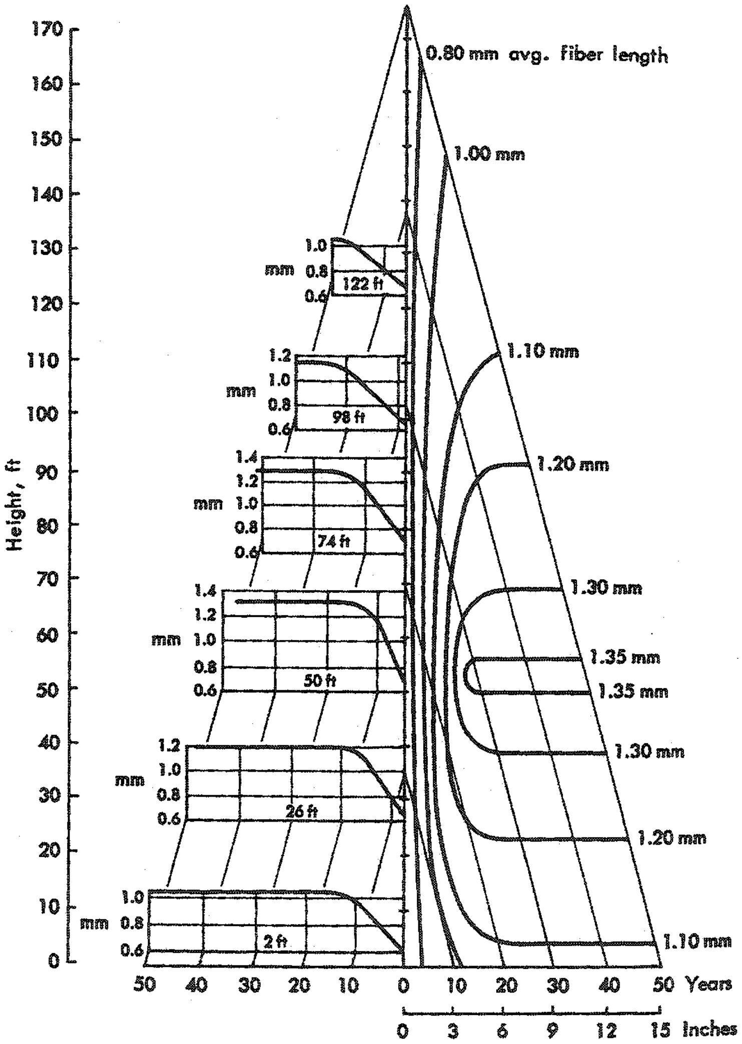


Figure 3. Variation of fiber length in the radial and vertical directions in *Eucalyptus regnans* (Panshin and de Zeeuw (1980) – adapted from Bisset and Dadswell (1949)).

Vessels

Vessel length radial variation is similar to fiber length radial variation. The amount of increase is however much less than what fibers experience (Panshin and de Zeeuw 1980). The vessel elements of diffuse porous wood species increase in length moderately compared to fibers but much greater than vessel elements in ring porous species.

The radial variation of vessel lengths was found by Hejnowicz and Hejnowicz (1958) to be similar to the radial variation of fiber lengths in European aspen. At a height of 3.31 m, vessel lengths increased from approximately 0.25 mm near the pith to 0.65 mm near the bark.

Vertical Variation

Fibers

Some studies examining the vertical variation of hardwood fibers have supported the initial findings by Sanio while other studies have conflicting findings. The vertical variation of increasing fiber length from the ground up, until reaching a maximum length at a certain height and then decreasing up to the top is supported by Bisset and Dadswell (1949) with eucalyptus (Figure 3), Hejnowicz and Hejnowicz (1958) with European aspen, and Einspahr *et al.* (1972a) with trembling aspen. This vertical variation pattern was found when following the same outer growth rings from bottom to top.

The trembling aspen studied by Einspahr *et al.* (1972a) came from three sources: 17-year-old naturally grown trembling aspen; 10-year-old plantation grown trembling aspen; and 10-year-old plantation grown triploid poplar hybrids. The vertical variation was the same in all three sources of trembling aspen. In the outer portion of the tree, following the same growth ring, mean fiber length was found to reach a maximum length at a height of 2 m (Figure 4). After 2 m, mean fiber length decreased with increasing height. Mean fiber length had a different vertical variation in the interior of the trees. In the interior, mean fiber length started high at the base and then continually decreased upward.

Hejnowicz and Hejnowicz (1958) reported that the maximum mean fiber length occurred at approximately half the height of the stem. Hejnowicz and Hejnowicz (1958) examined the vertical variation of mean fiber length based on different criteria. When mean fiber length was examined at a given distance from the pith at various heights, mean fiber length remained constant. When mean fiber length was examined by following a growth ring from the base to the top, mean fiber length increased upwards to a point and then decreased up to the top.

Vessels

The vertical variation of vessel lengths has been examined in shagbark hickory (*Carya ovata* (Mill.) K. Kock) by Pritchard and Bailey (1916), European aspen by Hejnowicz and Hejnowicz (1958), and Japanese basswood (*Tilia japonica* Simk.) by Fukazawa and Ohtani (1982).

Pritchard and Bailey (1916), and Hejnowicz and Hejnowicz (1958) found that vessel lengths increased up the stem until a maximum was reached at a certain height (a third to half the height) and then decreased up to the top, when following the same growth ring from the base to the top. Hejnowicz and Hejnowicz (1958) also examined the vertical variation of vessel length at a set distance from the pith at various heights. When examined in this way, mean vessel length increased from ground level up to 2 m above ground level and then remained the same length throughout the rest of the stem.

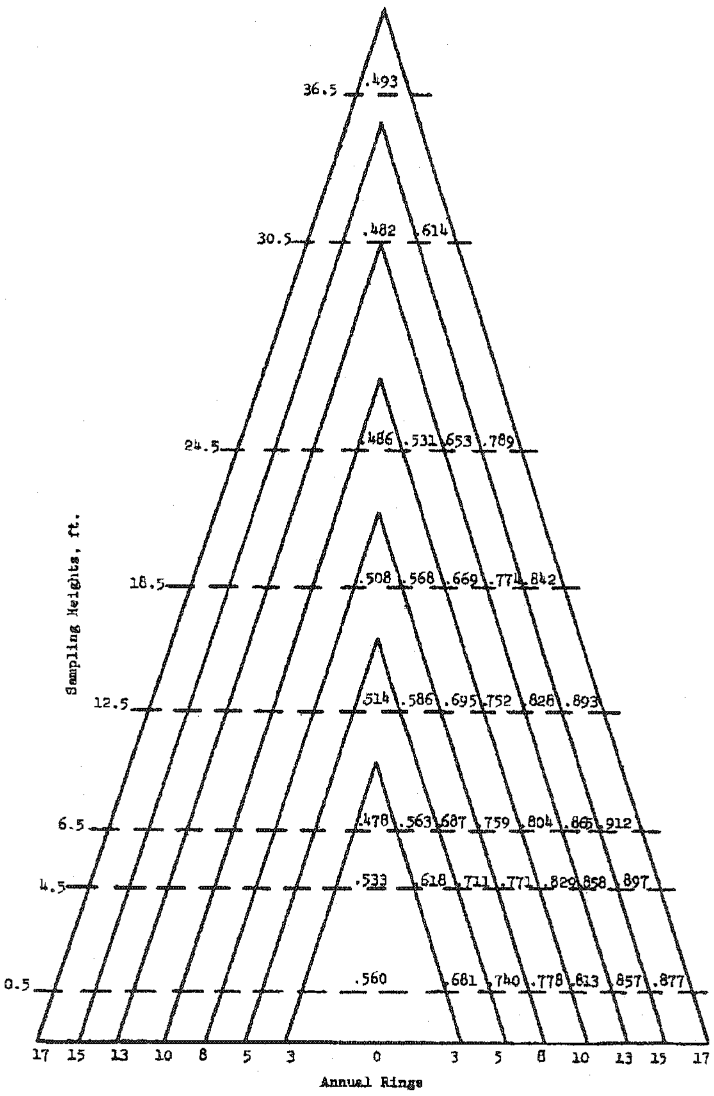


Figure 4. Schematic view of within-tree variation of fiber length in naturally grown *Populus tremuloides*. Values are based on a mean of five *P. tremuloides* grown in a sucker stand (Einspahr 1972a).

Cell Length Increase Rate

Yang *et al.* (1986) reported that the rate of tracheid length increase, in the juvenile wood zone, increased with increasing height in tamarack (*Larix laricina* (Du Roi) K. Kock.). The same pattern was also reported by Feng (2001) in a single stem of jack pine (*Pinus banksiana* Lamb.). Taylor (1968) found that the rate of fiber length increase was highest at breast height, and decreased with increasing height in a yellow-poplar (*Liriodendron tulipifera* L.).

RELATIVE DENSITY

Relative density is defined as the ratio of the density of a material to the density of water (Haygreen and Bowyer 1996). Relative density is calculated using an oven dry weight. The volume of wood can be determined at any moisture content. Generally the green volume is preferred due to the possibility of unequal shrinkage during drying (Smith 1954). Relative density is a unit-less measure since it is a ratio. An older termed used to refer to this ratio is specific gravity.

Relative density is regarded as the single most important physical property of wood (Zobel and van Buijtenen 1989; Haygreen and Bowyer 1996). Relative density has an effect on the yield, strength and general quality of most of the products produced from wood. Many mechanical properties of wood are highly correlated with relative density. For example, an increase in the strength and stiffness of wood is related to an increase in relative density.

Relative density is influenced by several characteristics of wood such as cell size and wall thickness, ratio of early-wood to late-wood, amount of ray cells, the size and amount of vessel elements (Zobel and van Buijtenen 1989). Kaeiser and Boyce (1964) state for *Populus*, that fibers are the most important factor affecting relative density, while vessels are the second most important.

Radial Variation

Panshin and de Zeeuw (1980), report three general radial variation patterns for relative density in the stem (Figure 5):

1. Relative density increases from the pith outward to the bark. The increase may be linear or curvilinear.
2. Relative density initially decreases outward from the pith, followed by an increase toward the bark. The relative density at the bark may be higher or lower than that near the pith.
3. Relative density decreases from the pith outward to the bark. The decrease may be linear or curvilinear.

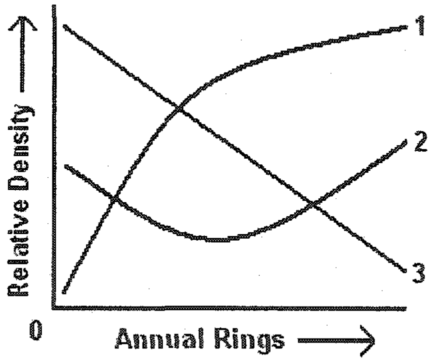


Figure 5. Typical curves (1, 2 and 3) for the radial variation of relative density from pith to bark (Panshin and de Zeeuw 1980).

A fourth relative density radial pattern is identified by Zobel and Sprague (1998). The pattern is characterized as: relative density increasing from the pith outward, levelling off and then as the tree approaches maturity, decreasing rapidly toward the bark. Relative density in hardwoods has been found to exhibit all four patterns. A fifth pattern has been identified by Wong (1986). In a suppressed tree relative density exhibits a horizontal line through the radial direction (Wong 1986).

The radial variation of relative density in hardwoods is a lot less consistent than the variation shown by softwoods (Panshin and de Zeeuw 1980). The variation in diffuse porous hardwoods is attributed to the proportionate volumes of vessel and fiber cell wall substance. The diameters of vessels tend to increase and the number of vessels per unit area decrease with increasing distance from the pith. Fibers in contrast change much less in diameter. An increase in relative density toward the bark would result if the proportion of fibers increased, the fiber-wall thickness increased, or both increased toward the bark. The proportion of fibers is reported to increase toward the bark in *Populus* (Panshin and de Zeeuw 1980).

Radial variation in relative density also occurs within a growth ring (Panshin and de Zeeuw 1980). Generally relative density is at a minimum in the early-wood portion of a growth ring and at a maximum in the late-wood portion. The change in relative density within a growth ring can be abrupt or gradual depending on the nature of the transition from early-wood to late-wood. In diffuse porous woods, the increase in relative density is a result of proportionate changes in vessel volume, fibrous tissue and cell wall thickness.

Numerous studies have examined relative density of *Populus* species (Marton *et al.* 1968; Posey *et al.* 1969; Einspahr *et al.* 1972b; Roos *et al.* 1990). A maximum relative density of 0.477 and a minimum relative density of 0.352 were found in one-year-old black cottonwood shoots by Cech *et al.* (1960). Roos *et al.* (1990) found that the mean relative density in the juvenile wood zone was 0.377 and in the mature wood zone 0.445. Wood samples where obtained from the lower portion of trembling aspen stems. Posey *et al.* (1969) study on eastern cottonwood found that relative density at breast height ranged from 0.30 to 0.50, with a mean of 0.404.

Valentine (1962) studied relative density radial variation at breast height in mature trembling aspen. The radial variation of relative density in the trembling aspen was found by Valentine (1962) to be attributed to the differences in distance from the pith. This was found to be the case when radial distance was considered both as a fixed distance from the pith and as specific years of growth. Valentine (1962) indicated that the relationship between relative density and distance from the pith may not be strictly linear, or is not linear throughout the entire radius of the stem. The mean relative density values for locations ranged from 0.343 to 0.432. Individual tree mean relative density values ranged from 0.293 to 0.471. The difference in means between locations was found to be statistically significantly different.

Brown and Valentine (1963) describe the general radial variation of relative density, at approximately 0.9 m from the ground, in the trembling aspen they studied as:

> "The innermost ring or two has a high specific gravity. There is a rather sharp decrease in the successive rings, up to about a distance of 1.5 cm from the pith. This is followed by large increases up to a distance of approximately 4 cm. Thereafter the rate of increase drops, so that the specific gravity values for successive rings to the cambium exhibit only slight if any increase."

The mean relative density values for one of the trembling aspen clone groups ranged from 0.410 to 0.461 and for a clone group with lower values 0.344 to 0.386 (Brown and Valentine 1963).

The radial variation of wood density at breast height has also been reported to be highly variable by Yanchuk *et al.* (1984) in trembling aspen at least 36-years-old. The radial variation of wood density was characterized as being high at the pith, decreases substantially a short distance from the pith, then continually increasing for the remaining distance from the pith. Einspahr *et al.* (1972b) found a similar radial variation pattern in 17-year-old naturally grown trembling aspen at various heights. In the naturally grown aspen, relative density was high at the pith, decreased moderately between three to five growth rings from the pith and then increased beyond the fifth growth ring.

Vertical Variation

Relative density in hardwoods does not exhibit a consistent or dominant vertical variation pattern (Panshin and de Zeeuw 1980). The lack of a consistent pattern is partly attributed to the diversity of the proportions of cell types in different parts of a stem. Site quality and other growth influences have also been found to affect the variation of relative density (Panshin and de Zeeuw 1980).

Einspahr *et al.* (1972b) studied the vertical variation of relative density in 17-year-old naturally grown trembling aspen and 10-year-old plantation grown poplar hybrids. The vertical variation was similar in both sources of aspen. The vertical variation was examined by following specific groups of growth rings from the base of the tree up to the height at which the rings end. In the naturally grown aspen, relative density in all the groups of growth rings, started high at the base of the tree and decreased upward (Figure 6). In the poplar hybrids Einspahr *et al.* (1972b) reported that relative density in growth rings 0 to five decreased from the base of the tree up to 1.4 m and then remained relatively constant at the remaining heights. In growth rings 5 to 8, relative density decreases up to 3.8 m and then remains relatively constant. In growth rings 9 to 10 relative density decreases up to 5.6 m, before remaining relatively constant.

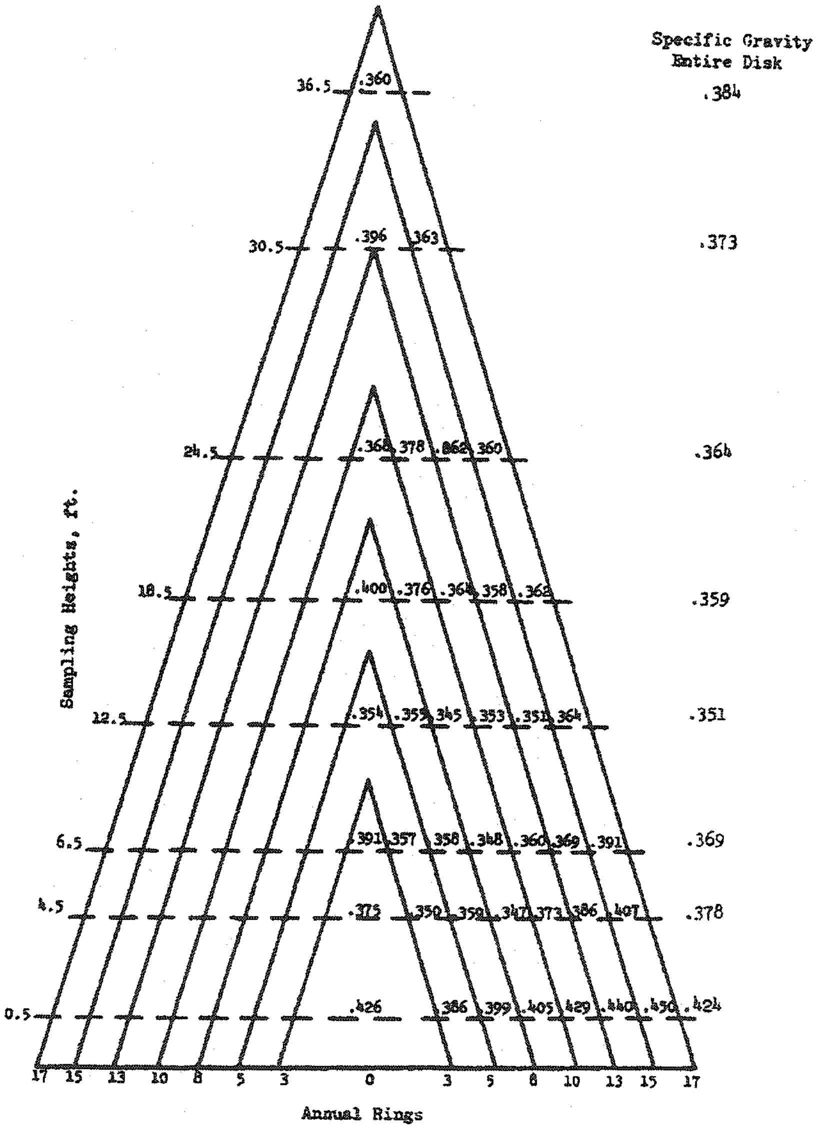


Figure 6. Schematic view of within-tree variation of specific gravity in naturally grown *Populus tremuloides*. Values are based on a mean of five *P. tremuloides* grown in a sucker stand (Einspahr 1972b).

RING WIDTH

Many variations in wood properties have been incorrectly associated with ring width, when in fact the variations are a result of juvenile wood (Zobel and van Buijtenen 1989). Initial conclusions had been made that juvenile wood characteristics were a result of a high growth rate (wide ring width) near the tree center. This has since been found to be a misconception, as wide rings do not cause juvenile wood.

Diameter growth rate, based on the amount of increase in diameter inside bark for a 5 year period between rings 3 through 7 from the pith, was reported in eastern cottonwood to have a high of 28.0 cm and a low of 2.0 cm by Posey *et al.* (1969). Valentine (1962) reports mean ring widths for the 23 locations that trembling aspen was studied ranged from 2.31 mm to 2.99 mm. The trees studied by Valentine (1962) all had a minimum diameter at breast height of 17.8 cm.

JUVENILE WOOD

The wood in the stem of a tree can be divided into two zones based on the differences in the structure and properties of the wood (Panshin and de Zeeuw 1980). One zone creates an inner core about the pith that extends from ground level to the crown tip (Figure 7). The second zone encases the first zone but only from ground level up to an undetermined height.

The lack of understanding of the juvenile and mature wood zones has resulted in the use of numerous terms for these two zones (Rendle 1958; Di Lucca 1989). The inner column has been referred to as: pith wood, core wood (Perry and Wang 1958), inner wood (Shupe *et al.* 1997), immature wood or youthful wood (Rendle 1958), crown-formed wood (Larson 1962; Panshin and de Zeeuw 1980) and, juvenile wood (Rendle 1958; Larson 1962; Tsoumis 1968; Panshin and de Zeeuw 1980; Yang *et al.* 1986).

The other wood zone has been referred to as: outer wood or exterior wood (Perry and Wang 1958; Rendle 1958), adult or mature wood (Rendle 1958; Panshin and de Zeeuw 1980) and stem-formed wood (Paul 1957). The terms juvenile wood and mature wood will be used to identify the two wood zones in this study.

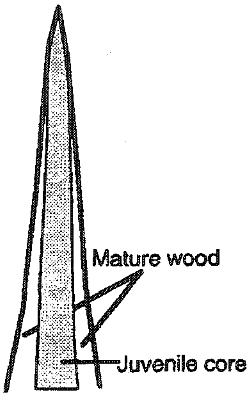


Figure 7. Illustration of the general location of the juvenile and mature wood zones in a tree stem (Yang and Benson 1997).

The lack of understanding of juvenile wood zone has also resulted in numerous proposed definitions of juvenile wood. A comprehensive definition of juvenile wood is given by Yang and Benson (1997):

> "Juvenile wood is the secondary xylem at the center of a tree formed throughout the life of the tree. The width or duration of juvenile wood decreases upward to the tree crown. This width is species-specific, can be affected by environmental conditions and is the result of an aging process of the cambial initials. The anatomical, chemical and physical features of juvenile wood increase or decrease gradually from the pith toward the mature wood. Most important, the strength of juvenile wood is weaker than the mature wood."

Characteristics of Juvenile Wood

Major differences have been found between juvenile and mature wood in all wood properties that have been studied. The characteristics of the mature wood are considered "normal" for a species (Panshin and de Zeeuw 1980).

Specific characteristics of juvenile wood can not be described due to the considerable variation that occurs between the conifers and the hardwoods, as well as among species, provenances within species and individual trees within provenances (Zobel and Sprague 1998). The differences between juvenile wood and mature wood are well known in conifers but very little research has been done with hardwood species (Zobel and Sprague 1998). The juvenile wood zone in hardwoods is generally less distinct than that of conifers, especially the diffuse porous woods where the differences in properties between juvenile wood and mature wood can be quite small (Zobel and Sprague 1998).

Generally properties in the juvenile wood zone, compared to the mature wood zone can be characterized as (Yang *et al.* 1986; Zobel and Sprague 1998);

1. Shorter fiber and vessel lengths.
2. Higher proportion of fibers in the juvenile wood zone.
3. Lower proportion of vessels in the juvenile wood zone.
4. Thinner cell walls.
5. Smaller tangential cell dimensions
6. Lower relative density.
7. Lower late-wood proportions
8. Lower cellulose content.
9. Lower strength.
10. Higher longitudinal shrinkage.
11. Larger microfibril angles.
12. Larger cell lumens.
13. Higher lignin content.
14. Larger amounts of reaction wood.
15. Larger amounts of spiral grain.
16. Higher degree of knottiness.

Generally juvenile wood has wider growth rings than mature wood. However this is not always the case. Narrow growth rings may occur in the juvenile wood zone as a result of the tree being suppressed during early growth (Yang *et al.* 1986).

Many of the properties are inter-related and lead to undesirable effects. The thinner cell walls of juvenile wood cells results in the lower relative density of juvenile wood. Since the microfibril angle is larger it causes greater longitudinal shrinkage.

The different characteristics of juvenile wood compared to mature wood affect the properties of wood products. Juvenile wood has pulp yields that are often 15 percent less than mature wood because of its lower relative density, higher lignin and lower cellulose content. The shorter cell lengths and greater microfibril angle in juvenile wood results in paper with a lower tear strength. The thinner cell walls of juvenile wood make it easier to flatten them thereby creating a greater bonding potential resulting in paper with a higher tensile and burst strength (Smith and Briggs 1986). Research has shown that dimension lumber cut from the juvenile wood core can have only 50 to 70 percent of the mechanical strength and stiffness of lumber cut from mature wood, depending on species and lumber grade (Kretschmann 1998). The larger occurrence of spiral grain in juvenile wood, leads to more defects during dying and manufacturing.

Formation of Juvenile Wood

A universally excepted explanation for the cause of the formation of juvenile wood does not exist. Instead there are a variety of hypothesis that have been put forward, each having its own proponents.

Many researchers attribute the production of juvenile wood to the influence the growth hormone auxin, produced in the crown of the tree, has on the cambium initials (Larson 1962; Zobel and Sprague 1998; Sauter *et al.* 1999). As the crown becomes increasingly distant from the cambium, the cambium is subjected to decreasing levels of auxin triggering the production of mature wood. Since auxin is produced by the crown, some researchers have suggested that silvicultural practices that affect the crown have an impact on juvenile wood development.

The hypothesis that the formation of juvenile wood continues until the annual height increments become less, was tested by Kucera (1994). Kucera (1994) concluded; "…a transition phase between formation of the juvenile wood and the mature wood at stump height level…clearly coincides with the culmination of the current height increment".

Some researchers have suggested that the apical meristem has an influence on the production of juvenile wood, through the production of auxins (Kucera 1994; Zobel and Sprague 1989).

Yang *et al.* (1986; 1994) hypothesize that it is the age of the cambial initials which determines whether juvenile, transition or mature wood is formed. Yang *et al.* (1994) reported that the age of the cambial initials was strongly related to the width of the juvenile wood zone.

A less common concept by Gartner (1996) attempted to relate the production of juvenile wood with the presence of photosynthetic bark. Gartner's (1996) hypothesis was the photosynthetic layer in the periderm, connected to the vascular cambium through rays, controls the type of wood produced by chemical reactions. Gartner (1996) does acknowledge that this method does not apply for all species.

A hypothesis that explains more the purpose of having juvenile and mature wood is based on the support function of the stem of the tree, given by Schniewind (1962). Schniewind (1962) maintains that the pattern of juvenile and mature wood closely follows the mechanical strength efficiency and conductive-storage functions found in the stem of the tree.

The concept that wide ring widths during the early development of a tree cause juvenile wood formation is not widely accepted (Zobel and Sprague 1998). This concept has been rejected since trees with narrow ring widths in the juvenile wood zone have exhibited the accepted radial variation of cell size and relative density, indicating the presence of juvenile wood.

JUVENILE-MATURE WOOD DEMARCATION

Developing methods which provide an accurate estimation of the proportion and size of the juvenile wood zone in a tree is necessary. This permits the separation of the juvenile wood from the mature wood allowing the appropriate allocation of a wood type to a particular end-product where the negative influences will be minimized (Sauter *et al.* 1999). An accurate estimation of the juvenile wood zone also allows for accurate estimates of the volumes of juvenile wood and mature wood.

Since wood properties undergo a transition from the juvenile wood to the mature wood, it is not possible to demarcate an exact line between the two zones (Zobel and Sprague 1998). The absence of an exact line makes it difficult to establish a scientifically reliable boundary between the two zones (Yang *et al.* 1986; Di Lucca 1989; Sauter *et al.* 1999).

A variety of methods of varying complexity and objectivity have been developed to demarcate the juvenile-mature wood boundary. Examples of methods that have been implemented by researchers to demarcate the juvenile-mature wood boundary include: iterative linear regression (Yang *et al.* 1986), linear segmented regression (Bendtsen and Senft 1986; Di Lucca 1989; Roos *et al.* 1990), non-linear segmented regression (Sauter *et al.* 1999; Evans *et al.* 2000), piecewise linear regression (Abdel-Gadir and Krahmer 1993), discriminate analysis (Bendtsen and Senft 1986), analysis of slope (Bendtsen and Senft 1986), subjective analysis (Bendtsen and Senft 1986), and visual inspection of graphic plots (Zobel *et al.* 1959; Bendtsen and Senft 1986).

All the demarcation methods rely on the change in characteristic that a specific property exhibits going from the juvenile wood zone to the mature wood zone. The change of both anatomical and mechanical wood properties has been utilized by researchers. Examples of properties that have been utilized are: cell length (Yang *et al.* 1986), wood density (Abdel-Gadir and Krahmer 1993; Sauter *et al.* 1999), relative density (Di Lucca 1989; Roos *et al.* 1990), ring width (Yang *et al.* 1986, 1994), microfibril angle, longitudinal shrinkage, modulus of rupture (MOR) (Evans *et al.* 2000; Roos *et al.* 1990) and modulus of elasticity (MOE) (Bendtsen and Senft 1986; Roos *et al.* 1990; Evans *et al.* 2000).

The availability of a variety of wood properties for demarcating the juvenile-mature wood boundary creates another complication for consistent results. The transition point between the juvenile wood zone and mature wood zone occurs at different locations within the same tree depending on the property being used (Zobel and van Buijtenen 1989). As a result, the location of a boundary is not consistent when comparing results using different properties (Bendtsen and Senft 1986). For example, mechanical properties and relative density appear to mature earlier than cell length and microfibril angle resulting in a smaller juvenile wood zone (Bendsten and Senft 1986; Di Lucca 1989).

Evans *et al.* (2000) found that MOR was not a reliable indicator for the boundary between the juvenile-mature wood. In contrast Evans *et al.* (2000) found that the radial profile of MOE showed a clear expected juvenile wood curve, thus making it a good property for identifying the juvenile-mature wood boundary.

The use of relative density may not be a reliable indicator of the presence of juvenile wood in hardwoods. The relative density of many hardwoods displays considerable variation in the radial profile (Fukazawa 1984; Evans *et al.* 2000).

Yang and Benson (1997) provide four advantages for using the change in cell length as the criteria for demarcating the juvenile-mature wood boundary: "(1) can be applied to both natural and plantation grown trees, (2) can be used in both conifers and hardwoods, (3) cell length has a high degree of heredity in nature and (4) cell length is not greatly affected by growth ring width".

The use of ring width as a criterion for locating the boundary has been found to be inadequate in natural grown trees, but adequate for plantation grown trees (Yang *et al.* 1986).

JUVENILE WOOD ZONE

Juvenile Wood Zone Shape

Many researchers have believed that the juvenile wood zone has a cylindrical shape (Rendle 1958; Zobel and McElwee 1958; Panshin and de Zeeuw 1980). However other investigations have found that a cylindrical shape does not accurately describe the shape of the juvenile wood zone. Groom *et al.* 2002 reports that the shape of the juvenile wood zone in a loblolly pine (*Pinus taeda* L.) was biconical. The boundary of the juvenile wood zone was found to taper "from the stump to below the live crown and a similar taper from the crown to the tip of the main bole" (Groom *et al.* 2002). The boundary was determined from normalizing the results of the radial pattern of modulus of elasticity, fiber ultimate tensile stress, cross-sectional area and microfibril angle at different heights.

Yang *et al.* (1986) investigated the juvenile wood zone in tamarack and found that the juvenile wood zone had a conical shape. The demarcation of the boundary was based on tracheid length and growth ring width. A conical shape for the juvenile wood zone was also found in a plantation grown Japanese cedar (*Cryptomeria japonica* D. Don.) by Yang *et al.* (1994). Yang *et al.* (1994) used growth ring width as the criterion for determining the boundary since it was a plantation grown tree. Feng (2001) found that the juvenile wood zone in a single stem of jack pine had a conical shape. An iterative linear regression method using tracheid length as the criterion was used for demarcating the boundary.

Juvenile Wood Zone Width

As an excepted general guideline the juvenile wood zone occurs up to the first 5 to 20 rings (Zobel and Sprague 1998). The size of the juvenile wood zone is reported by Di Lucca (1989) as mainly depending on growth rate regardless of species. Since silvicultural practise can influence growth rate, the size of the juvenile wood zone can also be affected.

Di Lucca (1989) reports that the average age of the juvenile-mature wood boundary in second-growth Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) occurred at ages "23, 23, 21 and 23 years for sections sampled at breast height, 20 and 40 percent of total height, and for all sections, respectively". The boundary was estimated using relative density and a linear and segmented regression method.

A study done on a trembling aspen by Fujiwara and Yang (2000) found that the juvenile wood zone lasted for 22 years, at a height of 1.3 m. The boundary was determined using fiber lengths, with an iterative regression method. The iterative regression method with tracheid lengths was used to demarcate the juvenile-mature wood boundary at various heights in an 81-year-old dominant and an 83-year-old suppressed tamarack (Yang *et al.* 1986). In the dominant tree the boundary in the north aspect was found to occur at ages 45, 37, 25, 21, 15, 9, 4, at heights (m) 0.15, 1.5, 4.5, 7.5, 10.5, 13.5, and 16.5, respectively.

Lee and Wang (1996) study of Japanese cedar found that the juvenile-mature wood boundary occurred at the 23rd growth ring at breast height. Determination of the boundary was based on latewood tracheid length.

In order to account for the transition phase, Roos *et al.* (1990) identified a 'transition point' and a 'point of maturity' instead of a single boundary location in trembling aspen. The transition point was found to occur at ages 15, 16 and 16 based on relative density, MOR and MOE, respectively. The point of maturity is reported as occurring at ages 30, 29 and 28 based on relative density, MOR and MOE, respectively. The transition point and point of maturity ages where based on studies done on the wood from 1.8- to 2.4- m butt logs.

The width of the juvenile wood zone in the east and west aspect was found not to be statistically significantly different in Japanese cedar (Yang *et al.* 1994). A non-statistically significant difference was also the case with the width of the mature wood zone. The non-statistical significant difference result occurred when the juvenile wood zone was expressed as either width (mm) or number of rings.

The width of the juvenile wood zone was found to vary widely along the length of a loblolly pine stem (Groom *et al.* 2002). Groom *et al.* (2002) found that the juvenile wood zone was the widest at stump height with 14 growth rings, and narrowest slightly below the live crown with less than 5 growth rings.

Fukazawa and Ohtani (1982) found that the juvenile wood zone in a 150-year-old Japanese basswood had a "radius of 8 cm at 1.3 m height, of 4 cm at 5.3 m height and of 3 cm at 11.3 m". At 5.3 m, the juvenile wood zone consisted of 28 growth rings. The determination of the boundary was based on an examination of the radial variation of length, diameter and frequency of wood elements such as vessel elements and libriform fibers.

Feng (2001) also found that the juvenile wood zone was the widest in jack pine at stump height (0.15 m), with 30 growth rings in the east aspect and 28 in the west aspect. The juvenile wood zone was the narrowest at a height of 15.4 m with 6 growth rings in the east aspect and 7 growth rings in the west aspect. Feng (2001) reports that when the width of the juvenile wood zone is expressed as distance from pith, the narrowest width in the west aspect occurred at 13.4 m, with all other rankings remaining unchanged. The boundary was determined using the radial variation of tracheid length and an iterative regression method.

Juvenile Wood Percentage

The proportion of juvenile wood by volume decreases considerably with increasing age of the tree (Zobel and van Buijtenen 1989). As a general guide line plantation grown trees contain a higher percentage of juvenile wood, than naturally grown trees.

Researchers have reported that 85 percent of the wood volume in 15-year-old loblolly pines was juvenile wood, while only 19 percent of the wood volume in 40-year-old trees was juvenile wood (Zobel and Sprague 1998). Yang *et al.* (1986) study of a dominant (81-year-old) and suppressed (83-year-old) tamarack found that approximately 44 percent of the total volume of both trees was juvenile wood. Feng (2001) reported the percentage of juvenile wood in a 60-year-old jack pine was 30 percent. The jack pine was found to consist entirely of juvenile wood up to the age of 26 (Feng 2001).

MATERIALS AND METHODS

STUDY TREE

The study tree was obtained from the Lakehead University Jack Haggerty Forest, located approximately 37 km north of Thunder Bay at a longitude of 89°22' and latitude of 48° 39'. The profile of the study tree was to be a trembling aspen ranging in age from 50 to 60-years-old, with a crown in the dominant/co-dominant canopy layer and without extensive rot.

During the selection of a study tree, the stems of potential trembling aspen trees were examined for signs of fruiting bodies that would indicate internal rot. The study tree was found in a mixed wood, upland site. Before felling the study tree, the north and south aspects were marked on the stem with paint. Once the tree had been felled, interval distances were measured with a 30 m tape and marked on the stem with paint. The north aspect was also labelled at the location that discs were to be cut. The first disc was taken at a height of 0.15 m from the ground. The next disc was taken at breast height (1.3 m) and then all subsequent discs were taken at 2 m intervals thereafter (Figure 8).

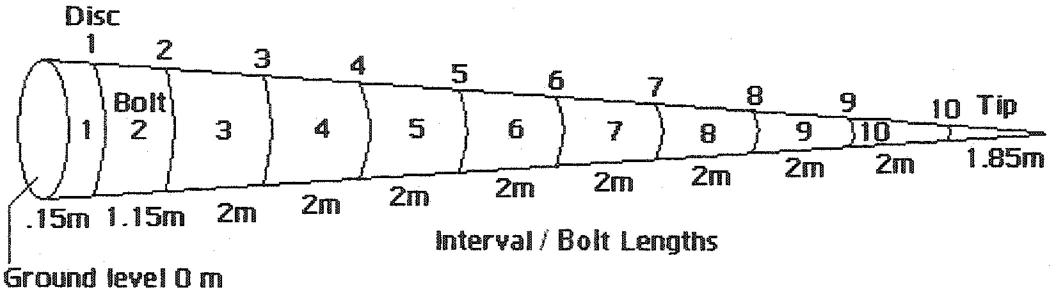


Figure 8. Illustration of where the discs were cut from the study tree.

The final disc was obtained at 17.3 m, the last full 2 m interval. This left a remaining tip length of 1.85 m, for a total tree height of 19.15 m. Two discs were cut at each height. The thickness of the discs ranged from 4 cm to 8 cm. As the discs were cut from the stem they were labelled with a number (one starting at the base) to indicate their position in the stem and the north aspect was labelled on the cross-sectional surface of the disc facing the crown of the tree. One complete set of discs was used as the primary set and the second set of discs was kept aside as a reserve set.

SEGMENT BLOCK PREPARATION

A diameter strip was cut out of each disc. The diameter strips from discs 2 to 10 where cut in the east-west aspect, while the diameter strip from disc 1 was cut in the north-south aspect. The diameter strip for disc 1 was cut in a different aspect in order to accommodate damage that occurred to the stump during the felling process. The diameter strips were cut approximately 2.5 cm wide and encompassed the pith.

Both aspects and disc number were labelled on the diameter strips. The cross-sectional surface of the diameter strip was then sanded with a belt sander. As soon as the diameter strips were cut and sanded, attempts were made to mark the growth rings with a felt tip marker. Difficulty was encountered in identifying the growth rings with the naked eye, due to their faintness. Thus a ‘best attempt’ was made to mark the location of the rings. This resulted in the markings not corresponding exactly to the ring locations. Once all the diameter strips had been processed, the cross-sectional surface that was marked was photocopied.

The diameter strips were cut up based on the markings, creating 'segment blocks'. This was done with a meat cleaver. Initially a diameter strip was split in half at the pith, creating two radius strips. The first segment block was then cut from the pith end of a radius strip. The first marking was counted as one while the following markings were counted successively. On occasions where successive markings where too close together to be slit apart, the two markings would be kept together, creating a segment block that contained two smaller markings. The resulting block would be given the number of the second marking, so that the final segment block number would reflect the number of markings for a particular radius strip and not the number of segment blocks. Each segment block was identified with a number code that identified the disc, aspect and marking number. The identification number was written directly on the radial side of the segment block with a pencil and a marker.

RELATIVE DENSITY

The relative density of each segment block was determined using the maximum moisture content method developed by Smith (1954). Valentine (1962) found the maximum moisture content method produced relative density values that were comparable to the volumetric method. The formula for calculating relative density using the maximum moisture content method is:

$$R.D. = \frac{1}{\frac{M_m - M_o}{M_o} + \frac{1}{G_{so}}}$$

Where:

R.D. = relative density.
M_m = maximum moisture content weight.
M_o = oven dry weight.
G_{so} = relative density of cell wall substances (average value = 1.53).

The relative density of cell wall substances varies slightly between species. The value of 1.53 for G_{so} was selected since it is identified by Smith (1954) as being an average value. This value is also consistent with the findings by Valentine (1962) for trembling aspen.

Maximum moisture content refers to a condition in which the cell lumen and cell wall voids are completely occupied with water. In order for the segment blocks to reach a maximum moisture content state, they where placed in beakers filled with water and placed under intermittent vacuum pressure. The segment blocks were deemed to have reached their maximum moisture content when two successive weight measurements did not change by more than 0.05 g. A random sample of segment blocks was weighed after nineteen days. The same samples were weighed again seven days later, at which time the weight change did not exceed 0.05 g.

After the maximum moisture content weight was obtained the segment blocks where placed in an oven, in order to dry the segment blocks down to an oven dry state. The oven was set to a temperature of 100^0 C (± 3^0 C). The segment blocks were deemed to have reached their oven dry weight when two successive weight measurements did not change by more than 0.05 g. A random sample of segment blocks was weighed after four days. The same segment blocks were weighed again two days later, at which time the weight change did not exceed 0.05 g.

During the drying process a fire occurred in the oven as a result of an inaccurate temperature setting, causing extreme temperatures in the oven. The fire resulted in the damage to segment blocks from six of the twenty radius strips. The six radius strips came from discs 4, 5, 7, 8 and 9, which where from heights 5.3 m, 7.3 m, 11.3 m, 13.3 m and 15.3 m respectively. Disc 8 had segment blocks from both aspects damaged, while the other discs had damage to segment blocks originating from the west aspect only. The salvaged segment blocks from the six radius strips that had losses were discarded. The damaged and discarded segment blocks were replaced with segment blocks produced from the corresponding reserve discs.

CELL LENGTH MEASUREMENT

Further processing of the segment blocks was required before the fibers and vessels could be measured. A small sliver of wood was radially split off of each segment block and placed in a test tube. Each test tube was labelled with the corresponding segment block number. A maceration solution was then added to the test tubes, with just enough to submerge the wood sliver. The maceration solution consisted of glacial acetic acid (CH_3COOH) and hydrogen peroxide (H_2O_2), mixed at a ratio of 1:1 (Franklin 1945; Panshin and de Zeeuw 1980). Paraffin wax was placed over the opening of the test tube to reduce the loss of the maceration solution through evaporation. A small hole was poked into the paraffin wax in order to prevent pressure build up. The test tubes where then placed in a multi block heater in order to accelerate the chemical reaction dissolving the lignin. The multi block heater was set to a temperature of approximately 60^0C. The test tubes were kept in the multi block heater until the lignin had been dissolved by the maceration solution, after approximately 48 hours. The lignin was known to have been dissolved when the wood slivers had turned pure white.

Once the lignin had been dissolved the maceration solution was drained from the test tube. The wood sliver was then rinsed a minimum of three times with water. After rinsing, one-third of the test tube was again filled with water. The test tube was then shaking vigorously in order to separate the wood cells to create a pulp. A small sample of pulp was then transferred to a glass slide. Water was used as the mounting medium. The cells were then viewed with a Canlab (circa 1970) compound light microscope and measured with an ocular micrometer. The magnification used was as follows: ocular 10x and objective lens 4x or 10x. At 40x magnification each interval on the ocular micrometer represented 24 microns and at 100x magnification 10 microns. The higher magnification was used for the vessels.

The minimum number of cells that needed to be measured from each segment block in order to obtain an assessment of cell length within an allowable error and probability level was determined statistically (Yang and Pulkki 2002). An allowable error of the mean of 5 percent and a probability level of 0.05 were selected as the parameters. Preliminary measurements of 20 randomly selected fibers and vessels from a randomly selected segment block were used to provide estimates for the parameters necessary for the sample size calculation. The sample size calculation determined that at least 34 fibers and 35 vessels needed to be measured. To standardize the measurements 35 fibers and 35 vessels were measured from each segment block. The sample size calculation is provided in Appendix I. Only undamaged cells were measured.

RING WIDTH & COUNT

Counting of the rings and measuring their width was performed on the reserve strips. Due to the difficulty experienced previously in locating the rings, other steps were taken to enhance there visibility. The cross-sectional surface of the diameter strips was first sanded. Water was then applied to the diameter strips to soften the wood. A razor blade was then used to cut the cross-sectional surface of the diameter strips. This was done to create a 'clean' cut surface, in which the cell features were preserved. The diameter strips were then examined under a Bausch and Lomb academic stereozoom dissecting microscope (model asz4513) using magnifications ranging from 10.5x to 45x. While examining the diameter strips under the microscope, the rings were marked with a pencil in order to highlight them to make their location visible with the naked eye.

The diameter strips were then scanned using a Hewlett-Packard scanjet 5470C scanner. Scanning was done at a resolution of 600 dpi, with true colour and at 100 percent scale. Ring width was then measured off the images using the measuring tool in Adobe Photoshop 6.0. A sample of Photoshop measurements was compared to measurements made with Media Cybernetics Image-Pro Plus and measurements made using a ruler on the actual diameter strips. The Photoshop lengths were similar to the lengths measured using the other methods (non-statistically tested).

The six reserve radius strips which were used for replacing the fire damaged segment blocks did not have their rings counted or ring widths measured prior to being split into replacement segment blocks. The radius strips were only photocopied. Since only the west aspect radius strips from reserve discs 4, 5, 7 and 9 where used for replacement, the east aspect radius strips were available for counting the rings and measuring their ring widths. As a result of both aspects of reserve disc 8 being used for replacement, there was no ring count or ring width data for this disc. The missing ring widths were estimated using an average of the ring widths from adjacent discs and / or the opposite aspect, for each ring. For example, the estimated ring width during year - 20 for radius strip 4 - west was determined by averaging the ring width that occurred in year - 20 in radius strip 4 - east and radius strip 3 - west.

The number of rings counted in the east aspect on radius strips 4, 5, 7 and 9 were used for the west aspect as well. Since both radius strips from disc 8 where used as replacements the total number of rings for this strip was estimated. The number of rings for disc 8 was determined by using the average difference between the two adjacent discs (i.e., 7 and 9).

SEGMENT LENGTH

The distance between markings identified on the diameter strips was measured to determine the distance from the pith to the end of each segment block. The length between markings was measured off the photocopies taken of the diameter strips. On the photocopy a line was drawn through the middle of a radius strip. The distance between the markings was then measured along this line using a standard ruler, starting at the pith. The last distance was measured at the vascular cambium. For segment blocks which consisted of two markings, the cumulative distance of the two markings was recorded for the particular segment block.

DATA ANALYSIS

Radial Variation

The radial variation of fibers and vessels was examined by plotting the mean of the 35 length measurements of each cell type, of each segment block, expressed as distance from the pith. The radial variation of relative density was examined by plotting the single relative density value of each segment block expressed as distance from the pith. The radial variation of ring width at each height was plotted as a function of total rings in the study tree.

Juvenile-Mature Wood Demarcation

The juvenile-mature wood boundary was demarcated at each height in both aspects. Two methods were implemented, both of which are based on the definition that the juvenile wood zone is where cell length rapidly increases and the mature wood zone is where cell length exhibits one of the three patterns indicated in the literature review.

The two methods were conducted twice, first using the radial variation of fiber lengths and secondly using the radial variation of vessel lengths. The demarcated boundary based on the radial variation of fiber length was deemed the final location of the juvenile-mature wood boundary. From here on 'fibers' will be used as the cell type for the description of the demarcation methods. Disc 10 was considered to consist entirely of juvenile wood due to its size and height location in the study tree.

Initially the method described by Yang *et al.* (1986) was conducted. The location of the boundary derived from this method did not visually appear to adequately identify the transition point on the radial variation graphs. The inadequacy was probably due to the larger fluctuation in fiber length that occurred between successive segment blocks compared to tracheids, which exhibit very little fluctuation in length between successive rings.

A slightly modified version of the method described by Yang *et al.* (1986) was then conducted. A quadratic trend line was applied to the radial variation graphs of strips 2 to 9. A fourth order trend line was applied to the radial variation graph of strip 1 since it represented the fiber length radial variation better. The equation of each trend line was also produced. The graphs were then examined and using the juvenile-mature wood boundary determined with the Yang *et al.* (1986) method as a guideline, another point was selected as a temporary boundary. A mean mature fiber length, based on averaging all the points in the mature wood zone defined by the new temporary boundary, including the boundary point, was then calculated. The mean mature fiber length was then plotted on the graphs as a horizontal line parallel to the x-axis (Figure 9). The point of intersection (x-value) between the trend line and the plotted mean mature fiber length was then solved for. The solved x-value was then used as the final location of the juvenile-mature wood boundary for this study.

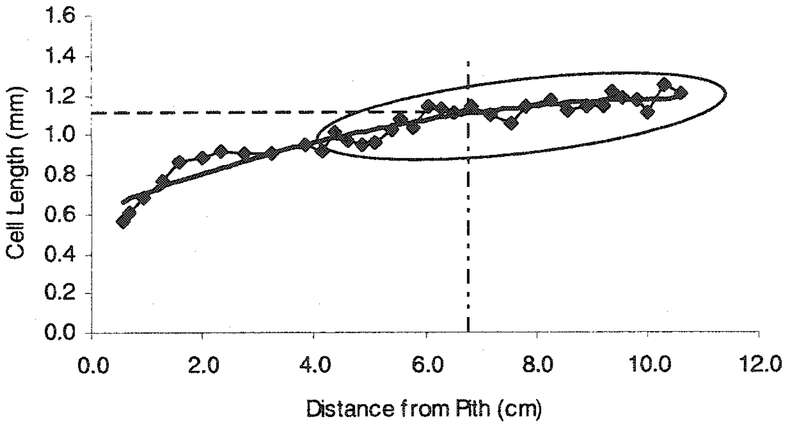


Figure 9. Example of the modified demarcation method. The circled points are the mature wood zone points used to calculate a mean mature fiber length.

Rate of Cell Length Increase

The rate at which the length of fibers and vessels increased in the juvenile wood zone was determined. The rate of cell length increase was determined by applying a simple linear regression line to the juvenile wood zone portion of the radial variation of cell length. The slope of the regression line represents the rate of increase in cell length, in millimetres, with increasing distance from pith, in centimetres. The regression line was not tested for adequacy of fit as the slopes were intended to be used only as a method to provide a relative comparison of cell length increase rates between and amongst heights and aspects. The regression was not intended to be used as a predictive model.

Volume

Juvenile, mature and total wood volume in the study tree's stem was calculated. Calculation of the mature wood and juvenile wood volume was based on the results of the demarcation of the juvenile-mature wood boundary. All volumes were calculated in cubic decimetres (dm^3). In order to calculate the volume of the study tree, the study tree was considered as a series of geometric shapes. The bolts defined by discs 1 to 10 were considered to exhibit a shape similar to a cylinder. The length of each bolt is the distance between successive discs. The volume of each bolt was calculated using Smalian's formula (Philip 1994):

$$Vol_{n+1} = \frac{A_n + A_{n+1}}{2} \times L_{n+1}$$

Where:

Vol_{n+1} = Volume of bolt number n+1 at the *x*th ring (dm^3)
A_n = Area of $disc_n$ at the *x*th ring (dm^2)
A_{n+1} = Area of $disc_{n+1}$ at the *x*th ring (dm^2)
L_{n+1} = Length of $bolt_{n+1}$ (dm)
n = disc number (1, 2,…, 10)

The area of each disc was calculated using the formula of a circle (Philip 1994):

$$A_n = \pi r_n^2$$

Where:

A_n = Area of disc n at the *x*th ring (dm^2)
r_n = Radius of disc n at the *x*th ring (dm)
π = Constant pi (3.14159)
n = disc number (1, 2,…, 10)

The mean of the east and west aspect radii was used as the radius. The radius of each aspect was obtained by summing the ring width measurements. The area of each disc was calculated starting with the radius for the last ring, i.e., starting at the bark. The area of the disc at subsequent rings was calculated based on the total radius minus the width of the previous rings (older rings). Since there is not another disc before disc 1, the formula used to calculate the volume of bolt one was (Murchison and Gooding 1999):

$$Vol_1 = A_1 \times L_1$$

Where:

Vol_1 = Volume of bolt 1 at the *x*th ring (dm^3).
A_1 = Area of disc 1 at the *x*th ring (dm^2).
L_1 = Length of bolt 1 (dm).

The length of the first bolt is the distance from the ground to the height at which disc 1 was cut (i.e., 0.15 m). The volume of the tip portion of the study tree was calculated using the formula of a cone (Murchison and Gooding 1999):

$$Vol_{tip} = \frac{1}{3} \times A_{10} \times L_{tip}$$

Where:

$\mathrm{Vol}_{\mathrm{tip}}$ = Volume of the tip at the *x*th ring (dm^3).
A_{10} = Area of disc 10 at the *x*th ring (dm^2).
$\mathrm{L}_{\mathrm{tip}}$ = Length of the tip (dm).

The total stem volume of the study tree at each ring was then determined by summing the volume of each of the geometric shapes comprising the study tree. The juvenile wood volume was also calculated by considering the study tree as a series of the same geometric shapes. The portion of each bolt considered to be juvenile wood was determined by the demarcation of the juvenile-mature wood boundary. A mean of the east and west boundary location was used. The distance from the pith to the juvenile-mature wood boundary was converted to a ring number. This was done by examining the radius values of each ring and selecting the ring with a radius that matched the closest to the radius of the juvenile-mature wood boundary. The juvenile wood volume was then calculated using one of four formulas. When a particular ring was in the juvenile wood zone at both ends of a bolt, the volume was calculated using Smalian's formula. Occasionally a particular ring was in the mature wood zone at one end of a bolt and in the juvenile wood zone at the other end. When this occurred the radius of the last ring in the juvenile wood zone was used and not the radius of the particular ring in the mature wood zone, creating a frustum of a cone (Figure 10).

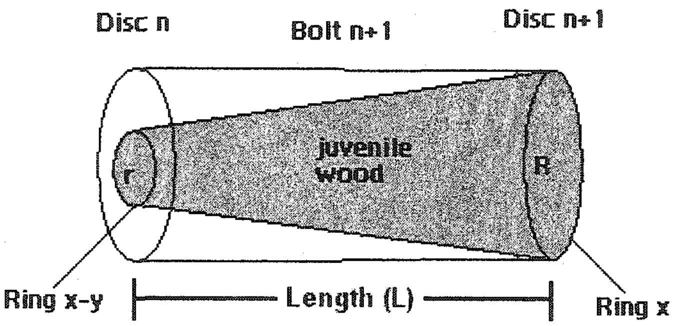


Figure 10. Illustration of how the juvenile wood zone created a frustum of a cone in a bolt, when calculating the juvenile wood volume at ring *x*.

When a frustum of a cone shape was created, the juvenile wood volume was calculated using the volume formula for a frustum of a cone (Wilson 2001):

$$Vol = \frac{\pi L}{3} \times \left(R^2 + Rr + r^2\right)$$

Where:

Vol = Volume of frustum at the *x*th ring (dm^3).
R = Radius of disc n+1 at the *x*th ring (dm).
r = Radius of disc n at the *x-y*th ring (dm).
L = Length of frustum (dm).

The small r in the formula represents the maximum radius of juvenile wood in the disc which has a juvenile-mature wood boundary shorter then the adjacent disc. The volume of juvenile wood in each bolt once a particular ring is in the mature wood zone in both discs, is simply the juvenile wood volume calculated for the last growth ring in the juvenile wood zone (i.e., on the boundary). The juvenile wood volume in the first bolt was calculated using the same formula as was used for calculating the total volume. Since disc 10 was considered to contain all juvenile wood, the entire tip volume was considered to be juvenile wood and calculated using the volume of a cone. The total volume of juvenile wood in the study tree is then the sum of the juvenile wood volumes of each geometric section. The mature wood volume of each bolt at a particular ring was obtained by subtracting the total volume of a bolt minus the total volume of juvenile wood in the bolt at that particular ring. The total mature wood in the study tree is then the sum of the mature wood in each geometric section.

Juvenile Wood Percentage: Volume & Basal Area

The volume of juvenile stem wood at a particular ring was expressed as a percentage of the total stem volume at the same ring using the formula:

$$\text{Juvenile Stem Volume } (\%) = \frac{\text{Juvenile Stem Volume } (\text{at ring } x)}{\text{Total Stem Volume } (\text{at ring } x)} \times 100$$

The percentage of the basal area that is juvenile wood at each ring, at all heights was calculated using the formula:

$$P.B.A.J. = \frac{\pi r_j^2}{\pi r_t^2} \times 100$$

Where:

P.B.A.J.	= Percentage of basal area that is juvenile wood.
r_j	= Radius of juvenile wood zone.
r_t	= Radius of the ring calculating the percentage for.

The percentage of basal area that is juvenile wood at each height was plotted against the percentage of stem volume that is juvenile wood in order to determine if a relationship exists between the two variables. Plots were done using the percentages calculated from the mean radius of the two aspects. The graph only shows the juvenile wood percentage of basal area from the ring at which the percentage is 100 percent to the last ring at each height.

Interval Age at Pith

The term 'interval age at pith' will be used to refer to the age of the pith at the time it first developed at a particular height, counted from the time of initial germination of the tree. The age of the pith at 0.15 m were assumed to be one-year-old since trembling aspen commonly regenerates from root suckers, which generally grow taller than 0.15 m in the first year. At subsequent heights the age of the pith can be determined by subtracting the total number of rings at the height in question, from the total number of rings at height 0.15 m and adding the age of the cambial initials at height 0.15 m.

The age of the pith was plotted against the mean width of the juvenile wood zone in order to determine if a relationship exists between these two variables. Two plots were created, one with the juvenile wood zone expressed as number of rings and one with the juvenile wood zone expressed as distance from the pith. In order to determine the strength of the linear relationship between these variables a coefficient of correlation was calculated for both plots. A two tailed *t*-test was used to test the significance of the coefficient of correlations (McClave and Dietrich 1994).

ANOVA

The means of fiber length, vessel length and relative density where tested using a three-way analysis of variance (ANOVA). The factors and levels examined in the ANOVA are presented in (Table 1).

Table 1. Factors and their levels used in the ANOVA.

Factor	Levels
Zone	Juvenile
	Mature
Aspect	East (North)
	West (South)
Height	0.15
	1.3
	3.3
	5.3
	7.3
	9.3
	11.3
	13.3
	15.3

The final height (i.e., 17.3) was not include in the ANOVA analysis, since at that height there where no observations in the mature wood zone. Not all the observations per treatment combination where used in the ANOVA. The number of observations used per treatment combination was the number of observations in the treatment combination with the fewest observations. This allowed for an equal number of observations per treatment combination creating a balanced design. The observations used in the

ANOVA were randomly selected from the total observations of the particular treatment combination (Tabachnick and Fidell 1989).

Multiple comparisons of significant interactions and main effects (i.e., height) were done using a least significant difference (LSD) test procedure. In order to provide a visual method of estimating significantly different means, treatment means where plotted along with a reference *t* distribution (Box *et al.* 1978).

RESULTS

FIBER LENGTH

Radial Variation

Fiber length radial variation at heights 0.15 m to 15.3 m, in both aspects, can be characterized as increasing rapidly from the pith outwards in the juvenile wood (jw) zone, followed by a transition zone in which the rate of increase in fiber length is reduced, followed by a mature wood (mw) zone in which the variation was not consistent amongst the heights (Figure 11). At height 0.15 m in both aspects, fiber length maintained a relatively constant length in the mw zone. From 1.3 m to 7.3 m in both aspects, fiber length either gradually increased or decreased in the mw zone. From 9.3 m to 15.3 m, in both aspects, fiber length continued to gradually increase in the mw zone. The radial variation at 17.3 m, only exhibited the beginning of the jw zone, which was characterized by rapidly increasing fiber length.

At all heights fiber length at the pith was generally between 0.4 to 0.6 mm. At heights 0.15 m to 11.3 m fiber length increased up to approximately 1.1 to 1.2 mm in the mw zone. At heights 13.3 m and 15.3 m fiber length increased up to approximately 1.0 mm in the mw zone. At 17.3 m, fiber length had only increased up to 0.7 mm. The same general radial variation was exhibited in both aspects at all heights.

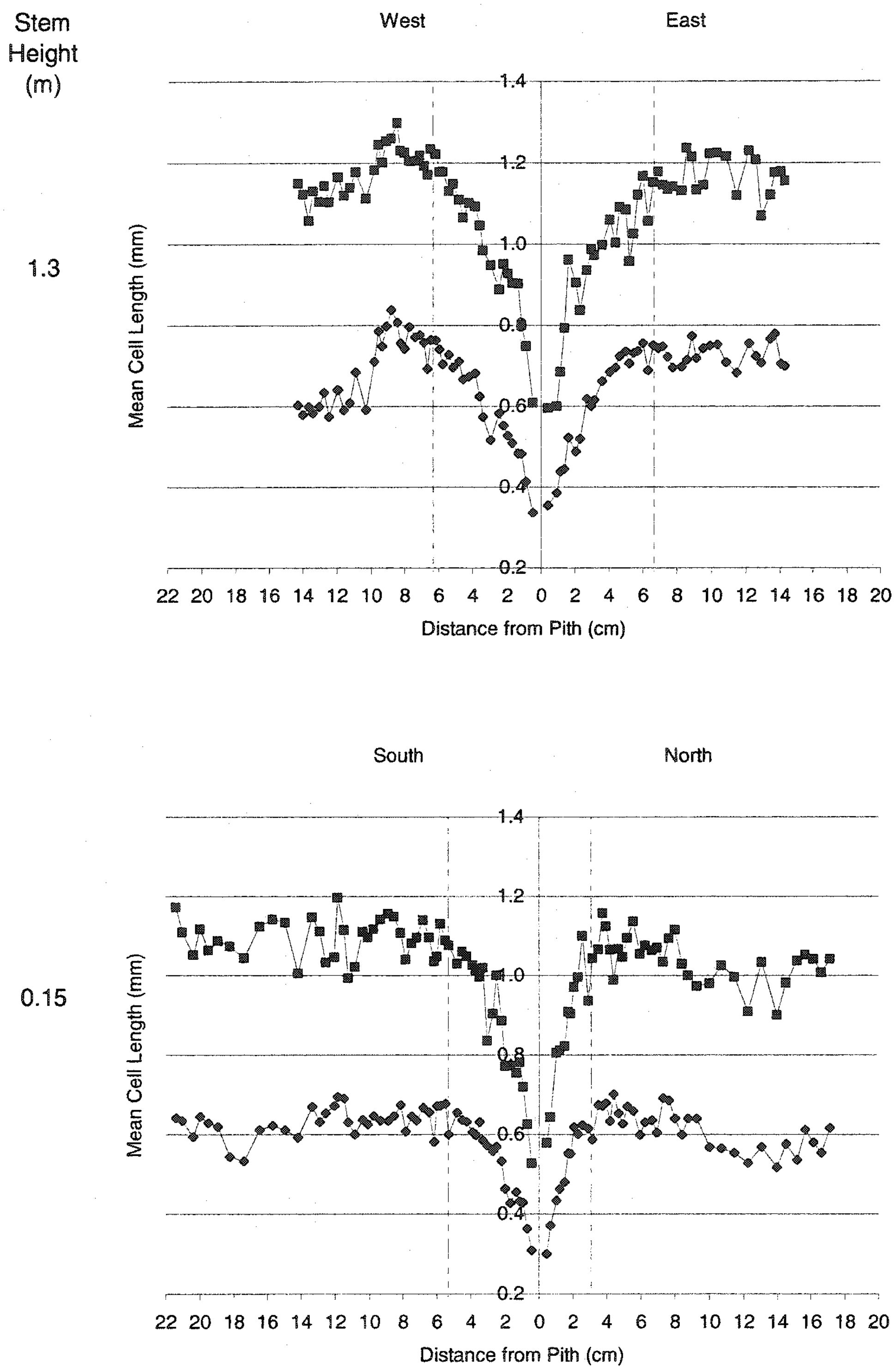


Figure 11. Radial variation of mean fiber (squares) and vessel (diamonds) lengths in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines.

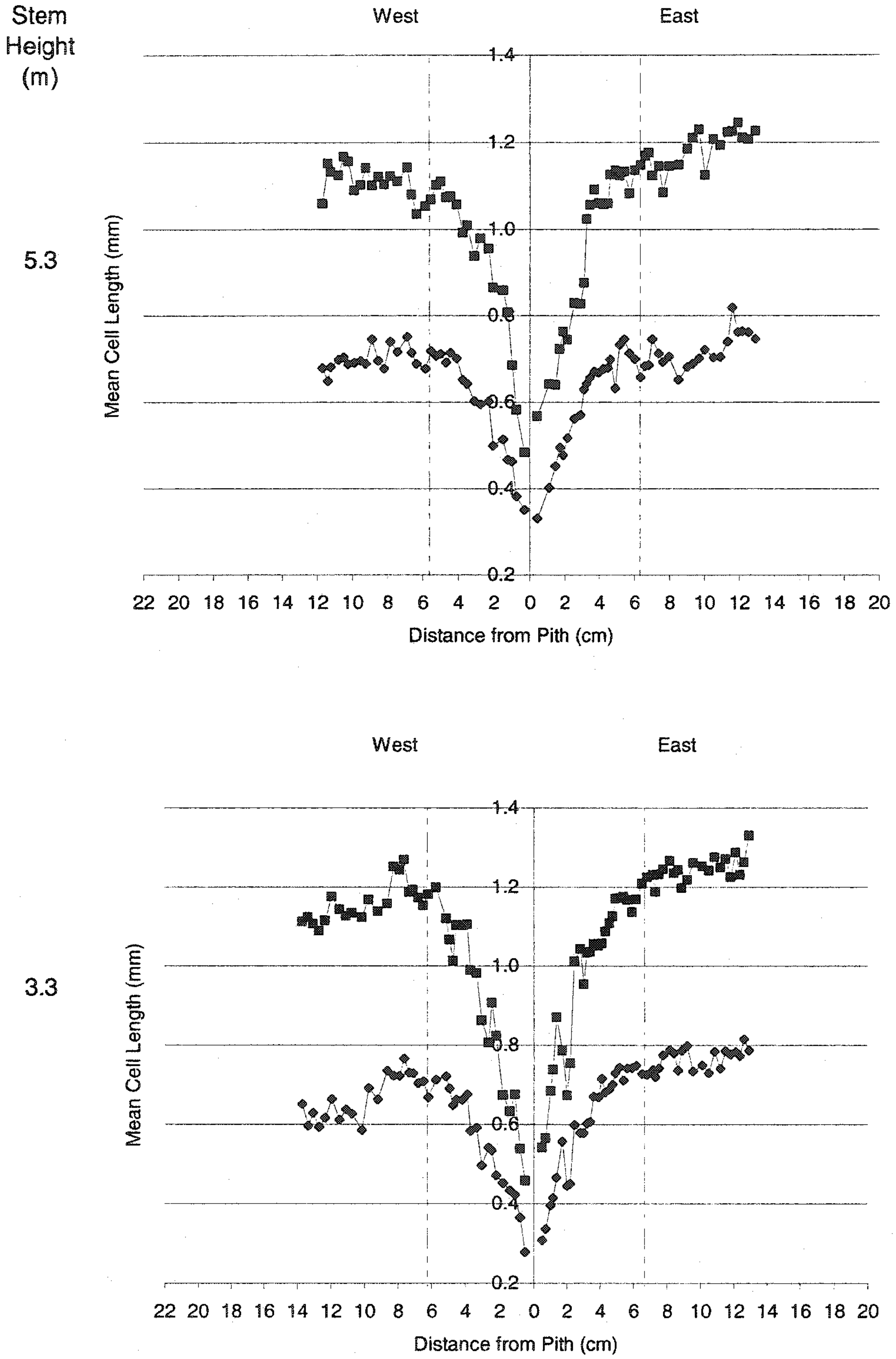
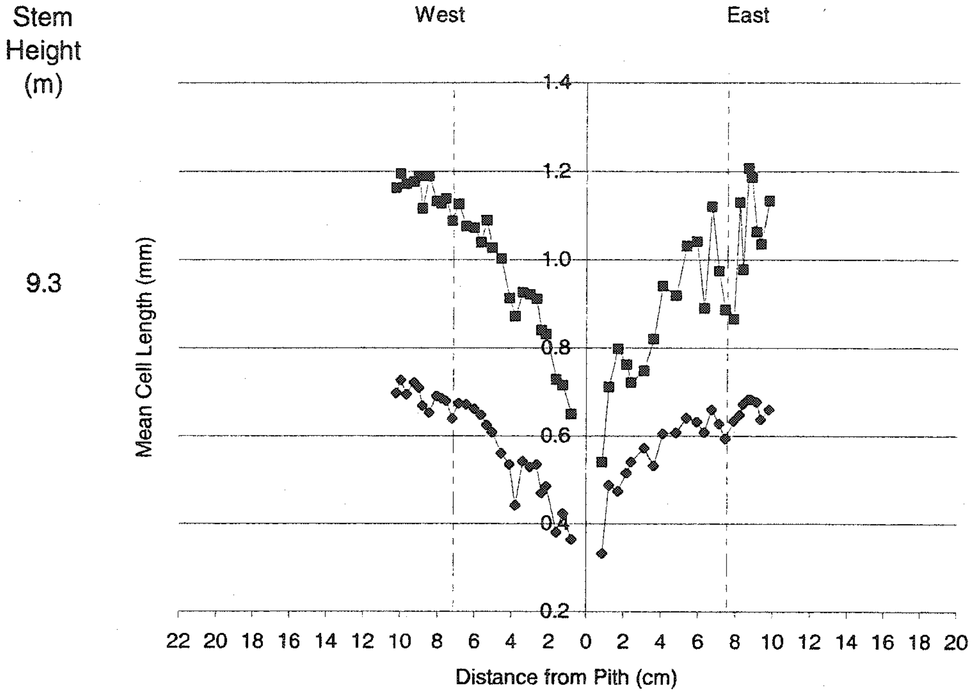


Figure 11. (Continued) Radial variation of mean fiber (squares) and vessel (diamonds) lengths in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines.



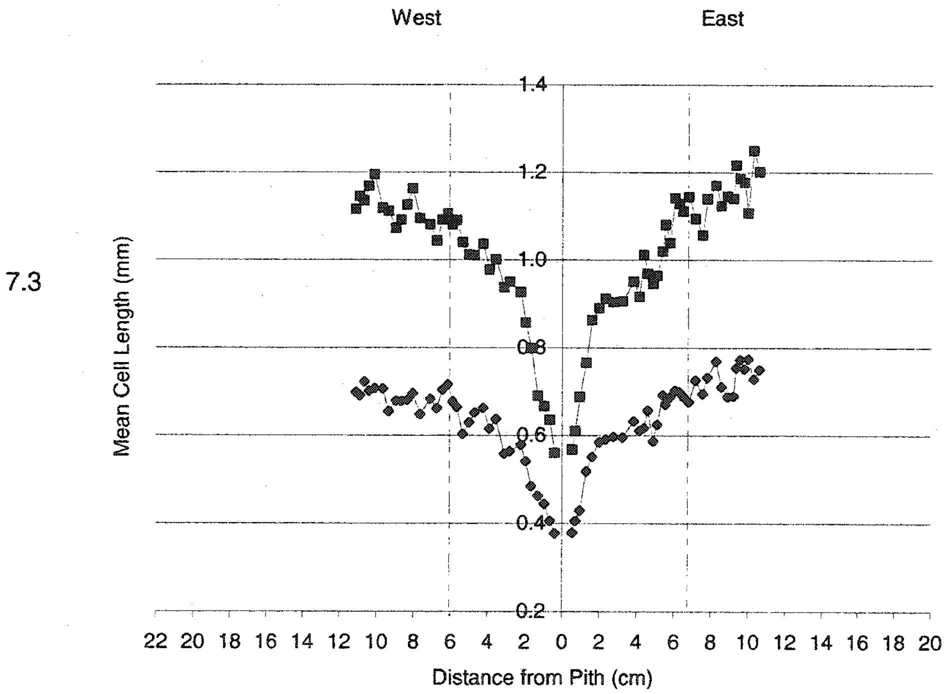


Figure 11. (Continued) Radial variation of mean fiber (squares) and vessel (diamonds) lengths in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines.

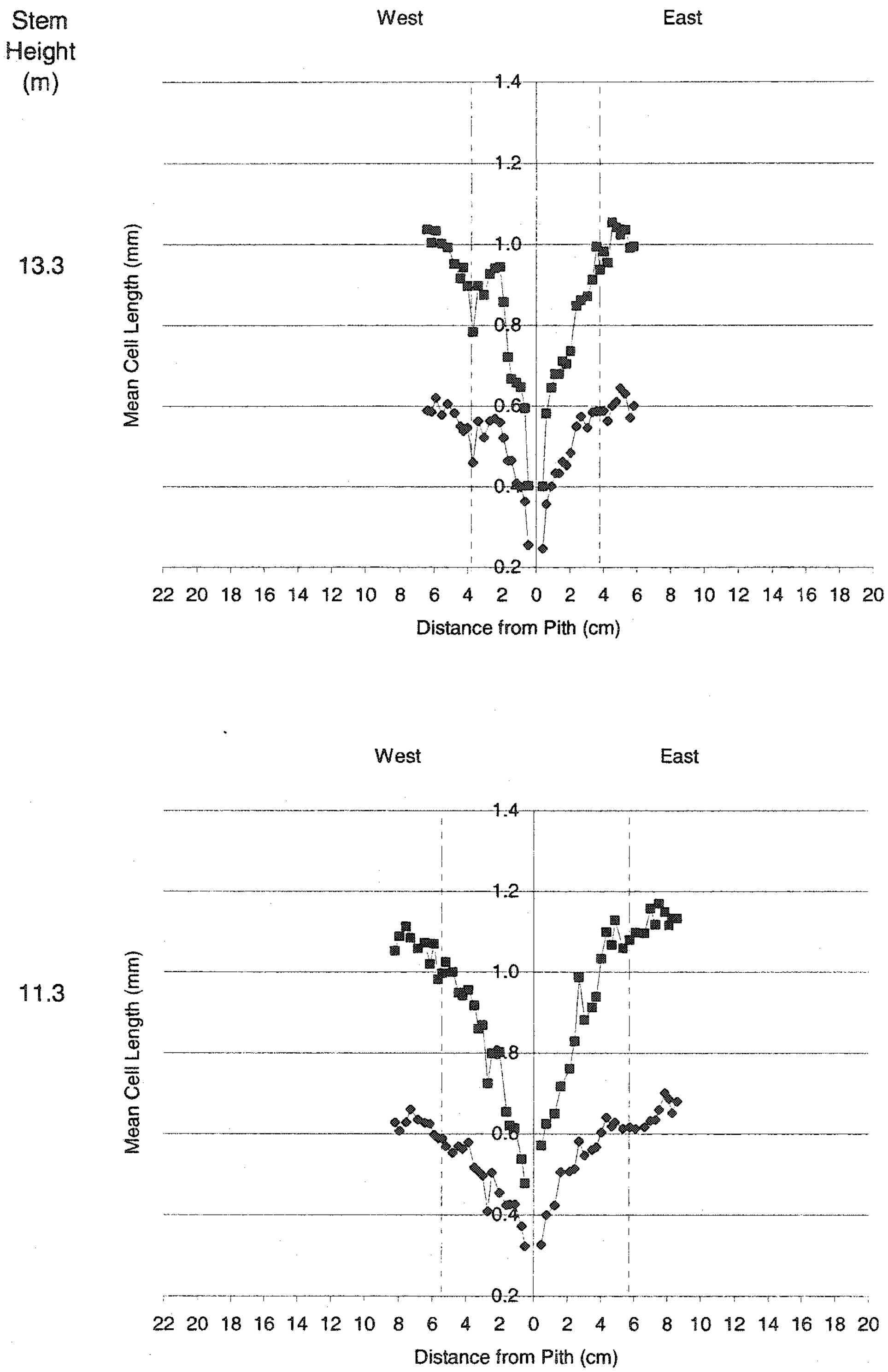


Figure 11. (Continued) Radial variation of mean fiber (squares) and vessel (diamonds) lengths in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines.

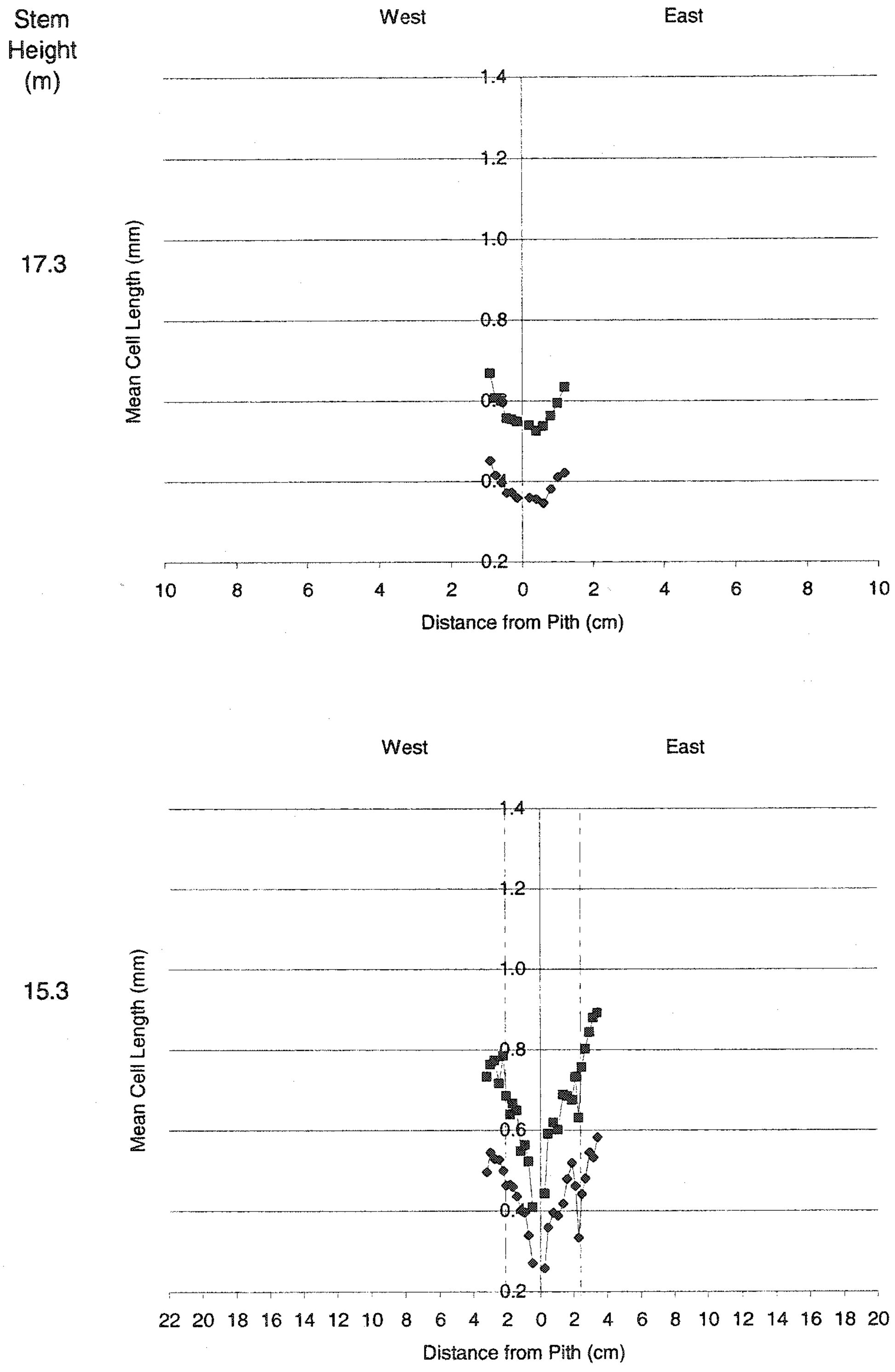


Figure 11. (Continued) Radial variation of mean fiber (squares) and vessel (diamonds) lengths in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines.

ANOVA

The ANOVA found that the three-way interaction, aspect x zone x height, the two-way interactions, zone x height and aspect x height, and the main effects height, zone and aspect were all significant (Table 2).

Table 2. ANOVA results for fiber length.

Source	df	SS	MS	F-ratio	Prob.	Sig.
Const	1	5894.340	5894.340	200260.000	≤ 0.0001	**
Aspect	1	0.190	0.190	6.456	0.0111	*
Zone	1	76.152	76.152	2587.300	≤ 0.0001	**
Aspect x Zone	1	0.087	0.087	2.963	0.0852	
Height	8	76.966	9.621	326.870	≤ 0.0001	**
Aspect x Height	8	3.673	0.459	15.599	≤ 0.0001	**
Zone x Height	8	0.766	0.096	3.255	0.0011	*
Aspect x Zone x Height	8	0.866	0.108	3.677	0.0003	**
Error	6264	184.367	0.029			
Total	6299	343.067				

* - Significant (alpha = 0.05) ** - Highly Significant (alpha = 0.01)

Aspect x Zone x Height Interaction

Mean fiber lengths and a reference t-distribution have been plotted to provide a visual method of estimating significantly different means (Figure 12).

Mean fiber length in both wood zones, increased in length from heights 0.15 m to approximately 3.3 m. After 3.3 m, mean fiber length steadily decreased with increasing height. At each height the jw mean fiber lengths were all significantly shorter than the mw mean fiber lengths from the same height. The jw zone had four heights where the mean fiber lengths of both aspects were not significantly different. The jw zone had three heights where the mean fiber length in the west was significantly longer, and two heights where the mean fiber length in the east was significantly longer.

The mw zone had three heights where the mean fiber lengths of both aspects were not significantly different. The mw zone had two heights where the west mean fiber length was significantly longer and four heights where the mean fiber length in the east was significantly longer.

The mw mean fiber lengths of both aspects at 15.3 m were not significantly different from some of the jw mean fiber lengths at other heights. At 15.3 m, the jw mean fiber lengths of both aspects were significantly different and were significantly different from all other mean fiber lengths.

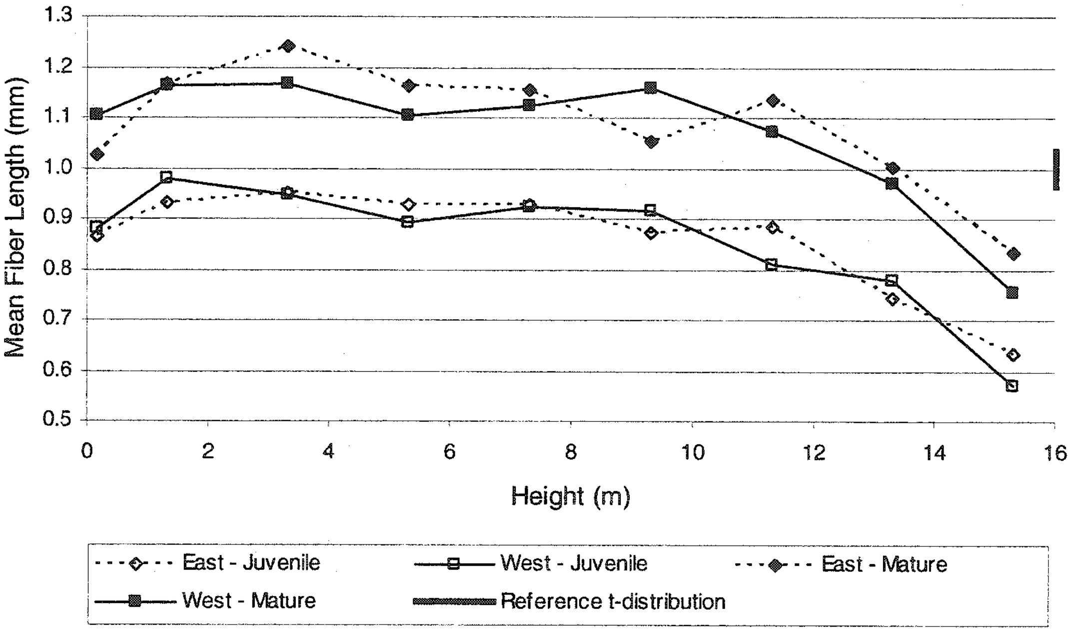


Figure 12. Aspect x zone x height fiber length means plotted with a reference t-distribution with scale factor 0.01296.

Aspect x Height Interaction

There were three heights in which a significant difference did not occur between aspects at the same height (Figure 13). At four heights the east aspect had significantly longer mean fiber lengths, while at two heights the west aspect had significantly longer mean fiber lengths.

At 13.3 m, there was not a significant difference between aspects, but the mean fiber lengths were significantly different from the means at all the other heights. At 15.3 m, there was a significant difference between aspects and the means are significantly different from means at all the other heights.

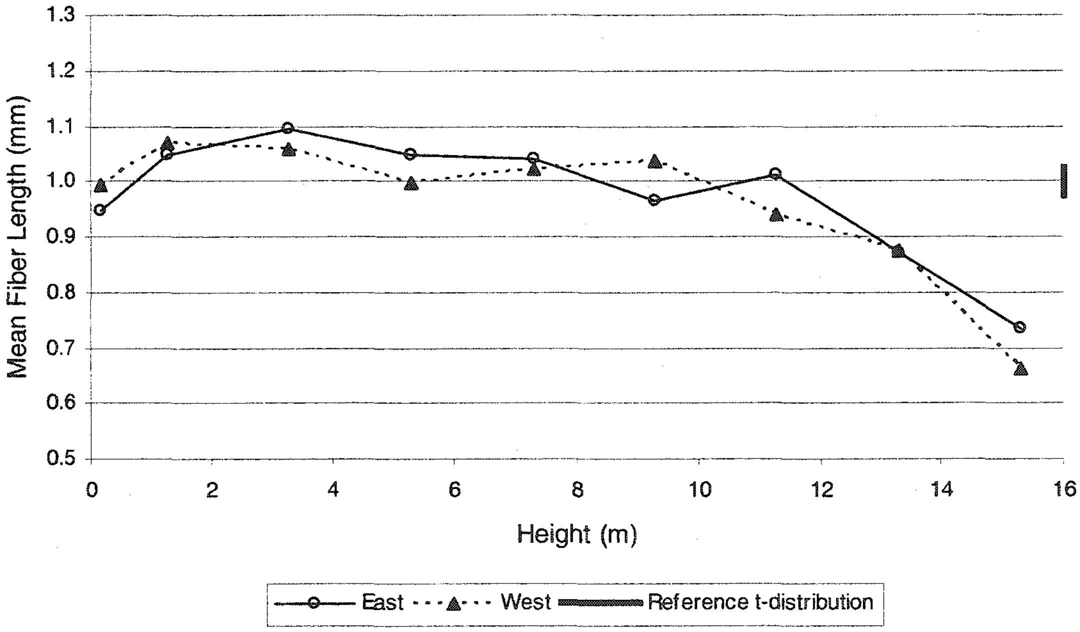


Figure 13. Aspect x height fiber length means plotted with a reference t-distribution with scale factor 0.00916.

Zone x Height Interaction

At all heights the mean fiber length in the jw zone was significantly smaller than the mean fiber length in the mw zone at the same height (Figure 14). At heights 15.3 m and 13.3 m, the jw and mw mean fiber lengths were significantly different from all the other jw and mw mean fiber lengths.

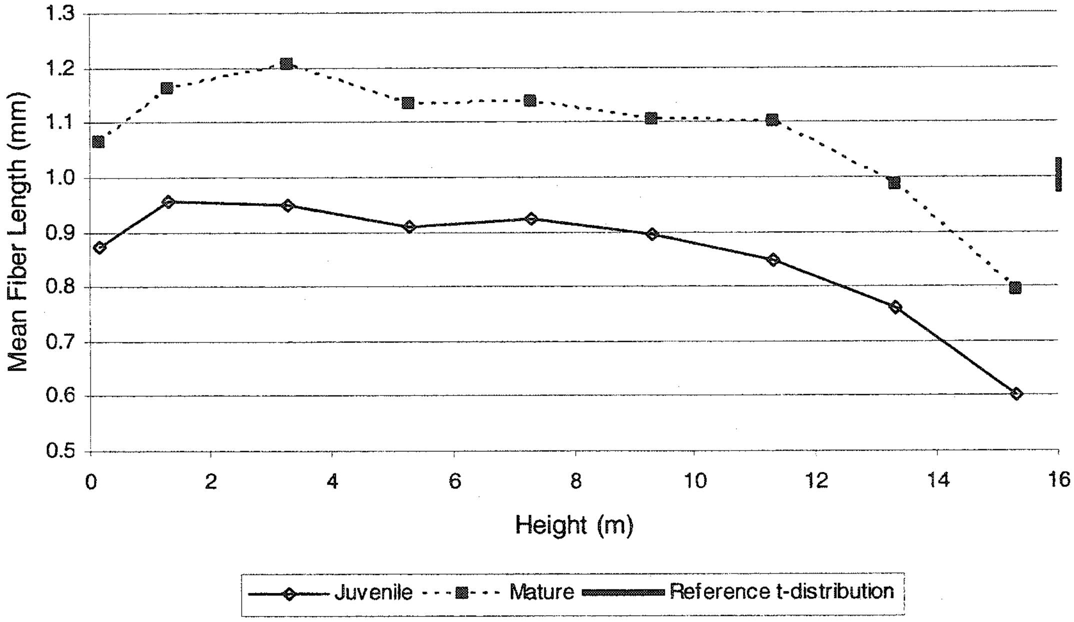


Figure 14. Zone x height fiber length means plotted with a reference t-distribution with scale factor 0.00916.

Zone

The jw zone had a significantly shorter mean fiber length than the mw zone (Table 3). The mean jw fiber length was 20 percent smaller than the mean mw fiber length.

Table 3. Mean fiber length of each zone.

Level of Zone	Mean Fiber Length (mm)
Juvenile	0.857
Mature	1.077

Height

An LSD test conducted on height means, found that most of the heights had mean fiber lengths which were significantly different from each other (Table 4).

Table 4. LSD test results for mean fiber length associated with height.

Height (m)	15.3	13.3	11.3	9.3	7.3	5.3	3.3	1.3
13.3	*							
11.3	**	**						
9.3	**	**	**					
7.3	**	**	**	**				
5.3	**	**	**	*	ns			
3.3	**	**	**	**	**	**		
1.3	**	**	**	**	**	**	ns	
0.15	**	**	ns	**	**	**	**	**

* - Significant (alpha = 0.05) ** - Highly Significant (alpha = 0.01)
ns - Not significant

Aspect

The west aspect had a significantly shorter mean fiber length than the east aspect (Table 5).The mean west aspect fiber length was 1.2 percent smaller than the mean east aspect fiber length.

Table 5. Mean fiber length of each aspect.

Level of Aspect	Mean Fiber Length (mm)
East	0.973
West	0.962

VESSEL LENGTH

Radial Variation

The radial variation of vessel length at heights 0.15 m to 15.3 m, in both aspects, can be characterized as increasing rapidly from the pith outwards in the jw zone, followed by a transition zone in which the rate of increase in vessel length was reduced, followed by a mw zone. The variation in the mw zone was not consistent amongst the heights (Figure 11). At height 0.15 m in both aspects, vessel length remained relatively constant in the mw zone. From 1.3 m to 7.3 m in both aspects, vessel length either gradually increased or decreased in the mw zone. At heights 9.3 m to 15.3 m, in both aspects, vessel length continued to gradually increase in the mw zone. The radial variation at 17.3 m, only exhibited the beginning of the jw zone, which was characterized by rapidly increasing vessel length.

At all heights vessel length at the pith was generally between 0.2 to 0.4 mm. At heights 0.15 m to 13.3 m vessel length increased up to approximately 0.6 to 0.7 mm in the mw zone. At height 15.3 m vessel length increased up to approximately 0.58 mm in the mw zone. At 17.3 m, fiber length had only increased up to 0.4 mm. The same general radial variation was exhibited in both aspects at all heights.

The radial variation of vessel length closely resembled the radial variation of fibers when comparing the same height and aspect. The only difference between the two cell types was the magnitude of their lengths.

ANOVA

The ANOVA found that the three-way interaction, aspect x zone x height, the two-way interaction, aspect x height, and the main effects height, zone and aspect were all significant (Table 6).

Table 6. ANOVA results for vessel length.

Source	df	SS	MS	F-ratio	Prob.	Sig.
Const	1	2228.970	2228.970	159330.000	≤ 0.0001	**
Aspect	1	0.308	0.308	21.990	≤ 0.0001	**
Zone	1	23.533	23.533	1682.200	≤ 0.0001	**
Aspect x Zone	1	0.026	0.026	1.875	0.1709	
Height	8	25.298	3.162	226.040	≤ 0.0001	**
Aspect x Height	8	1.339	0.167	11.966	≤ 0.0001	**
Zone x Height	8	0.071	0.009	0.639	0.7457	
Aspect x Zone x Height	8	0.253	0.032	2.257	0.0209	*
Error	6264	87.631	0.014			
Total	6299	138.459				

* - Significant (alpha = 0.05) ** - Highly Significant (alpha = 0.01)

Aspect x Zone x Height Interaction

Mean vessel length in both wood zones, increased in length from heights 0.15 m to approximately 3.3 m. After 3.3 m, mean vessel length steadily decreased with increasing height (Figure 15). At all heights the jw zone mean vessel lengths were significantly shorter than the mw zone mean vessel lengths from the same height.

In the jw zone there were five heights that did not have significant differences between aspects. In the jw zone, at three heights, mean vessel length in the east was significantly longer than in the west, while at one height the mean vessel length in the west was significantly longer.

In the mw zone there were three heights that did not have significant differences between aspects. In the mw zone, at four heights the mean vessel length in the east aspect was significantly longer than in the west, while at two heights the mean vessel length in the west was significantly longer.

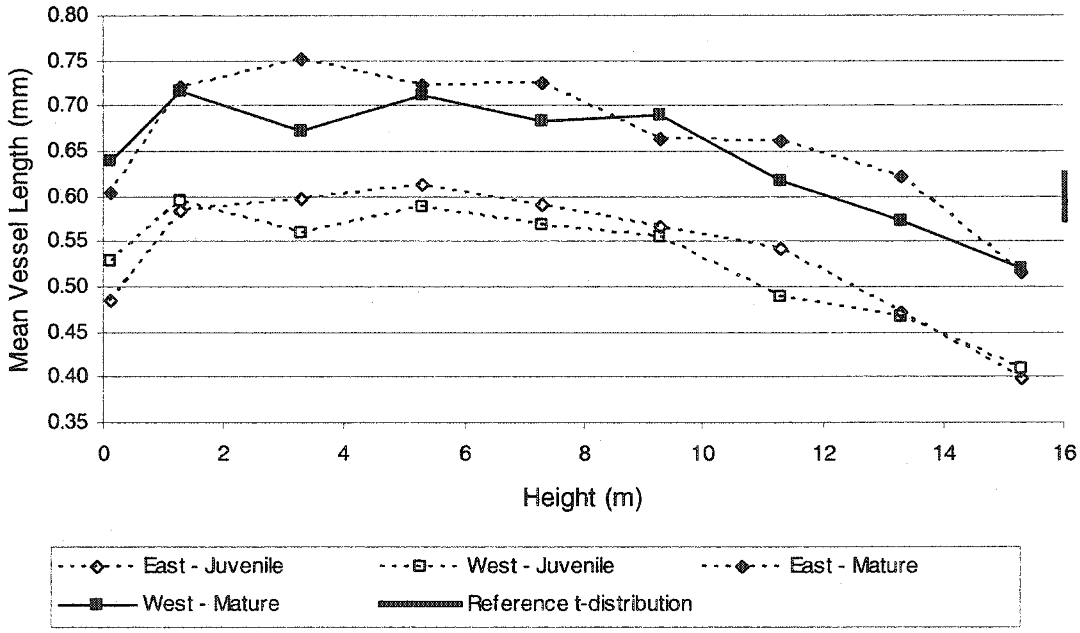


Figure 15. Aspect x zone x height vessel length means plotted with a reference t-distribution with scale factor 0.00894.

The mean vessel lengths at 15.3 m, in the jw zone, did not have a significant difference between aspects, but were significantly different from all the other means.

The mw zone mean vessel lengths at 15.3 m were not significantly different from some of the jw zone mean vessel lengths.

Aspect x Height Interaction

There were three heights that did not have a significant difference in mean vessel length between aspects (Figure 16).

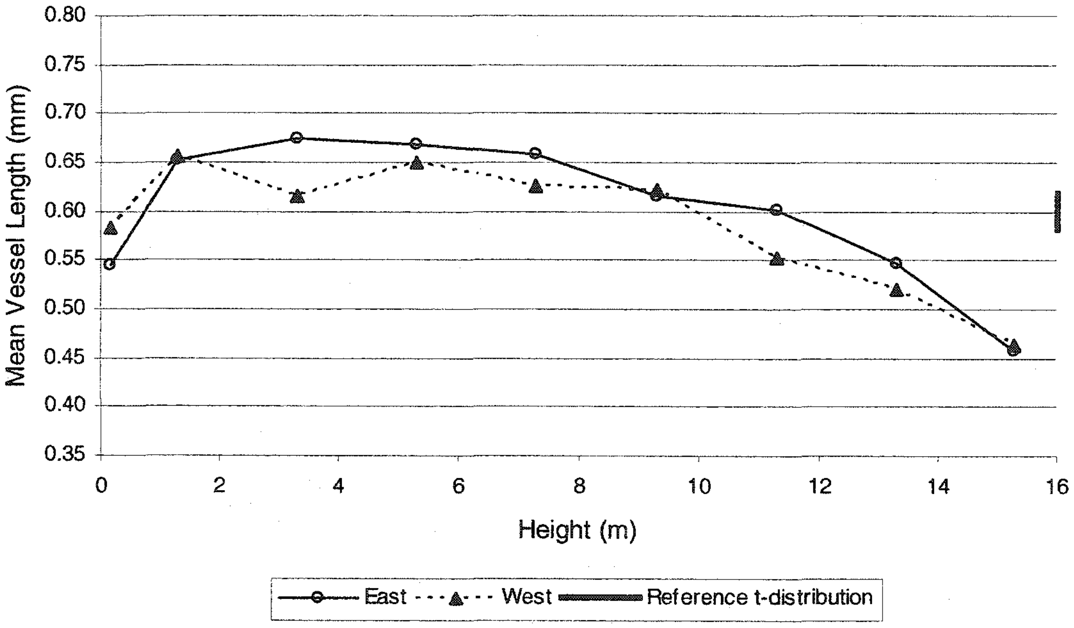


Figure 16. Aspect x height vessel length means plotted with a reference t-distribution with scale factor 0.00632.

At five heights the mean vessel length in the east aspect was significantly longer, while at one height the mean vessel length in the west aspect was significantly longer. The east and west aspect mean vessel lengths at 15.3 m were not significantly different, but were significantly shorter than all the other mean vessel lengths.

Zone

The jw zone had a significantly shorter mean vessel length than the mw zone (Table 7). The mean jw vessel length was 18.6 percent smaller than the mean mw vessel length.

Table 7. Mean vessel length of each zone.

Level of Zone	Mean Vessel Length (mm)
Juvenile	0.534
Mature	0.656

Height

An LSD test conducted on height, found that most of the heights had mean vessel lengths which were significantly different from each other (Table 8).

Table 8. LSD test results for mean vessel length associated with height.

Height (m)	15.3	13.3	11.3	9.3	7.3	5.3	3.3	1.3
13.3	**							
11.3	**	**						
9.3	**	**	**					
7.3	**	**	**	**				
5.3	**	**	**	**	**			
3.3	**	**	**	**	ns	*		
1.3	**	**	**	**	ns	ns	ns	
0.15	**	**	*	**	**	**	**	**

* - Significant (alpha = 0.05)　　** - Highly Significant (alpha = 0.01)
ns - Not significant

Aspect

The west aspect had a significantly shorter mean vessel length than the east aspect (Table 9). The mean west aspect vessel length was 2.3 percent smaller than the mean east aspect vessel length.

Table 9. Mean vessel length of each aspect.

Level of Aspect	Mean Vessel Length (mm)
East	0.602
West	0.588

CELL LENGTH INCREASE RATE

In the east aspect, fibers and vessels had a similar vertical variation in their rate of cell length increase (mm) with increasing distance from the pith (cm) (Table 10). The vertical variation did not exhibit any sequential pattern, but fluctuated amongst the heights. Generally the lower rates of cell length increase occurred around the 9.3 m height of the stem and the higher rates occurred in the top and bottom portions of the stem. The highest increase rate for fibers was 0.18 mm/cm, at a height of 0.15 m. The lowest increase rate for fibers was 0.06 mm/cm, at a height of 9.3 m. The highest increase rate for vessels in the east aspect was 0.13 mm/cm, which occurred at a height of 0.15 m. The lowest increase rate for vessels was 0.03 mm/cm, which occurred at a height of 9.3 m.

In the west aspect there was less of a similarity between the fibers and vessels vertical variation of rate of cell length increase with increasing distance from the pith.

The vertical variation did not exhibit a sequential pattern (Table 10). As in the east aspect the lowest increase rates generally occurred around the 9.3 m height. The highest increase rates where found at heights of 15.3 m and higher. The highest increase rate for fibers was 0.15 mm/cm, which occurred at 15.3 m and 17.3 m. The lowest increase rate for fibers was 0.07 mm/cm, which occurred at a height of 9.3 m. The highest increase rate for vessels in the west aspect was 0.12 mm/cm, which occurred at heights 15.3 m and 17.3 m. The lowest rate for vessels in the west aspect was 0.05 mm/cm, which occurred at heights 7.3 m, 9.3 m and 11.3 m.

Table 10. Rate of cell length increase from the pith to the juvenile-mature wood boundary in both aspects.

	Cell Length Increase Rate (mm/cm)			
	Fibers		Vessels	
Height (m)	West	East	West	East
17.3	0.15	0.10	0.12	0.07
15.3	0.15	0.09	0.12	0.06
13.3	0.12	0.14	0.07	0.09
11.3	0.11	0.11	0.05	0.06
9.3	0.07	0.06	0.05	0.03
7.3	0.09	0.07	0.05	0.04
5.3	0.10	0.11	0.07	0.07
3.3	0.13	0.10	0.07	0.07
1.3	0.08	0.08	0.06	0.06
0.15	0.10	0.18	0.06	0.13

RELATIVE DENSITY

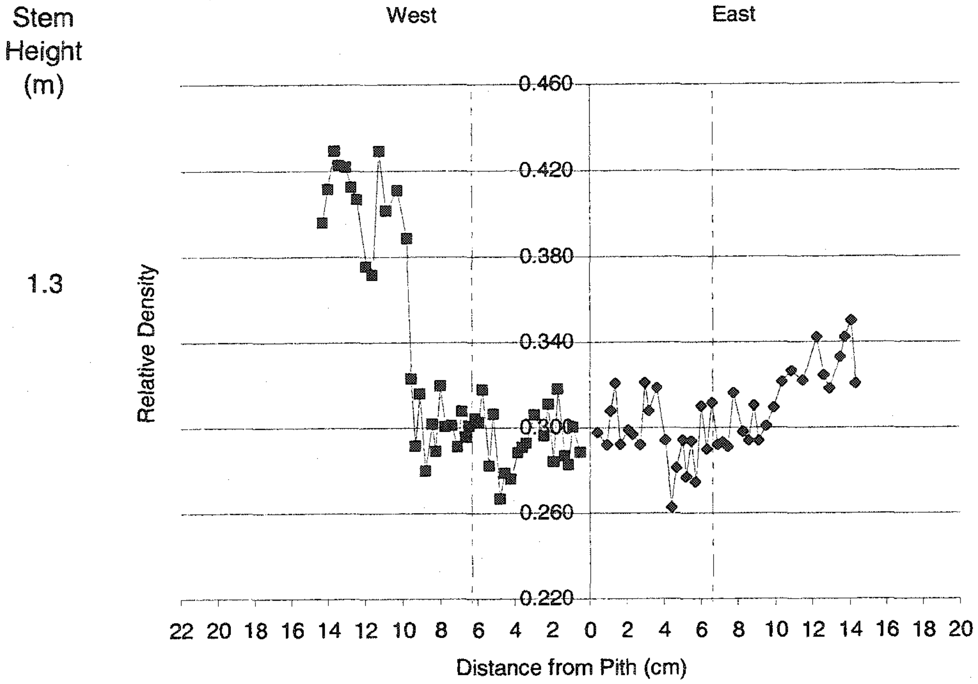
Radial Variation

Relative density did not have a consistent radial variation (Figure 17). Three radial variations were common to two or more of the height/aspect combinations. The remaining height/aspect combinations did not have similar radial variations.

The radial variation at heights 0.15 m (south and north aspects), 1.3 m (west aspect), and 3.3 m (west aspect), were similar. Starting at the pith, relative density for these heights decreased slightly for a short distance and then rapidly increased until reaching a maximum approximately 2 cm before the bark. After reaching the maximum, relative density values fell drastically to the bark.

The second similar radial variation occurred at 3.3 m (east aspect), 5.3 m (east aspect) and 15.3 m (west). At these heights, relative density was at its largest value at the pith. Advancing toward the bark, the relative density values decreased rapidly, until a minimum was reached. The minimum was reached at approximately 4 cm from the pith for heights 3.3 m and 5.3 m. At height 15.3 m the minimum was reached at approximately 2 cm from the pith. After the minimum value, relative density increased rapidly up to a point just before the bark. Between this high value and the bark, relative density decreased.

A third similar radial variation occurred at a height of 17.3 m in both aspects. From the pith, relative density remained relatively constant for four segment blocks. Relative density increased from the fourth to the fifth segment block where it was at a maximum value. Relative density then decreased sharply in the final segment block.



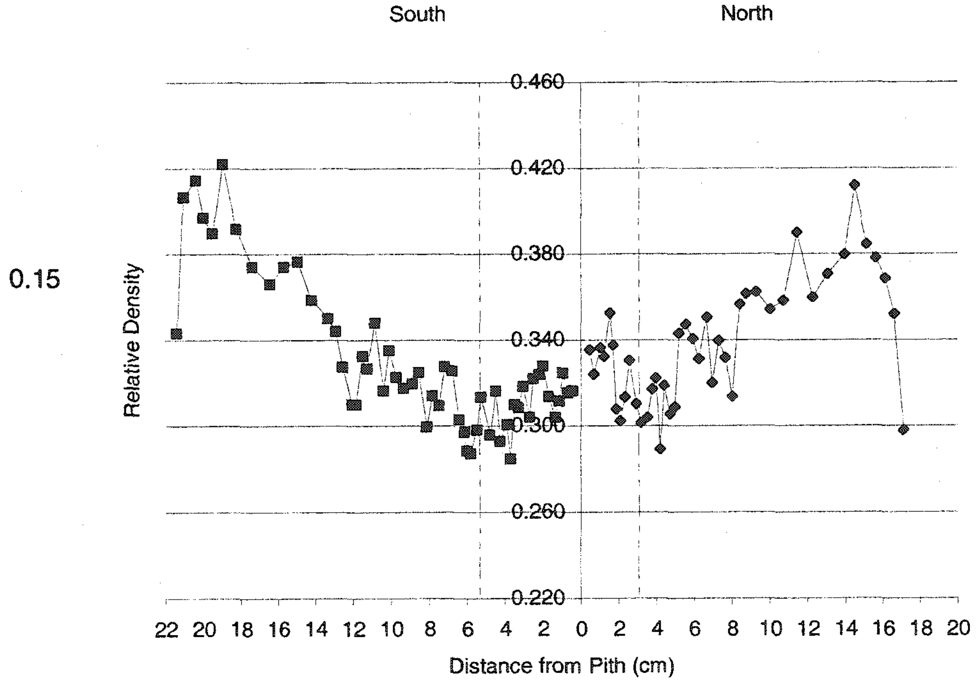
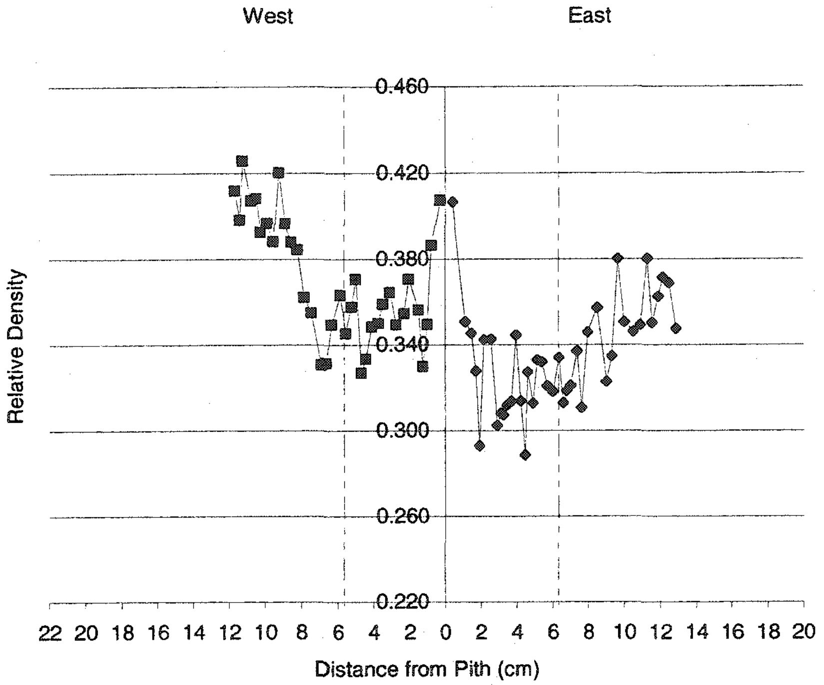


Figure 17. Radial variation of relative density in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines.

Stem
Height
(m)

5.3



3.3

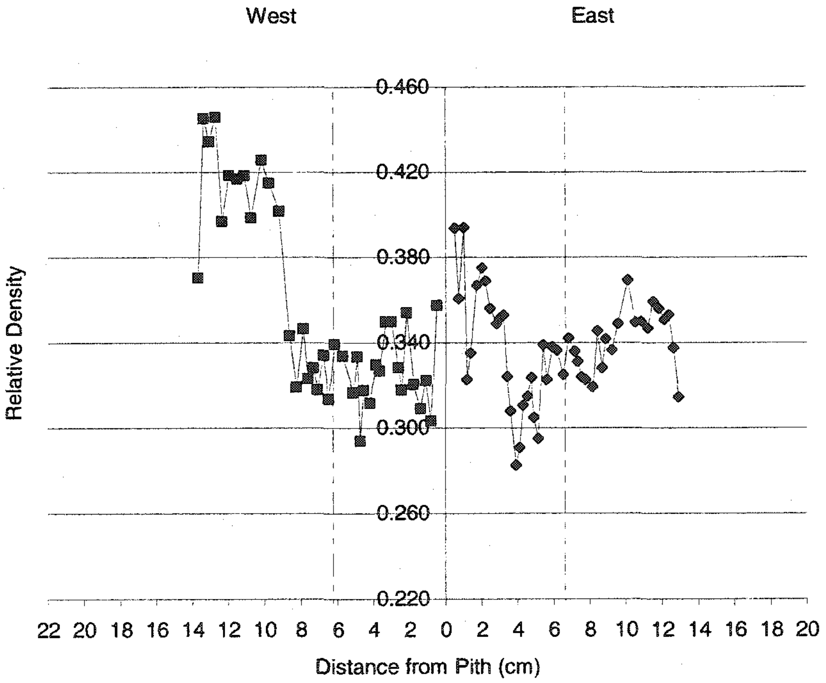
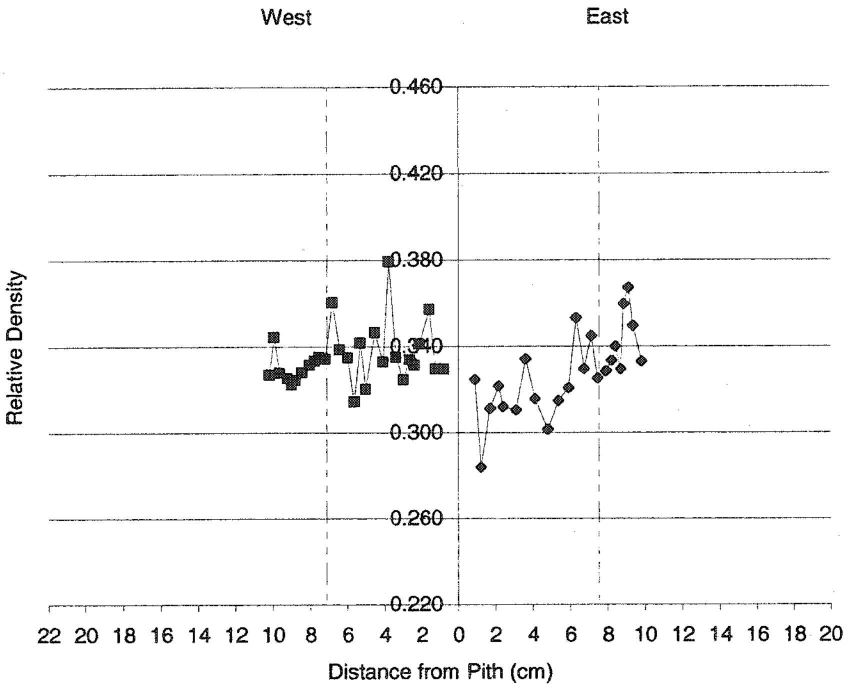


Figure 17. (Continued) Radial variation of relative density in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines.

Stem
Height
(m)

9.3



7.3

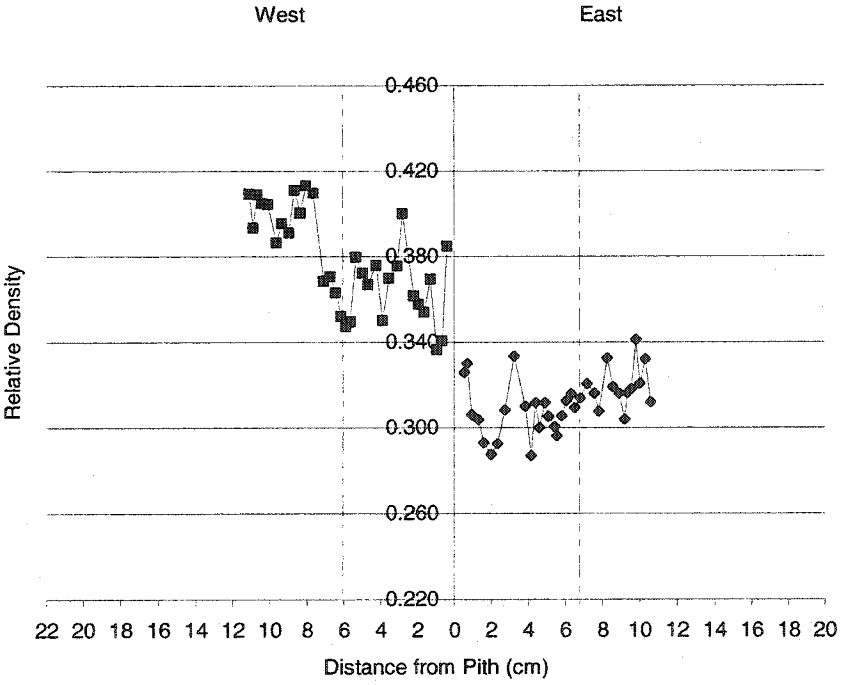
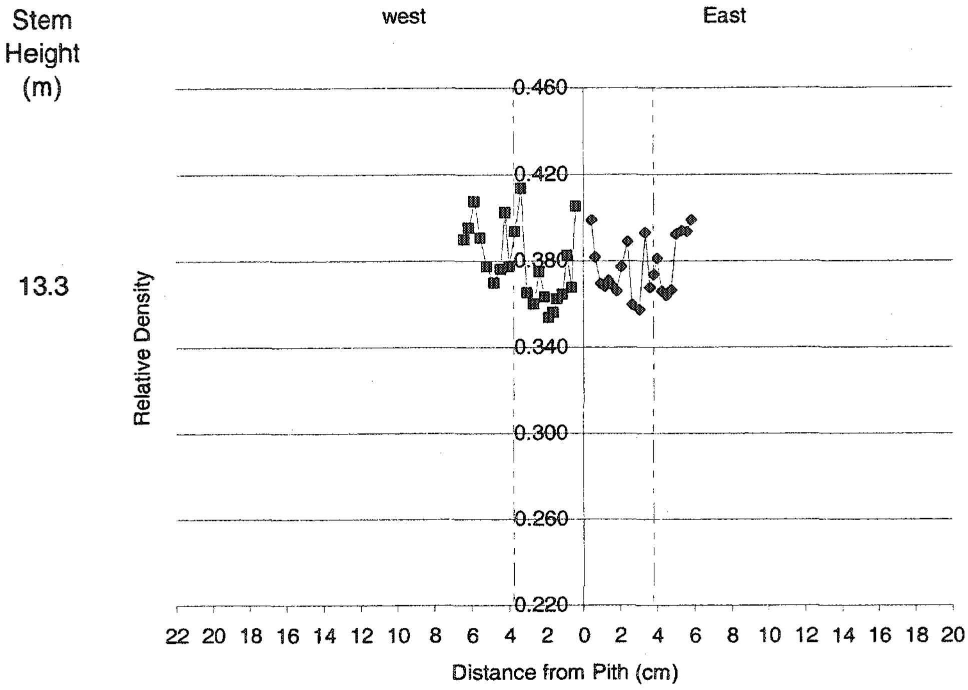


Figure 17. (Continued) Radial variation of relative density in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines.



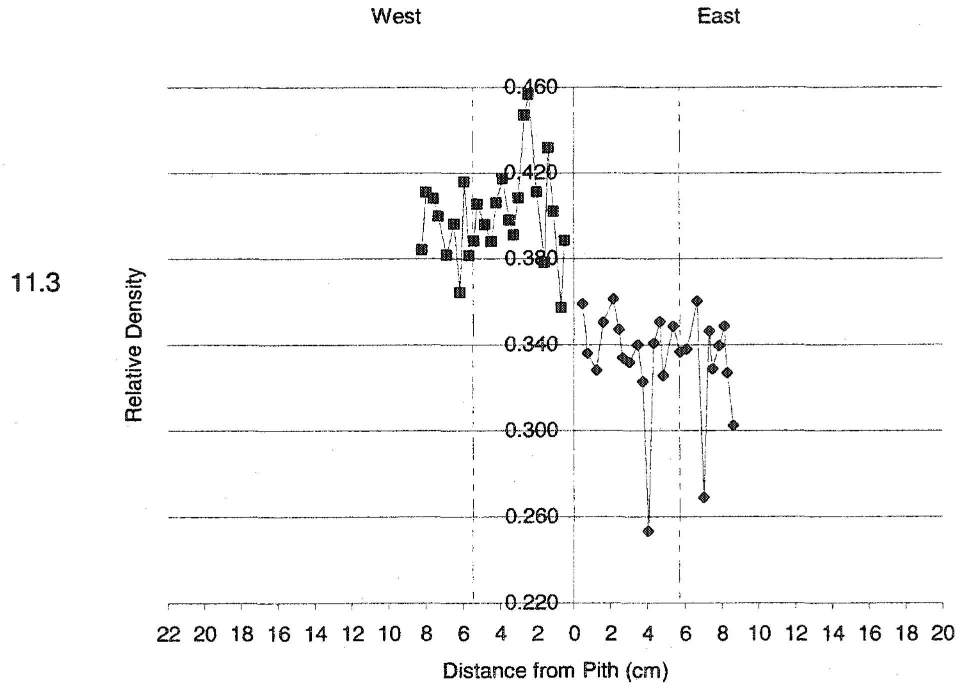
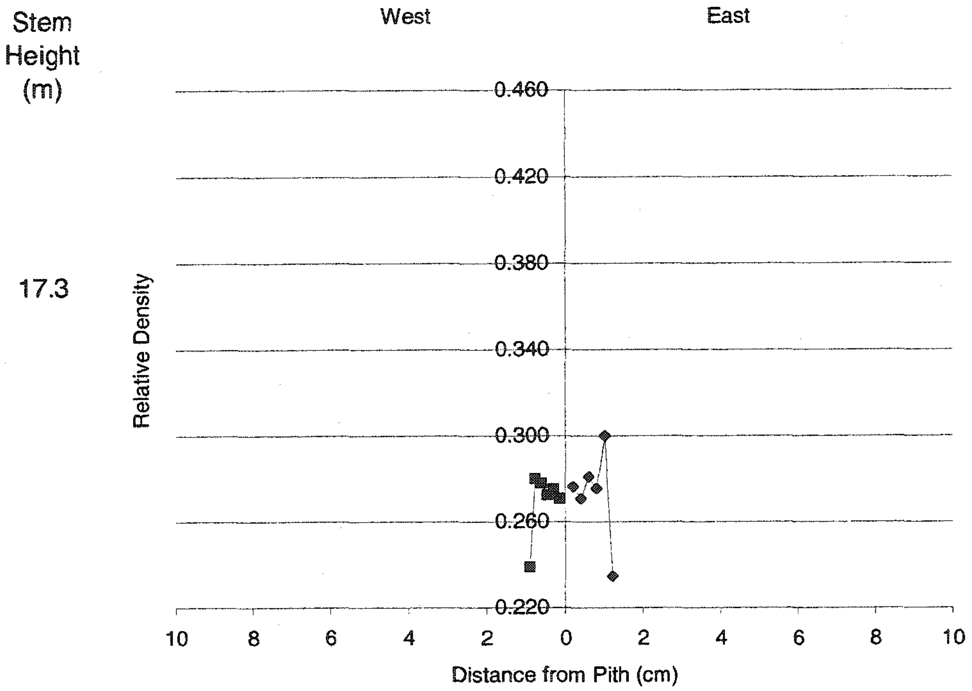


Figure 17. (Continued) Radial variation of relative density in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines.



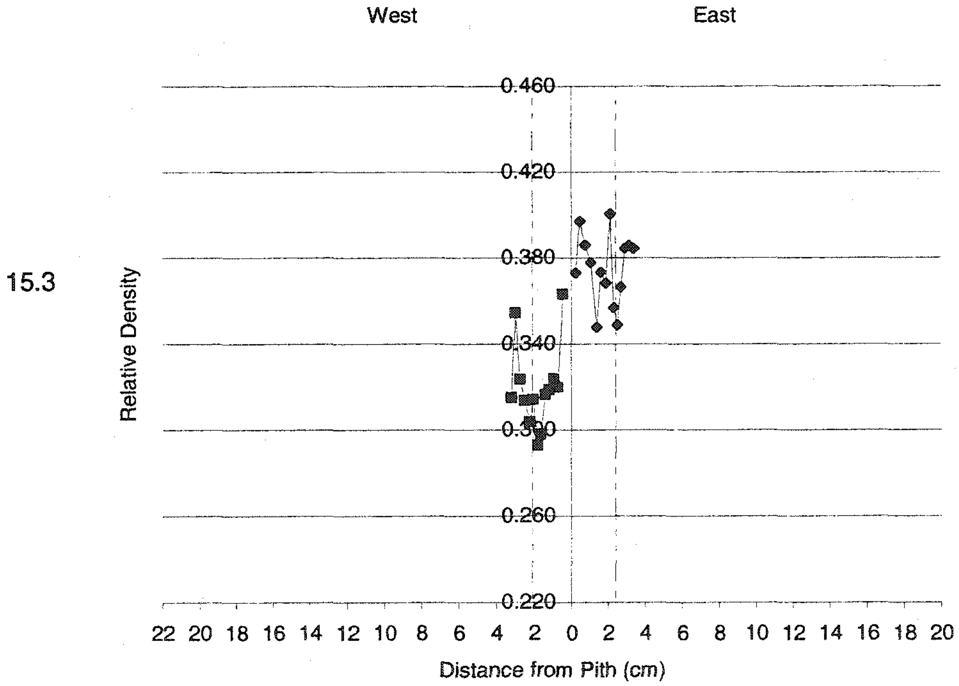


Figure 17. (Continued) Radial variation of relative density in both aspects at various heights. *Juvenile wood zone occurs from the pith outward to the vertical* dashed lines.

An irregular radial variation that should be noted occurred at a height of 11.3 m. Two segment blocks in the east aspect, one at 4.05 cm and the other at 7.0 cm from the pith, had relative density values that were much lower than any other segment blocks at any height. Another interesting feature of these two points is they were evenly split between the juvenile and mature wood zones. In the west aspect, the segment block at 2.45 cm from the pith, had a relative density value that was larger than any other segment block at any height.

ANOVA

The ANOVA found that the two-way interactions, zone x height and aspect x height, and the main effects height, zone and aspect were all significant (Table 11).

Table 11. ANOVA results for relative density.

Source	df	SS	MS	F-ratio	Prob.	Sig.
Const	1	21.8106	21.8106	39222.0000	≤ 0.0001	**
Aspect	1	0.0104	0.0104	18.6690	≤ 0.0001	**
Zone	1	0.0119	0.0119	21.4420	≤ 0.0001	**
Aspect x Zone	1	0.0004	0.0004	0.7555	0.3862	
Height	8	0.0583	0.0073	13.0960	≤ 0.0001	**
Aspect x Height	8	0.0524	0.0066	11.7870	≤ 0.0001	**
Zone x Height	8	0.0119	0.0015	2.6664	0.0093	**
Aspect x Zone x Height	8	0.0063	0.0008	1.4216	0.1922	
Error	144	0.0801	0.0006			
Total	179	0.2317				

* - Significant (alpha = 0.05) ** - Highly Significant (alpha = 0.01)

Aspect x Height Interaction

In both the east and west aspects, mean relative density did not exhibit any sequential pattern with increasing height (Figure 18). Four heights did not have a significant difference between mean relative densities in the east and west aspects. At four heights the mean relative density in the west aspect was significantly larger, while at one height the east aspect had the significantly larger mean relative density.

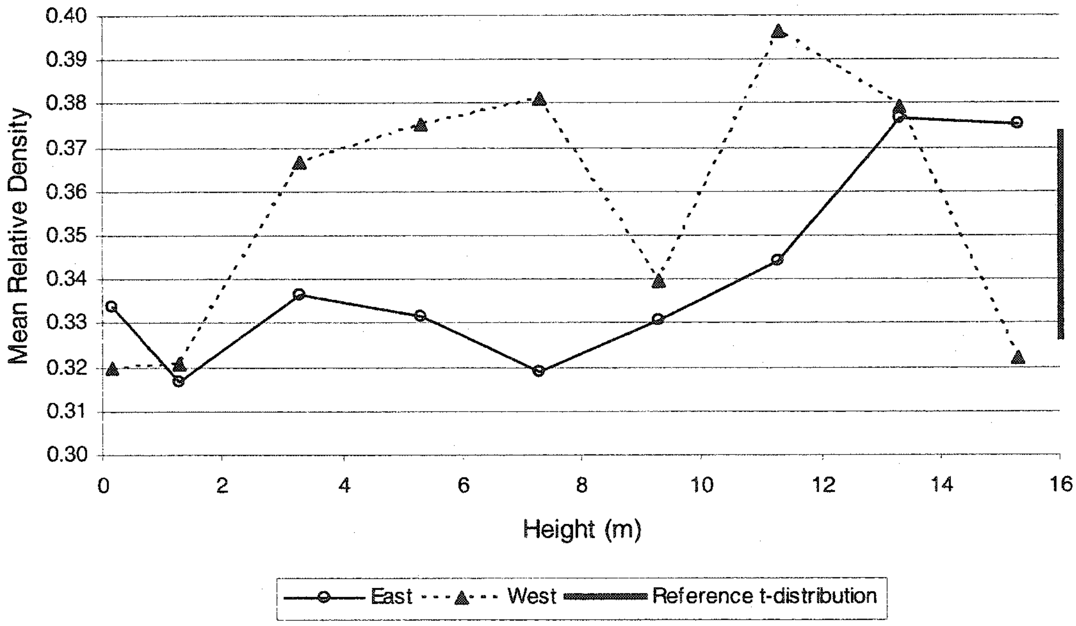


Figure 18. Aspect x height relative density means plotted with a reference t-distribution with scale factor 0.00774.

Zone x Height Interaction

In both the jw and mw zones, mean relative density did not exhibit any sequential pattern with increasing height (Figure 19). At six heights there were no significant differences between the mean relative densities in the jw and mw zones. At three heights the mw zone had a significantly larger mean relative density.

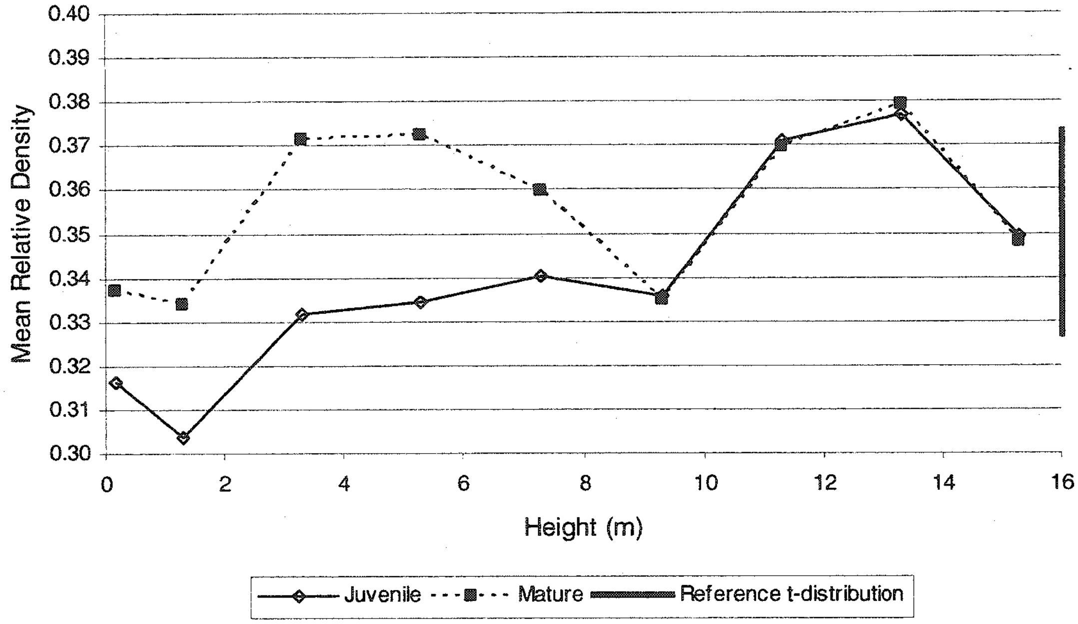


Figure 19. Zone x height relative density means plotted with a reference t-distribution with scale factor 0.00774.

Zone

The jw zone had a significantly smaller mean relative density than the mw zone (Table 12). The mean jw relative density was 4.5 percent lower than the mean mw relative density.

Table 12. Mean relative density of each zone.

Level of Zone	Mean Relative Density
Juvenile	0.340
Mature	0.356

Aspect

The east aspect had a significantly smaller mean relative density than the west aspect (Table 13). The mean east aspect relative density was 4.2 percent smaller than the mean west aspect relative density.

Table 13. Mean relative density of each aspect.

Level of Aspect	Mean Relative Density
East	0.341
West	0.356

Height

An LSD test conducted on height, found that eleven comparisons of mean relative densities were not significantly different (Table 14).

Table 14. LSD test results for mean relative density associated with height.

Height (m)	15.3	13.3	11.3	9.3	7.3	5.3	3.3	1.3
13.3	**							
11.3	**	ns						
9.3	ns	**	**					
7.3	ns	**	**	ns				
5.3	ns	**	*	*	ns			
3.3	ns	**	*	*	ns	ns		
1.3	**	**	**	*	**	**	**	
0.15	**	**	**	ns	**	**	**	ns

* - Significant (alpha = 0.05)
** - Highly Significant (alpha = 0.01)
ns - Not significant

RING WIDTH

Radial Variation

At heights 0.15 m to 7.3 m, ring width generally increased with increasing distance from the pith (Figure 20). At these heights ring width reached a maximum width at approximately five to ten rings from the bark. After the maximum width, ring width decreased in the five to ten rings leading up to the bark. At heights 9.3 m to 17.3 m, ring width fluctuated approximately within a range of ± 0.10 cm around the median of each height/aspect combination. Ring widths near the pith at heights 0.15 m to 7.3 m were generally much narrower than the width of rings near the pith at heights above 7.3 m.

The radial variation of ring width was visually similar between aspects at all heights. This is expected since a ring in the east aspects corresponds to the same ring in the west aspect and thus their widths should be similar. The small diameter of the disc at 17.3 m, resulted in the ring widths being identical in both aspects.

An exceptionally low ring width that was visible at heights 0.15 m to 7.3 m, occurred around rings 25 and 26. The reason for this low ring width can only be speculated. Another unusual ring width that should be noted occurred at a height of 3.3 m. The second ring at that height, or ring 12 in total tree age, had a very wide width. The wide ring was a result of the stem growing around an obstruction. The obstruction also had an impact on some subsequent rings by making them very narrow.

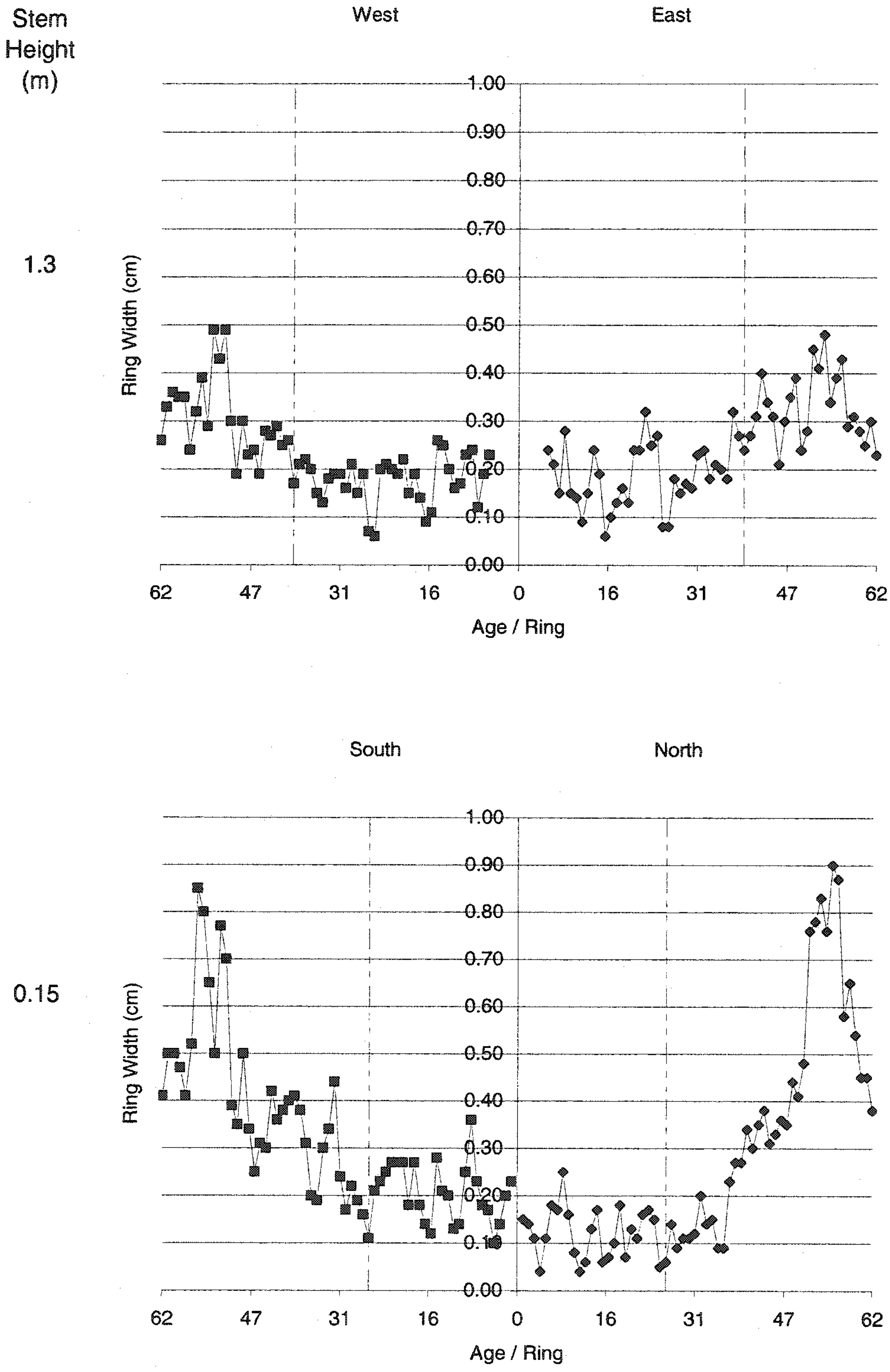
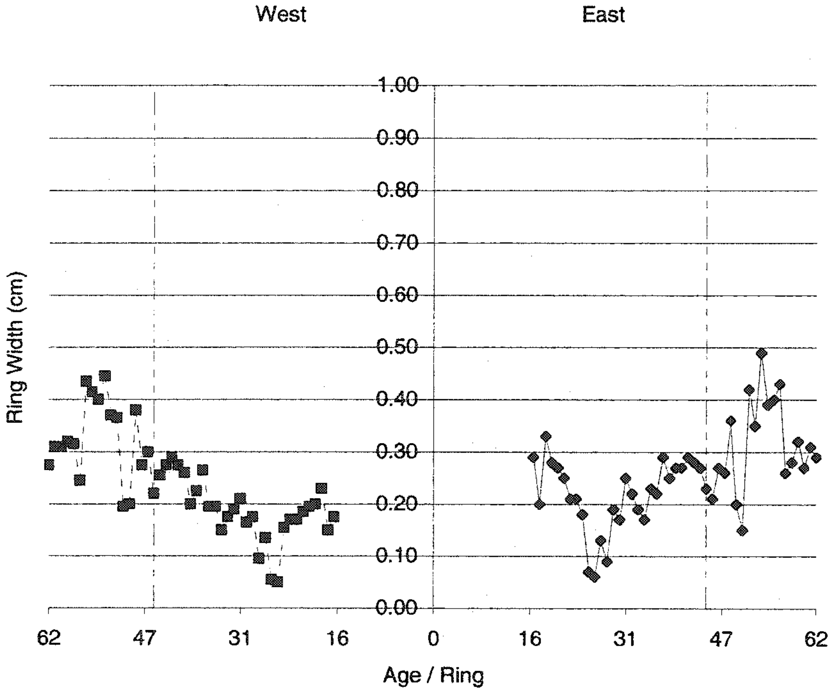


Figure 20. Radial variation of ring width in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines. Averaged ring widths are represented by dashed interval lines.

Stem
Height
(m)

5.3



3.3

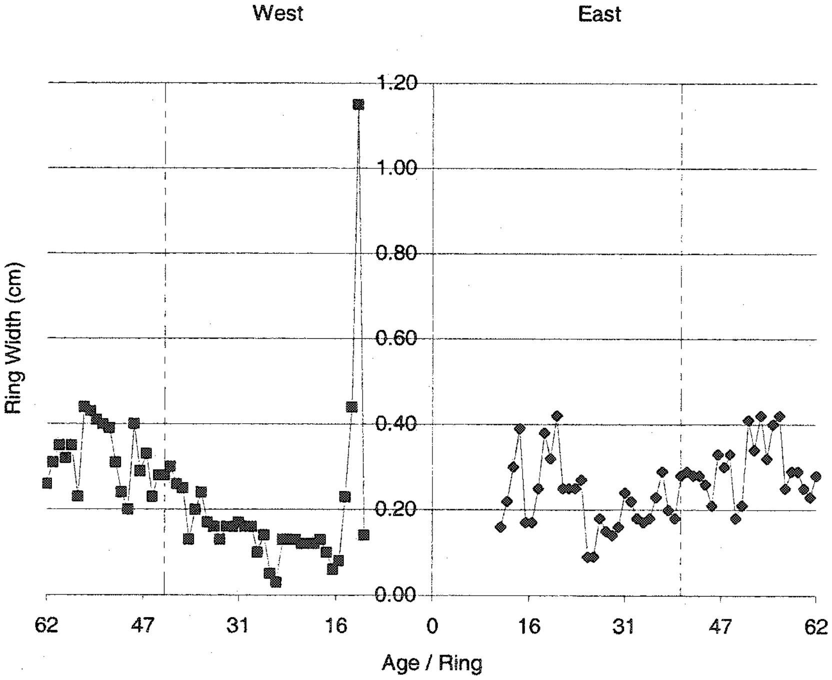


Figure 20. (Continued) Radial variation of ring width in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines. Averaged ring widths are represented by dashed interval lines.

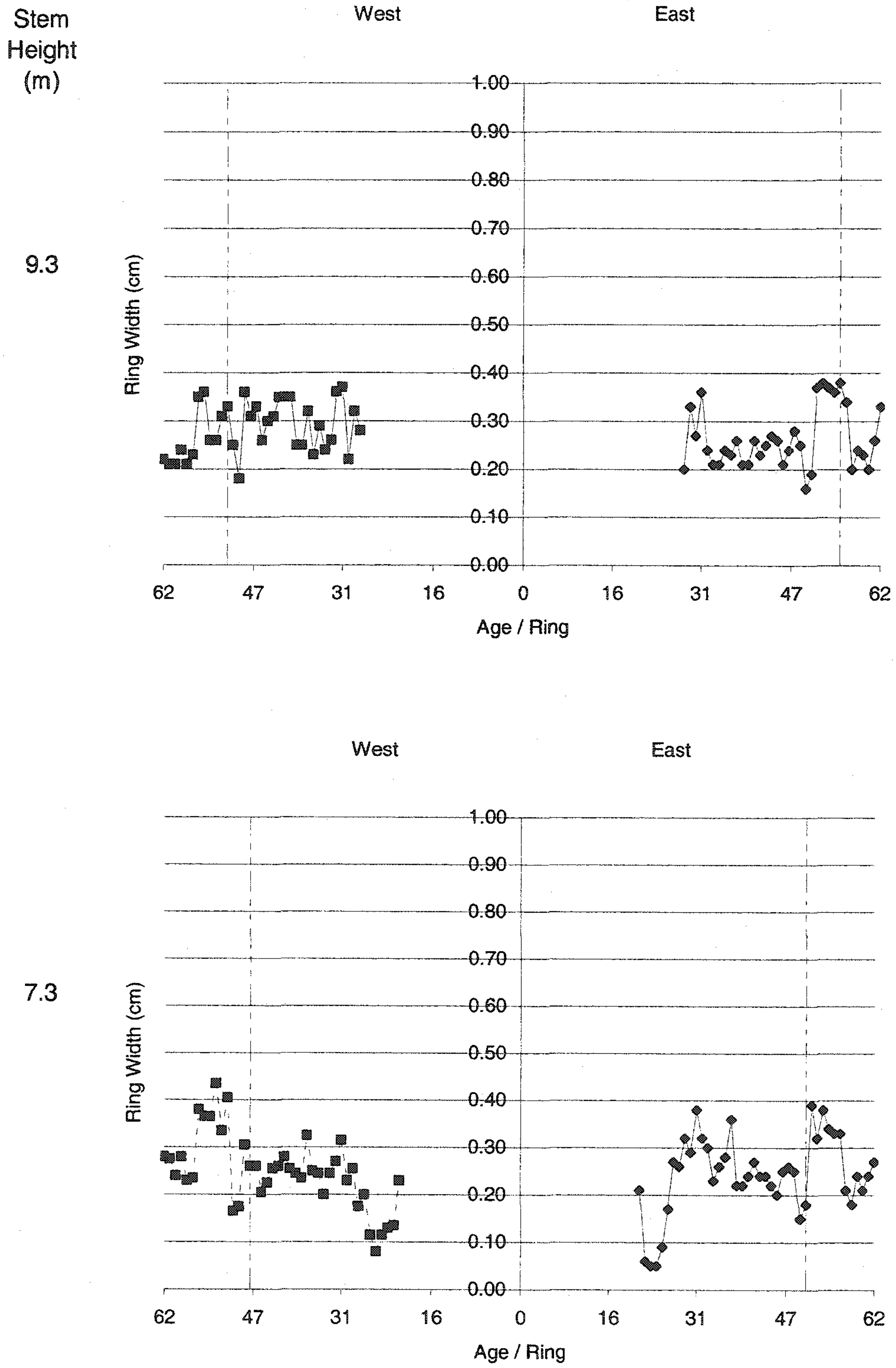
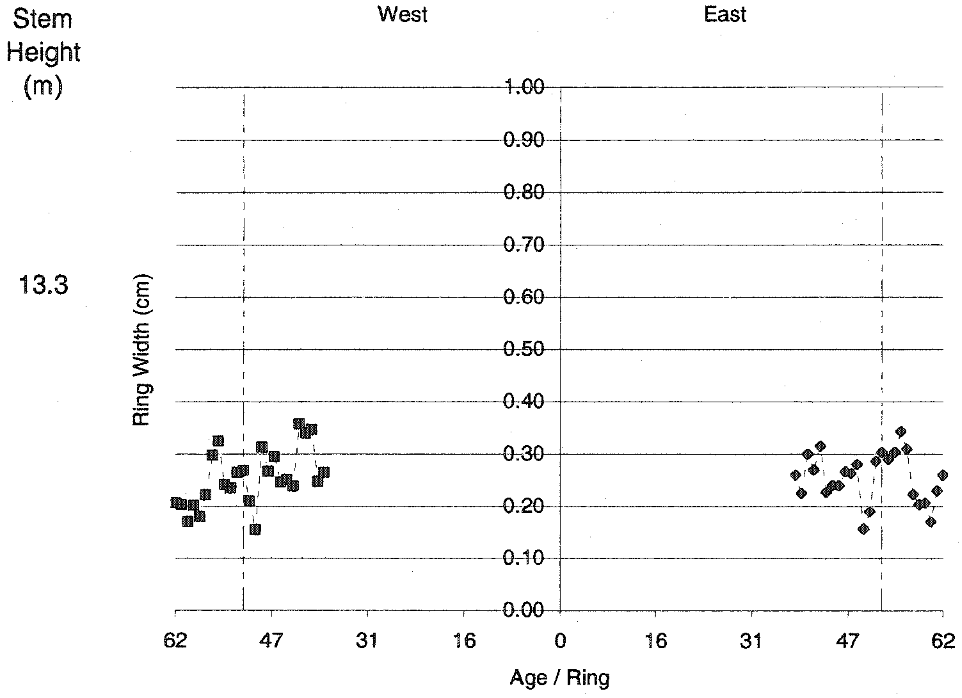


Figure 20. (Continued) Radial variation of ring width in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines. Averaged ring widths are represented by dashed interval lines.



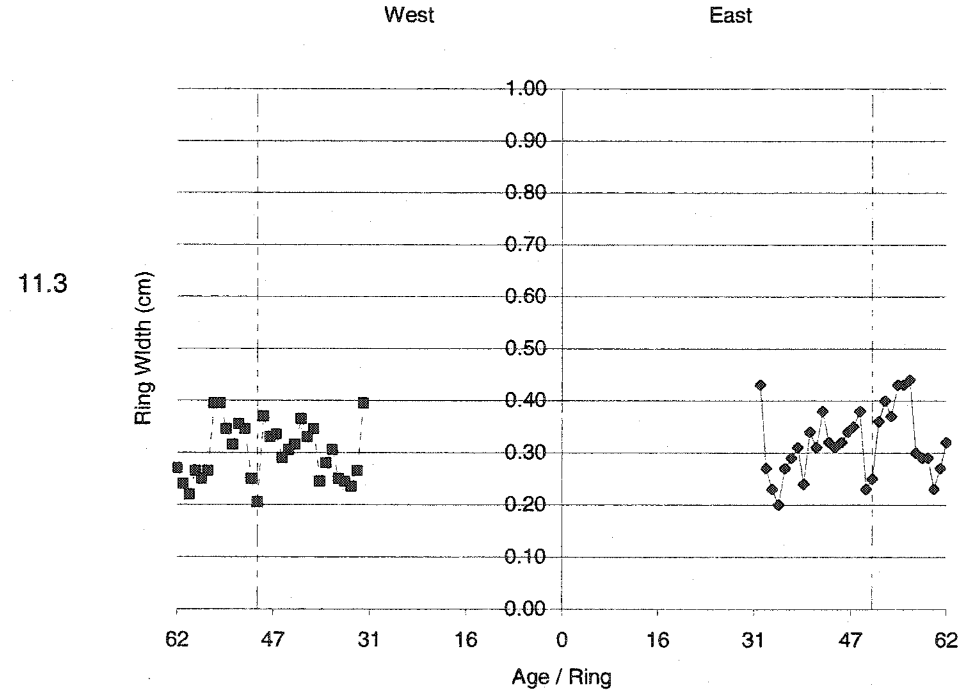


Figure 20. (Continued) Radial variation of ring width in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines. Averaged ring widths are represented by dashed interval lines.

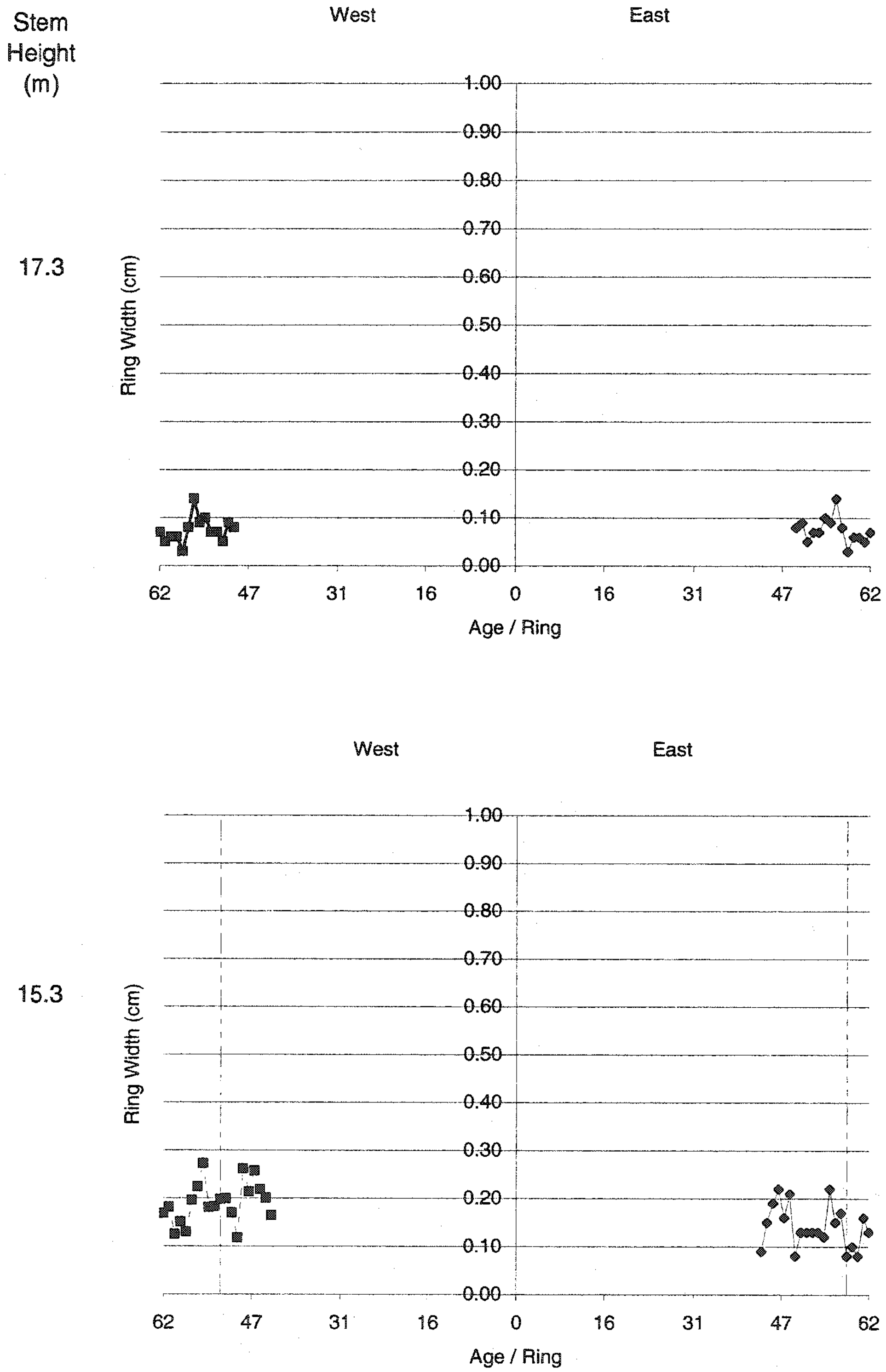


Figure 20. (Continued) Radial variation of ring width in both aspects at various heights. Juvenile wood zone occurs from the pith outward to the vertical dashed lines. Averaged ring widths are represented by dashed interval lines.

JUVENILE WOOD ZONE

Fiber Criterion

Distance from the Pith

When expressed as distance from the pith, the jw zone was at its widest in both aspects at a height of 9.3 m (Table 15). At 9.3 m the width of the jw zone was 7.55 cm and 7.12 cm in the east and west aspects, respectively. The jw zone was at its narrowest width in both aspects at 17.3 m. The width of the jw zone at this height was 1.04 cm, which is the entire length of the radius strip.

Table 15. Radius strip length and width of the juvenile wood zone expressed as distance from the pith, at various heights in the east and west aspects, determined from fiber length radial variation.

			Juvenile Wood Zone Width		
	Radius Strip Length		Distance from Pith		
Height (m)	West (cm)	East (cm)	West (cm)	East (cm)	Mean (cm)
17.3	1.04	1.04	1.04	1.04	1.0
15.3	3.81	2.83	2.09	2.41	2.2
13.3	6.35	6.36	3.77	3.79	3.8
11.3	9.32	9.90	5.45	5.71	5.6
9.3	9.93	9.23	7.12	7.55	7.3
7.3	10.47	10.28	6.05	6.77	6.4
5.3	11.24	12.02	5.64	6.33	6.0
3.3	12.50	13.35	6.25	6.65	6.5
1.3	13.33	14.19	6.31	6.66	6.5
0.15	19.95	17.11	5.33	3.08	4.2

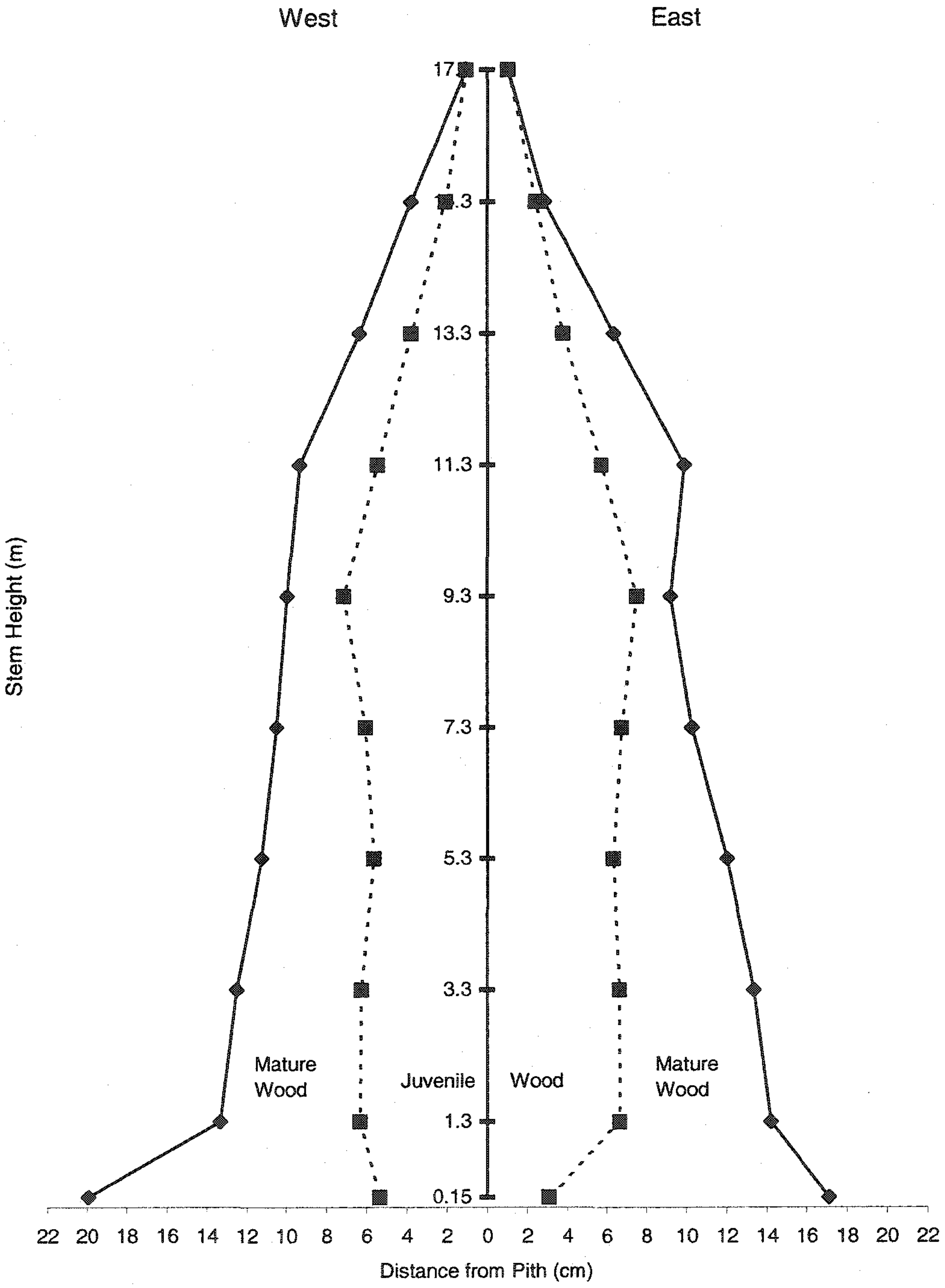


Figure 21. Schematic of the juvenile-mature wood boundary (dashed line), based on fiber length radial variation, and radius strip length (solid line), expressed as distance from the pith. Boundary is in the east and west aspects at heights 1.3 m to 17.3 m and in the south (west side) and north (east side) aspects at 0.15 m.

In the east aspect, starting at 0.15 m the width of the jw zone increased at 1.3 m (Figure 21). The width of the jw zone at 0.15 m was approximately half the width of the jw zone at 1.3 m. Between the heights 1.3 m to 9.3 m, the width of the jw zone ranged from 6.33 cm to 7.55 cm. After 9.3 m, the width of the jw zone steadily decreased up to the final height of 17.3 m.

The vertical variation in the width of the jw zone in the west aspect was similar to the vertical variation in the east aspect (Figure 21). In the west aspect the width of the jw zone increased going from 0.15 m to 1.3 m. In contrast to the east aspect, the jw zone at 0.15 m in the west aspect was 1 cm narrower than the jw zone at 1.3 m. The width of the jw zone ranged from 5.64 cm to 7.12 cm between the heights 1.3 m to 9.3 m. From 9.3 m to 17.3 m, the width of the jw zone steadily decreased as it did in the east aspect.

Number of Rings

When expressed as number of rings, the jw zone was at its widest in both aspects at 1.3 m with 35 rings (Table 16). In the east aspect the least amount of rings in the jw zone occurred at 17.3 m, with 14 rings. In the west aspect the least amount of rings in the jw zone occurred at 15.3 m, with 10 rings.

In the east aspect the jw zone width increased from a height of 0.15 m to 1.3 m (Figure 22). From 1.3 m to 3.3 m, the width of the jw zone decreased. Between 3.3 m to 9.3 m, the width of the jw zone remained relatively stable. After 9.3 m, the jw zone width gradually decreased up to 17.3 m.

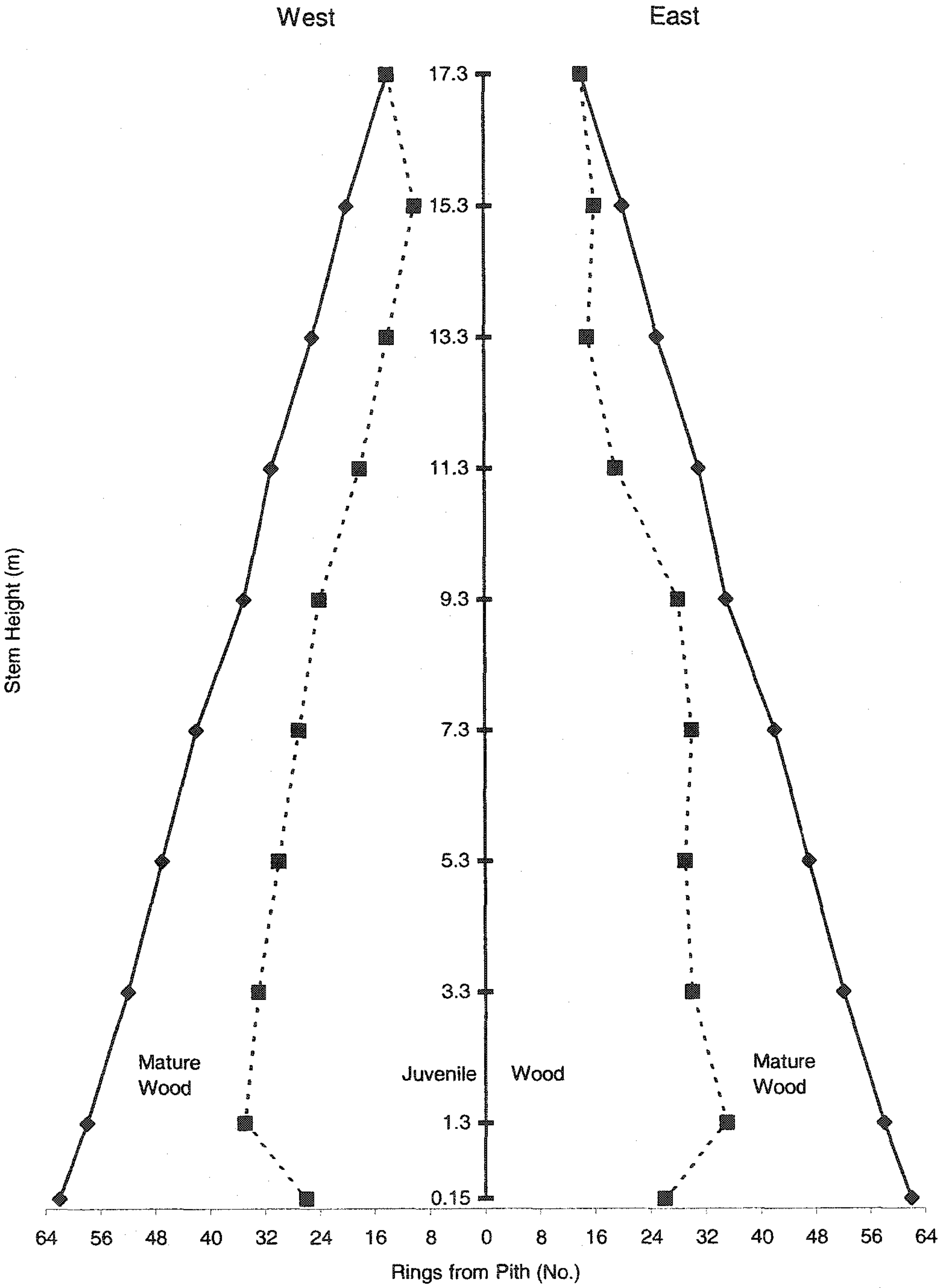


Figure 22. Schematic of the juvenile-mature wood boundary (dashed line), based on fiber length radial variation, and radius strip total rings (solid line), expressed as number of rings. Boundary is in the east and west aspects at heights 1.3 m to 17.3 m and in the south (west side) and north (east side) aspects at 0.15 m

In the west aspect, the jw zone width increased going from 0.15 m to 1.3 m (Figure 22). From 1.3 m to 15.3 m, the jw zone width steadily decreased, from 35 rings to 10 rings respectively. At the final height of 17.3 m, the width increased by 4 rings.

Table 16. Total number of rings and width of the juvenile wood zone expressed as number of rings, at various heights in the east and west aspects, determined from fiber length radial variation.

		Juvenile Wood Zone Width		
		No. of Rings		
Height (m)	Total Rings (No.)	West (No.)	East (No.)	Mean (No.)
17.3	14	14	14	14.0
15.3	20	10	16	13.0
13.3	25	14	15	14.5
11.3	31	18	19	18.5
9.3	35	24	28	26.0
7.3	42	27	30	28.5
5.3	47	30	29	29.5
3.3	52	33	30	31.5
1.3	58	35	35	35.0
0.15	62	26	26	26.0

Vessel Criterion

Distance from the Pith

Based on the radial variation of vessel lengths, the jw zone in the east aspect was at its widest width at 7.3 m, with a width of 6.68 cm (Figure 23). In the east aspect the jw zone was at its narrowest width at 17.3 m, with a width of 1.04 cm. From 0.15 m to 1.3 m, the width of the jw zone increased in the east aspect. The width of the jw zone at 0.15 m was approximately half the width of the jw zone at 1.3 m. Between 1.3 m and 9.3

m, the width of the jw zone fluctuated around 6.5 cm. From 9.3 m to 17.3 m, the width of the jw zone decreased.

In the west aspect, the jw zone was at its widest at 9.3 m, with a width of 7.1 cm when based on the radial variation of vessel lengths (Figure 23). The jw zone was at its narrowest width in the west aspect at 17.3 m, with a width of 1.04 cm. From 0.15 m to 1.3 m the width of the jw zone increased in the west aspect. The increase in width was much less than what occurred in the east aspect. Between 1.3 m and 5.3 m, the width of the jw zone fluctuated around 5.2 cm. After 5.3 m the width of the jw zone increased up to a height of 9.3 m. The width of the jw zone then continually decreased from 9.3 m to 17.3 m.

Boundary Comparison

The location of the juvenile-mature wood boundary based on the radial variation of vessel lengths was similar to the location of the boundary based on the radial variation of fiber lengths (Figure 23). The west aspect had the most number of heights, specifically between 0.15 m and 5.3 m, in which the boundary locations had a noticeable difference between the two criteria. In the west aspect the location of the boundary determined with vessel lengths was further from the pith at heights 7.3 m and 11.3 m. At the remaining heights the boundary determined with fiber length was either further from the pith or equal to, the location of the boundary when determined with vessel lengths.

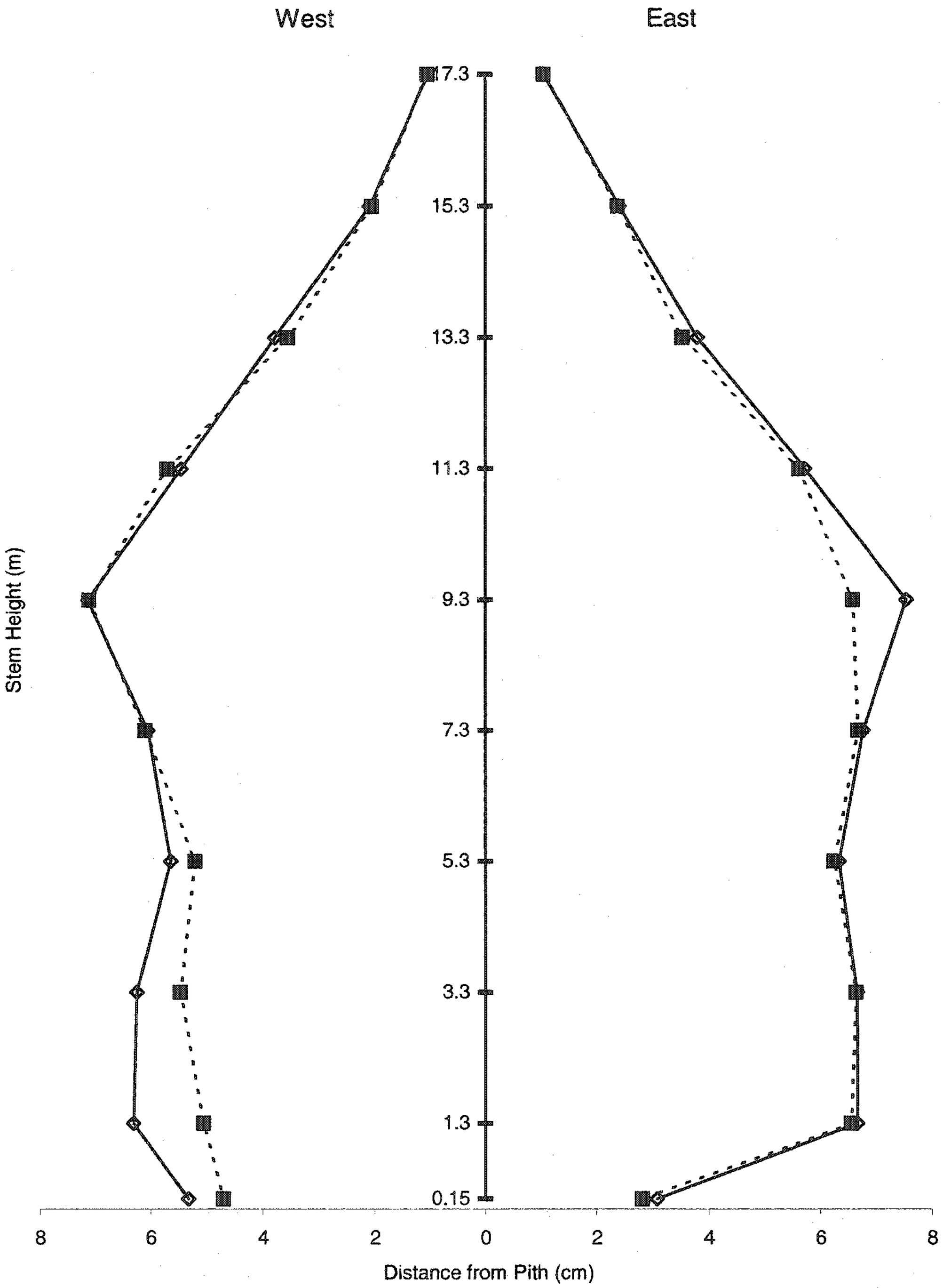


Figure 23. Comparison of the juvenile-mature wood boundary location based on the radial variation of vessel length (dashed line) and fiber length (solid line) expressed as distance from the pith. Boundary is in the east and west aspects at heights 1.3 m to 17.3 m and in the south (west side) and north (east side) aspects at 0.15 m.

In the east aspect the only height which had a large noticeable difference in boundary location between criteria was 9.3 m. In the east aspect the location of the juvenile-mature wood boundary determined with fiber lengths was at all heights, further from the pith or equal to, the distance from the pith that the juvenile-mature wood boundary was when determined with vessel lengths.

Juvenile Wood Volume Percentage

The juvenile, mature, and total stem wood volumes and percentage of juvenile wood calculations based on mean radii and a mean juvenile-mature wood boundary location, for each ring is provided in Appendix II.

At age 62 the total stem wood volume was 578.00 dm^3, mw stem volume was 416.31 dm^3, and jw stem volume was 161.69 dm^3 (Figure 24). The jw stem volume represented 27.97 percent of the total stem wood volume.

The stem of the study tree was entirely jw up to the age of 26. At age 26 the volume of jw was 22.32 dm^3. Between the ages of 27 and 39 the percentage of jw decreased slowly. The percentage of jw was 98.8 percent at age 27 and 91.49 percent at age 39. After age 39, the percentage of jw decreased rapidly over the remaining ages. The volume of jw reached a 'plateau' at approximately age 53, with a volume of 160.17 dm^3. This is not a true 'plateau', since there would always be jw, albeit a small amount, being produced in the crown of the tree.

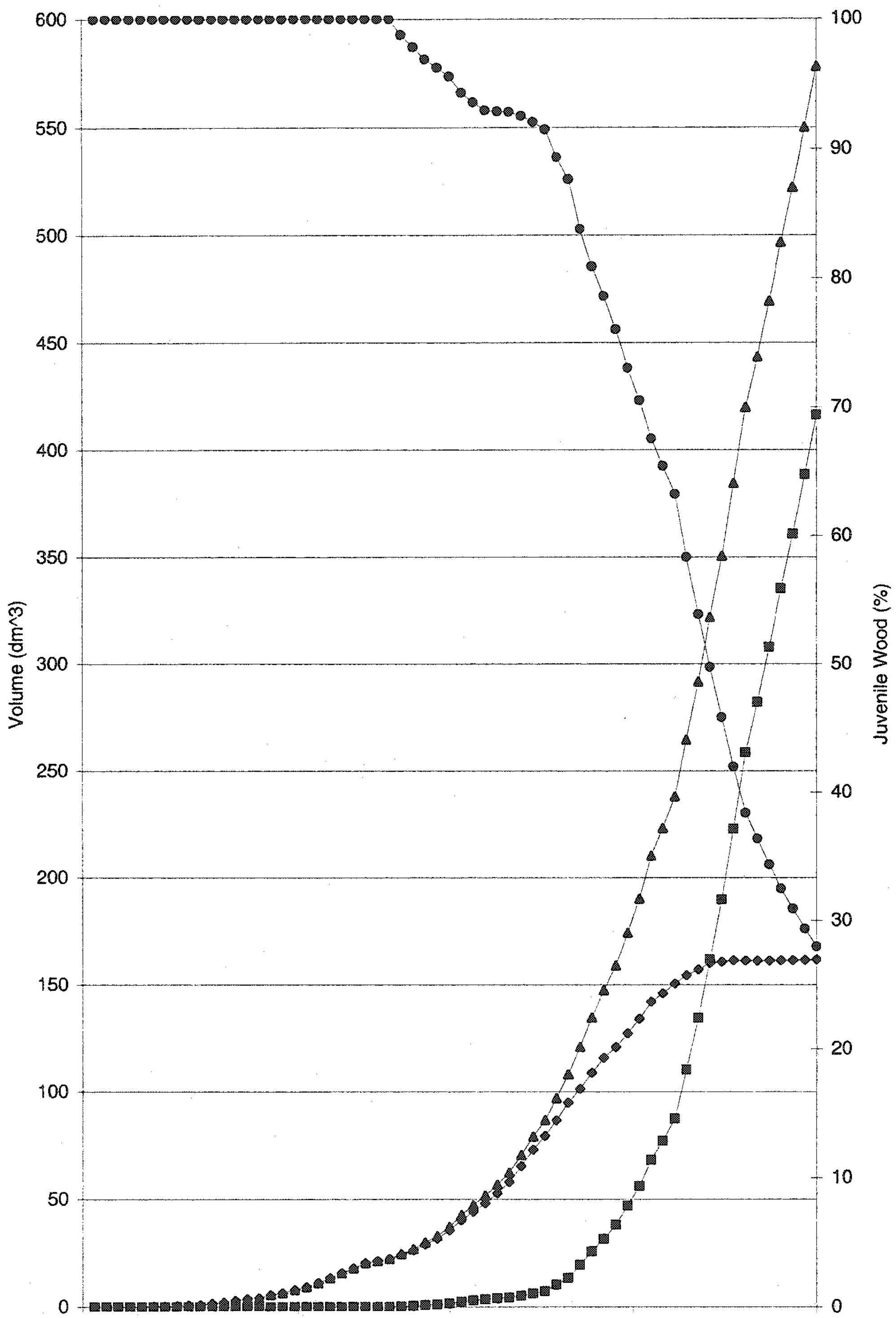


Figure 24. Juvenile (diamonds), mature (squares) and total (triangles) stem wood volume and percentage of juvenile wood (circles) based on a mean of the radii and a mean of the juvenile-mature wood boundary location.

The production of mw did not occur until the study tree was 27-years-old. The volume of mw at age 27 was 0.29 dm^3. The increase in mw volume had a pattern similar to an exponential curve (Figure 24). Total stem volume also exhibited an exponential curve.

RELATIONSHIP OF JUVENILE WOOD PERCENTAGES

The percentage of basal area that is jw, based on mean radii, for each ring at each height interval is presented in Appendix III.

Examining the relationship between the percentage of total stem volume that is jw and the percentage of basal area that is jw was done at all height intervals to determine the type of relationship at various heights. The relationship between these two jw percentages was linear and curvilinear, depending on height (Figure 25). At heights 0.15 m to 5.3 m, the relationship was curvilinear, while above 5.3 m the relationship was approximately linear.

A characteristic of the curves that should be explained is the overlapping of curves between the heights 7.3 m to 15.3 m. The overlapping of the curves is a result of the jw zone decreasing in width between heights 11.3 m to 17.3 m. The curves created from heights 0.15 m to 5.3 m did not overlap since the width of the jw zone remained relatively constant. There was only one point on the graph for height 17.3 m since the entire disc was considered to be jw.

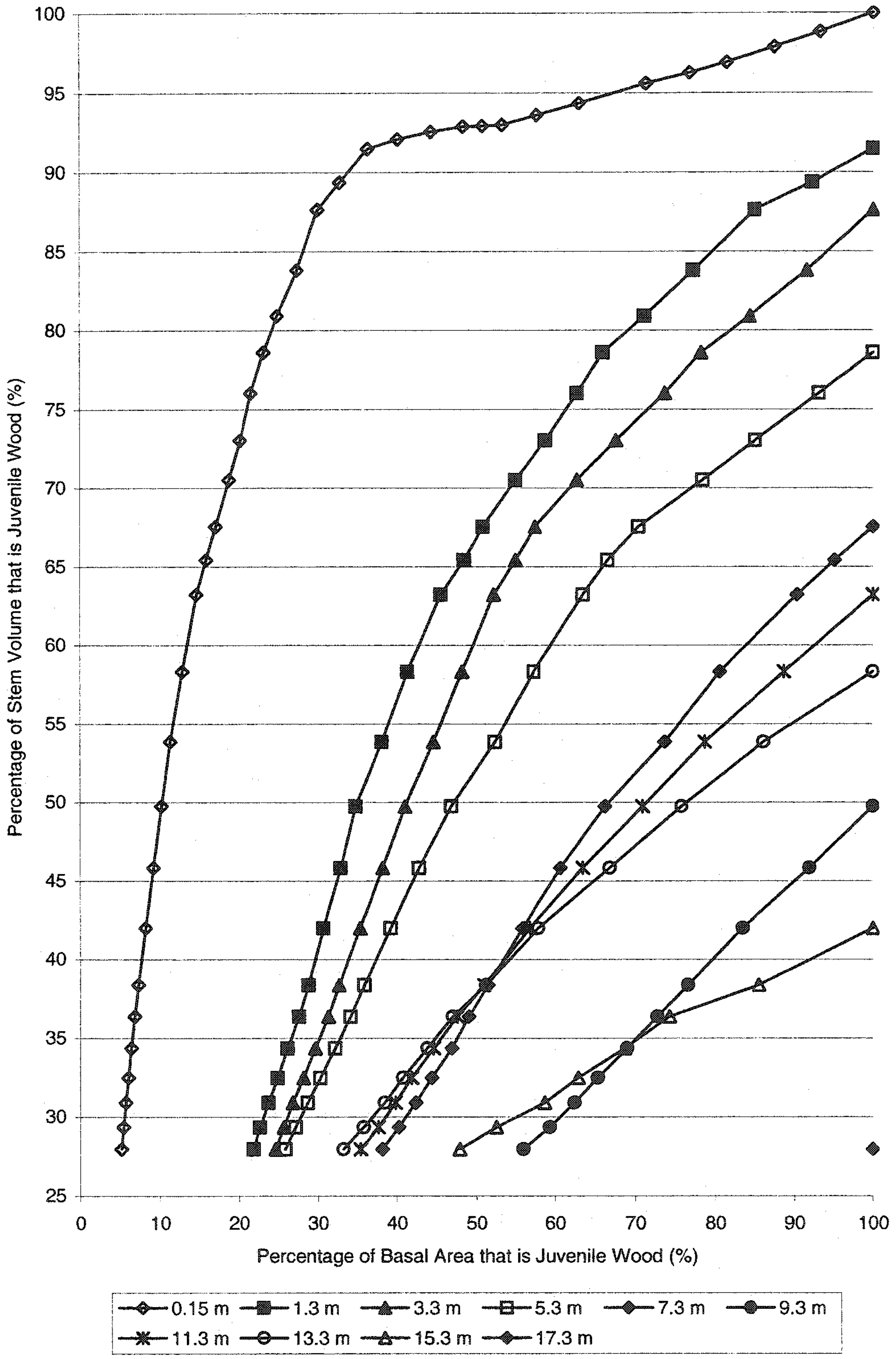


Figure 25. Relationship between juvenile wood expressed as a percentage of stem wood volume and percentage of basal area at various heights, based on mean radii.

RELATIONSHIP OF INTERVAL AGE AT PITH & JUVENILE WOOD ZONE WIDTH

Interval age at the pith increased with increasing height (Table 17). A non-linear relationship occurred between interval age and jw zone mean width expressed as distance from the pith (Figure 26). The relationship can be divided into two linear sections, separated at an interval age at the pith of 28, which occurs at 9.3 m. From the interval ages at the pith 5 to 28 (1.3 m to 9.3 m) there was a slightly positive linear relationship. From interval ages at the pith 28 to 49 (9.3 m to 17.3 m) there was a strong negative linear relationship. The correlation coefficient (r = -0.8261) was highly significant.

Table 17. Interval age at pith.

Height (m)	Interval Age At Pith (Years)
17.3	49
15.3	43
13.3	38
11.3	32
9.3	28
7.3	21
5.3	16
3.3	11
1.3	5
0.15	1

A strong negative linear relationship occurred between the interval age at the pith and jw zone mean width expressed as number of rings (Figure 27). The correlation coefficient (r = -0.9674) was highly significant.

The interval age at the pith and the jw zone mean width at 0.15 m were not included in the graphs of Figure 26 and Figure 27. Roots are reported by Hejnowicz and Hejnowicz (1958) to have an influence on the cambium initials in stem wood that are within close proximity to the roots. When the relationship at 0.15 m was included it deviated from the pattern created by the other relationships. Since the cambial initials may be influenced by the roots at 0.15 m, it was decided not to include data from this height.

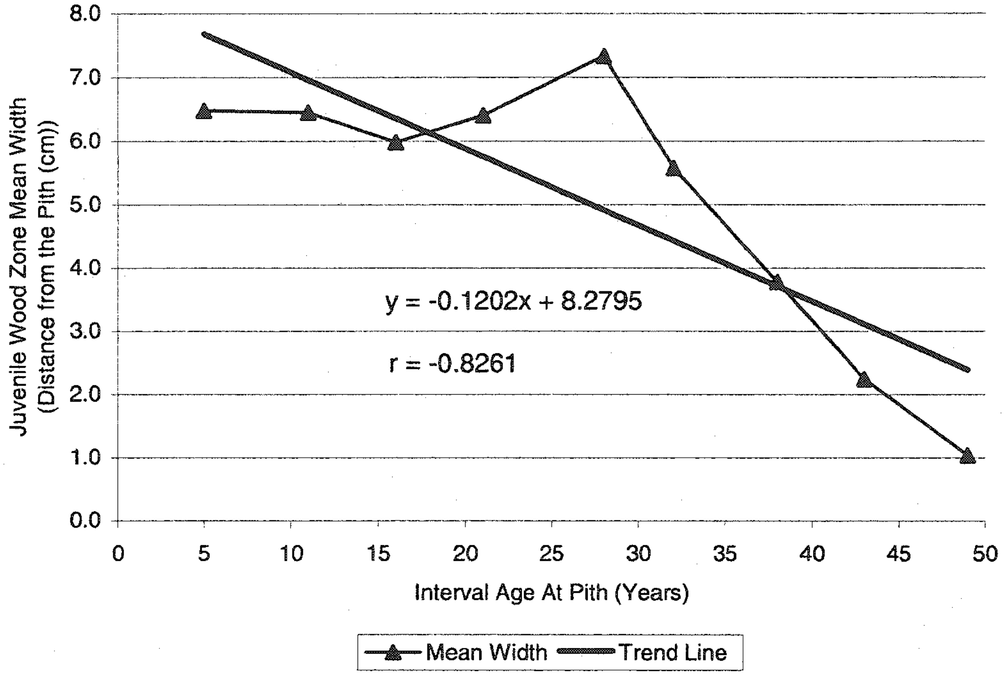


Figure 26. Relationship between interval age at pith and juvenile wood zone mean width expressed as distance from the pith.

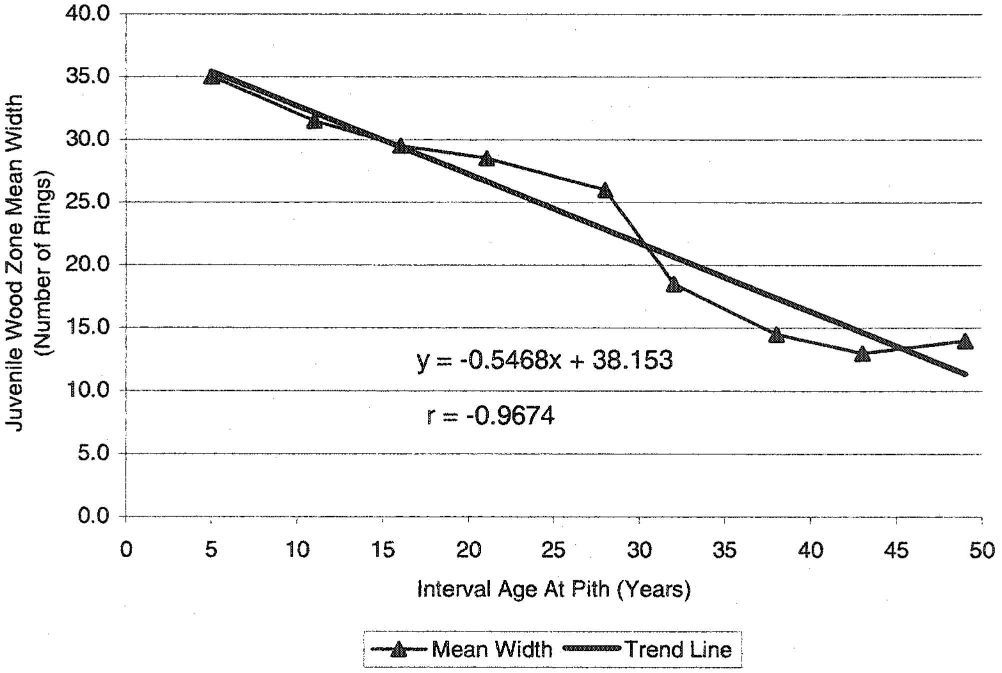


Figure 27. Relationship between interval age at pith and juvenile wood zone mean width expressed as number of rings.

DISCUSSION

FIBER LENGTH

Radial Variation

The radial variation of fiber length was consistent with the results of other researchers (Hejnowicz and Hejnowicz 1958; Panshin and de Zeeuw 1980; DeBell *et al.* 1998; Fujiwara and Yang 2000). All three possible radial variations in the mw zone identified by Panshin and de Zeeuw (1980) were exhibited.

The radial variation of fiber length at heights 0.15 m to 7.3 m, in both aspects, clearly exhibited all three zones of cell length elongation: jw zone, transitional wood zone and mw zone (Figure 11). From heights 9.3 m to 15.3 m, the jw and transitional wood zones were clearly present. The initial beginning of the mw zone was starting to develop at these heights. At 17.3 m only the jw zone was present. A reduction in the number of zones exhibited in the radial variation with increasing height was expected since the age of the stem becomes younger with increasing height.

Since the segment blocks were not delineated exactly by growth rings there may have been an unbalanced proportion of early-wood to late-wood between segment blocks. A larger proportion of late-wood could result in a longer mean fiber length and conversely a smaller amount of late-wood could result in a shorter mean fiber length (Panshin and de Zeeuw 1980). This could explain the large fluctuation in mean fiber length seen in the radial variation at times between successive segment blocks.

In non-storied hardwoods the increase in fiber length with increasing distance from the pith, has been suggested by Chalk *et al.* (1955) to be related to the changes in length the fusiform initials undergo.

Analysis of Means

The analysis found that there is a lot of variation in mean fiber length within the stem of the study tree. The most crucial significant source of variation in mean fiber length was the three-way interaction, aspect x zone x height.

Mean fiber length was very different depending on height. In both wood zones mean fiber length exhibited a slight parabolic shape with the peak around 3.3 m (Figure 12). The shortest mean fiber lengths occurred in the top portion of the stem. This variation in mean fiber length with height is similar to the variation reported by Hejnowicz and Hejnowicz (1958) in European aspen and Einspahr *et al.* (1972a) in trembling aspen.

Finding shorter fibers at the very top of the stem is expected since the wood at the top is mainly jw, which is known to have shorter cell lengths. However the jw mean fiber lengths at the very top were the shortest, being shorter than the jw mean fiber lengths at lower heights. The cause of shorter fiber lengths at the top of the tree could be speculated as being a result of water stress. In order for cell elongation to occur, there must be enough water present to maintain cells in a turgid condition (Kramer 1964). Perhaps being at the top of the tree, the fibers did not receive enough water to reach their full length potential.

Zone had a significant effect on mean fiber length. The jw zone means where at all heights significantly shorter than the mw zone means in both aspects, when comparing means from the same height. Comparisons of zone means amongst heights resulted in both significant and non-significant differences. Shorter jw zone mean fiber lengths were expected since this is an accepted fact. This result is a good indication that the juvenile-mature wood boundary was placed in an appropriate location, which also then assists with validating the modifications made to the Yang *et al.* (1986) demarcation method.

Aspect had a significant effect on mean fiber length. There was no dominating aspect in terms of consistently having a longer mean fiber length in either wood zone, when comparing aspects from the same height. The variation in length between aspects may be a result of the different aspects of the stem receiving different amounts of sun exposure, wind loads, and eccentric stem and crown growth (Wong 1986). Longer fibers may develop in certain aspects at particular heights depending on the mechanical strength requirements needed to support the tree, since fibers provide mechanical support (Tsoumis 1968; Jane 1956).

The results have shown that there are statistical differences in mean fiber length within the stem of the tree. Further research is required to determine if the differences in length would have a practical significance on the quality of wood based products. The eccentric variation of mean fiber length may make it logistically difficult to allocate specific sections of stem wood to the manufacturing of specific products based on the desired fiber length for a particular product.

VESSEL LENGTH

Radial Variation

The radial variation of vessel length was consistent with the results reported by Hejnowicz and Hejnowicz (1958) and Panshin and de Zeeuw (1980). All three of the possible variations in the mw zone identified by Panshin and de Zeeuw (1980) were exhibited.

The radial variation of vessel length at heights 0.15 m to 7.3 m, in both aspects, clearly exhibited all three zones of cell length elongation: jw zone, transitional wood zone and mw zone. From heights 9.3 m to 15.3 m, the jw and transitional wood zones were clearly present. The initial beginning of the mw zone was starting to develop at these heights. At 17.3 m only the jw zone was present. The reduction in the number of zones exhibited in the radial variation with increasing height was expected since the age of the stem becomes younger with increasing height.

As with the fibers, there may have been an unbalanced proportion of early-wood to late-wood in the segment blocks affecting the mean vessel lengths. The difference in length between early-wood and late-wood vessels has, however, been reported to be only slight (Panshin and de Zeeuw 1980).

Analysis of Means

The variation in mean vessel length was similar to mean fiber length. This is not unexpected since both cell types are derived from the same cambial fusiform initials. As occurred with mean fiber length, the most crucial significant source of variation in mean vessel length was the three-way interaction, aspect x zone x height.

Mean vessel length was very different depending on height. In both wood zones mean vessel length exhibited a parabolic shape with the peak around 3.3 m (Figure 15). The shorter mean vessel lengths were found in the top portion of the stem. The variation was very close to the vertical variation reported by Pritchard and Bailey (1916) in shagbark hickory and Hejnowicz and Hejnowicz (1958) in European aspen. The characteristic of having the shortest mean vessel lengths occurring at the top of the tree is consistent with the findings of other researchers (Pritchard and Bailey 1916; Hejnowicz and Hejnowicz 1958).

As with the fibers, the jw vessels at the top of the tree had the shortest length of all the vessels. Again this could be possibly explained by water stress (Kramer 1964). Since both fibers and vessels occur together, any water shortage in the top portion of the tree affecting fibers would also affect the elongation of vessels.

Zone had a significant effect on mean vessel length. The jw zone mean vessel lengths were significantly shorter than the mean vessel lengths in the mw zone, when comparing means from the same height and in both aspects. This result provides further support that the juvenile-mature wood boundary was placed in an appropriate location and assists with validating the modifications made to the Yang *et al.* (1986) demarcation method.

Aspect did have a significant effect on mean vessel length. However, as occurred with the fibers, neither aspect had a significantly longer mean vessel length at all the heights, in either wood zone.

The results have shown that there are statistical differences in mean vessel length within the stem of the tree. As with the fibers, further research is required to determine if the differences in length would have a practical significance on the quality of wood based products. The eccentric variation of mean vessel length would make it logistically difficult to allocate specific sections of stem wood to the manufacturing of specific products based on the desired vessel lengths for a particular product.

CELL LENGTH INCREASE RATE

The vertical variation of the increase in cell length with distance from the pith in the jw zone did not exhibit a sequential pattern. This contrasts findings by researchers studying softwoods which have reported uniform increases in the rate of cell length increase, by starting low at the base of the tree and increasing with height (Megraw 1985; Yang *et al.* 1986; Feng 2001). Taylor (1968) reported that the rate of cell length increase was greatest at breast height than at successive heights in yellow-poplar.

The variation in the cell length increase rate does, however, correspond to changes in the width of the jw zone. A lower cell length increase rate corresponds to a wider jw zone and a higher cell length increase rate corresponds to a narrower jw zone. A wider jw zone indicates the cambial initials took longer to reach the mw cell length, resulting in a lower cell length increase rate. A narrower jw zone indicates the cambial initials took less time to reach the mw cell length, resulting in a higher cell length increase rate. The rate of cell length increase in the jw zone could perhaps provide an indication of the duration of the jw phase.

The cell length increase rate variation for fibers and vessels was similar, with the difference being in the magnitude of the increase rate. The variation should be similar between fibers and vessels since they both originate from the same cambium fusiform initials. The difference in magnitude is likely a result of the fact that fibers experience much larger post-cambial elongation than vessels (Panshin and de Zeeuw 1980).

Calculation of the cell length increase rate is influenced by the location of the juvenile-mature wood boundary. Discrepancies in the boundary location due to different methods and criteria, could also lead to discrepancies in the cell length increase rate.

RELATIVE DENSITY

Radial Variation

Relative density did not have a radial variation common to all the heights and aspects. There are numerous factors that can cause a lot of variation in the radial variation of relative density. Panshin and de Zeeuw (1980) reported that in *Populus* the proportion of fibers increases near the bark, resulting in an increase in relative density near the bark. Higher relative density may be the result of the presence of reaction wood. Einspahr *et al.* (1972b) found higher relative density than expected, citing the reason to reaction wood. Increases in cell wall thickness from the pith outward could result in higher relative density in the mature wood zone (Panshin and de Zeeuw 1980).

Sample preparation may have contributed to the wide variation in relative density. Since the segment blocks where not delineated by growth rings, the segment blocks may have had an unbalanced proportion of early-wood and late-wood. Larger proportions of late-wood would result in a higher mean relative density.

The lack of a consistent radial variation for relative density would eliminate relative density as a viable criterion for determining the juvenile-mature wood boundary.

Analysis of Means

Mean relative density had an eccentric variation within the stem, as it both increased and decreased over the height of the stem. The larger mean relative density values occurred at two particular sections of the stem: between 3.3 m to 5.3 m and between 11.3 m to 13.3 m.

The occurrence of an eccentric variation in relative density with height has also been reported by (Panshin and de Zeeuw 1980). The variation in mean relative density with height is, however, different from the findings of Einspahr *et al.* (1972b). Einspahr *et al.* (1972b) reported that relative density started high at the base of the tree and decreased upward. However a comparison to Einspahr *et al.* (1972b) findings is not completely appropriate since they examined relative density differently. Einspahr *et al.* (1972b) examined the vertical variation of relative density by following specific rings from the base of the tree to the top. The relative density values reported by Einspahr *et al.* (1972b) in the 15th to 17th growth rings at 0.15 m, 1.98 m and 11.12 m was 0.45, 0.39 and 0.36, respectively. In this study at heights 0.15 m, 3.3 m and 11.3 m the mean relative density values of both aspects and wood zones was 0.33, 0.35 and 0.37.

Aspect had a significant effect on relative density, however neither aspect was significantly larger at all heights. At the majority of heights where there was a significant difference, the west aspect had the significantly larger relative density. Differences in mean relative density between aspects could be a result of several factors. There could be more reaction wood in one particular aspect or the rings could have a larger ratio of late-wood to early-wood due to the growing conditions in a particular aspect.

Zone had a significant effect on relative density, however neither zone was significantly larger at all heights. At all the heights where there was a significant difference, the mw zone had the significantly larger relative density. The lack of significant differences between zones at 7.3 m and above may be a result of the mw being younger than the mw at the lower heights, and as such may not have undergone all the biological changes, such as increased proportion of fibers, which would increase relative density from the jw zone.

RING WIDTH

Radial Variation

Ring width was found to increase from the pith outwards between heights 0.15 m and 7.3 m (Figure 20). At heights 9.3 m to 17.3 m, ring width fluctuated from the pith outwards but remained relatively stable. Since growth rings are continuous from the base of the tree to the top, a change in width for a particular ring can be seen at all heights the ring occurred at.

The narrower ring widths found near the pith at heights 0.15 m to 7.3 m are likely a result of the tree being suppressed by competition in its earlier years of growth. As the tree grew larger it was released from suppressing competition allowing it to produce wider growth rings farther from the pith at heights below 7.3 m and near the pith at heights above 7.3 m.

The radial variation of ring width found in this study provides further evidence against the hypothesis that juvenile wood occurs as a result of wide growth rings (Zobel and Sprague 1998). Despite having narrow rings near the pith, the wood still had shorter fibers and vessels near the pith, characteristic of juvenile wood.

Since environmental conditions can have a large influence on ring width, it is not a reliable criterion for determining the juvenile-mature wood boundary (Yang *et al.* 1986). Changes in environment conditions can result in narrower or wider ring widths producing an inconsistent radial variation which do not necessary reflect anatomical changes.

JUVENILE WOOD ZONE

The majority of the data analysis and the discussion of the results are entirely reliant on the assumption that the juvenile-mature wood boundary is in fact located in the correct location. Since only one tree was examined, the location of the boundary should be considered exploratory for future research on trembling aspen in the Thunder Bay area.

There is some discretion on the location of the boundary at 0.15 m in the north aspect. The location of the boundary could be considered in a transitional zone between the jw and mw zones and not an adequate representation for an exact transition point. Perhaps the modified Yang *et al.* (1986) demarcation method used to demarcate the boundary could be improved or further modified. Various researchers have noted that the change from the juvenile wood zone to the mature wood zone is transitional. Reporting a transitional range instead of a single transition point may provide a description of the boundary location that is more applicable.

Although a specific tree age is presented as the boundary, the transition from jw to mw should be assumed to be a gradual process that takes place over several years (Sauter *et al.* 1999). Groom *et al.* (2002) reported that the transition zone parallels in shape the jw zone and is between 5 to 15 rings in width depending on vertical location.

Juvenile Wood Zone Shape

The shape of the jw zone, based on the radial variation of fiber length, varied depending on how the boundary location was expressed. Expressing the boundary as distance from the pith resulted in two shapes separated at 9.3 m (Figure 21). From 9.3 m and higher the jw zone had a conical shape. From 9.3 m and lower the jw zone had a cylindrical shape that gradually tapered towards the base of the tree. When the boundary location was expressed as rings from the pith, the jw zone resembled a conical shape from 1.3 m to 17.3 m, with the base of the cone at 1.3 m (Figure 22). From 1.3 m to 0.15 m the jw zone had a frustum of a cone shape with the small diameter end at 0.15 m.

The shape of the jw zone, expressed either way, does not support the concept that the jw zone is cylindrical as identified by Rendle (1958), Zobel and McElwee (1958) and Panshin and de Zeeuw (1980). The conical shape of the jw zone, when expressed as rings from the pith, is in agreement with the findings of Feng (2001) and Yang *et al.* (1986).

Differences in the shape of the jw zone when the boundary location is expressed in different terms are an artefact of the measurement units. Distance from the pith was measured in centimetres and thus is influenced by the variation in ring width amongst heights. The number of rings from the pith is based on a numerical scale that is not influenced by natural variation and is consistent at each height.

Juvenile Wood Zone Width

When expressed as distance (in cm) from the pith, the jw zone was at its widest in both aspects at a height of 9.3 m. This is not consistent with the findings of Yang *et al.* (1986) and Feng (2001), who both reported that the jw zone was the widest at the base of the tree. The width of the jw zone at 9.3 m in this study was similar to the jw zone width reported by Feng (2001) for the base of the tree.

When expressed as distance from the pith, the jw zone was at its narrowest in both aspects at 17.3 m or the top of the tree. Yang *et al.* (1986) and Feng (2001) also reported that the jw zone was at its narrowest at the last height interval of their respective study trees. The jw zone was 1.04 cm wide at 17.3 m, which is within the range of widths reported by the mentioned researchers.

When expressed as number of rings, the jw zone between 0.15 m and 9.3 m was larger than the generally accepted guideline of 5 to 20 rings. Only from 11.3 m to 17.3 m did the number of rings in the jw zone fall within this guideline. The jw zone was at its widest in both aspects at 1.3 m. This is not consistent with the findings of Yang *et al.* (1986) and Feng (2001) who found that the jw zone was at its widest at stump height (0.15 m).

The number of rings in the jw zone at 1.3 m in both aspects was 35, which is both larger and smaller than the reports of other researchers at comparable heights.

Fujiwara and Yang (2000) reported that the jw zone at 1.3 m consisted of 22 rings in trembling aspen.

The jw zone was at its narrowest in the east aspect at 17.3 m and in the west aspect at 15.3 m or at the top of the tree, when expressed as number of rings. The results are consistent with the reports by Yang *et al.* (1986) and Feng (2001) who both found that the juvenile wood zone was the narrowest at the last top height interval.

Boundary Comparison

The location of the juvenile-mature wood boundary based on the radial variation of vessel lengths, was similar to the location of the boundary based on the radial variation of fiber lengths, when both were expressed as distance from the pith (Figure 23). This indicates that the radial variation of vessel length is an acceptable criterion for demarcating the juvenile-mature wood boundary. However, Fukazawa and Ohtani (1982) found in their study of Japanese basswood that the radial variation of vessel length could not be used to determine the juvenile-mature wood boundary. They report that there was not enough radial variation in vessel length to identify a jw and mw zone.

Juvenile Wood Volume Percentage

At age 62, the percentage of total stem wood volume that was jw was 28 percent based on a mean of the aspect radiuses (Figure 24). Feng (2001) reported that jw comprised 30 percent of the stem wood volume in a 60-year-old jack pine. Yang *et al.* (1986) reported that 44 percent of the total volume was jw in both an 81-year-old and 83-year-old tamarack.

The study tree was entirely jw up to the age of 26. Thus the production of mw did not occur until the 27th growth year. Once the study tree began producing mw, the percentage of jw decreased considerably with increasing age. In jack pine, Feng (2001) also found that the tree was entirely juvenile wood up to the age of 26.

Providing forest managers with the percentages of jw in trembling aspen at specific ages will allow them to estimate the amount of jw that would be harvested at certain rotational ages. Forest managers could then select rotational ages that result in desirable amounts of jw being harvested (Table 18).

Table 18. Percentages of juvenile wood volume in the study tree at five year intervals.

Tree Age (Yrs)	Juvenile Wood Volume (%)
5	100
10	100
15	100
20	100
25	100
30	96
35	93
40	89
45	76
50	63
55	42
60	31

RELATIONSHIP OF JUVENILE WOOD PERCENTAGES

The relationship between jw percentage of stem wood volume and jw percentage of basal area was curvilinear from the base of the tree up to approximately 5.3 m and then was linear at the remaining heights (Figure 25). Feng (2001) reported a linear relationship between the jw percentage of stem wood volume and jw percentage of basal area at a height of 1.4 m in a jack pine.

Since it is known that a relationship exists between the jw percentages future studies may focus on the development of a model to predict the percentage of jw in the stem based on a larger data set. The model could then be used to predict the percentages of jw in tree stems based on the percentage of basal area that is jw, measured from increment cores. The model should likely be developed from data collected at 0.15 m or 1.3 m, or at any other height easily reached from the ground.

RELATIONSHIP OF INTERVAL AGE AT PITH & JUVENILE WOOD ZONE WIDTH

The relationship between interval age at the pith and width of the jw zone expressed as distance from the pith can be considered as consisting of two linear segments divided at an interval age of the pith of 28 or at 9.3 m. The linear segment from interval age of the pith of 5 to 28 (1.3 m to 9.3 m) was slightly positive, while the second linear segment from interval age of the pith of 28 to 49 (9.3 m to 17.3 m) was strongly negative. This relationship corresponds with the relatively constant jw zone width from 1.3 m to 9.3 m, and a steadily decreasing jw zone width from 9.3 m to 17.3 m. Yang *et al.* (1986) report that a curvilinear relationship occurred between the age of the cambial initials at the pith and width of the jw zone expressed as distance from the pith in a dominant and suppressed tamarack. In a jack pine, Feng (2001) found a strong negative linear relationship between these two variables.

Despite the significant correlation coefficient (r = -0.8261) obtained when the width of the jw zone was expressed as distance from the pith, a linear trend did not adequately represent the relationship. However, a linear trend did adequately represent the relationship when the width of the jw zone was expressed as number of rings and the correlation coefficient was significant.

Interval age at the pith and width of the jw zone expressed as number of rings had a strong negative linear relationship (r = -0.9674). This relationship corresponds with the relatively constant decreases in the width of the jw zone form 1.3 m to 17.3 m, when expressed as number of rings as seen in Figure 22. This strong negative relationship was also found in a dominant and a suppressed tree of tamarack (Yang *et al.* 1986) and in jack pine (Feng 2001).

Based on the relationship of a decreasing jw zone width with height and an increasing tree age at the time of pith development with height, Yang *et al.* (1986) has suggested that there is an aging effect on the meristematic tissue resulting in 'older' cambial initials at the pith with increasing height. Yang *et al.* (1986) then attributes the production of fewer rings of jw, with height, to the 'older' age of the cambial initials. The results of this study due support the Yang *et al.* (1986) concept. However, since this study was not designed to evaluate the other concepts that attempt to elucidate the mechanisms that cause the transition of jw to mw they can not be discounted.

CONCLUSION

The radial variation of fiber and vessel length can be characterized as initially increasing rapidly from the pith outwards in the jw zone, followed by a transitional zone in which the rate of cell length increase was reduced, and then a mw zone in which the variation was not consistent amongst the heights. The shortest mean cell lengths occurred at the very top of the stem. For both cell types, the jw zone had significantly shorter mean cell lengths than the mw zone in both aspects, when comparing means from the same height. For both cell types and in both wood zones, neither aspect had a consistently longer mean cell length. The significance of differences in mean cell length among heights depended upon the heights being compared.

Cell length increase rates were found to be lower in the middle of the stem and higher at the top and bottom of the stem. The rate of cell length increase corresponded to the width of the jw zone. The increase rate for both vessels and fibers was similar.

The radial variation of relative density was highly variable amongst the heights but similar between aspects at the same height. The vertical variation of relative density was eccentric. At heights where there was a significant difference between zones, the mw zone had the significantly larger relative density. Neither aspect had a relative density that was consistently significantly larger at each height.

The modifications made to the Yang *et al.* (1986) demarcation method provided good results. The radial variation of vessel length was found to be a viable criterion for determining the juvenile-mature wood boundary.

The jw zone consisted of two shapes; a tapered cylindrical shape and a conical shape, when the boundary location was expressed as distance from the pith. When the boundary was expressed as number for rings, the jw zone also consisted of two shapes: conical shape and frustum of a cone. At age 62, the percentage of total stem wood volume that was jw was 28 percent. The study tree was entirely jw up to the age of 26.

A relationship was found to exist between the jw percentage of stem wood volume and jw percentage of basal area. Future studies could use this relationship to develop models predicting the jw stem wood percentages based on core samples.

There was a strong negative linear relationship between the interval age at the pith and the jw zone width expressed as number of rings. This suggests that there is an age effect on the cambial initials with height, causing a smaller jw zone.

Based on the results of this study, future investigators of wood properties, specifically those investigated in this study should be aware that the characteristics of wood properties vary depending on the location samples are collected from within a tree. Reporting of results should include noting the location samples are collected from in order to make valid comparisons.

Further investigations should increase the number of trees sampled. In order to keep the number of measurements to a manageable level, cell length measurements taken from the pith to the bark, could be taken at some interval, such as every fifth ring, that clearly illustrates the radial variation.

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APPENDICES

APPENDIX I

SAMPLE SIZE DETERMINATION FOR FIBER AND VESSEL LEGNTH MEASUREMENT

Cell Type	Initial Number Measured	Standard Deviation (S)	Mean ($\overline{X}$)	Allowable Error	Alpha Level (α)	Sample Size (N)
Fibers	20	0.1702	1.195	5.0 %	0.05	34
Vessels	20	0.1042	0.722	5.0 %	0.05	35

Sample size formula;

$$N = \frac{t^2_{\alpha/2,n-1} \times S^2}{E^2}$$

Where:

N = number of samples.
S = standard deviation.
E = allowable error of the mean. (E = mean x allowable error).
$t_{\alpha/2,\,n-1}$ = student t value (two-tailed) at desired alpha level and n-1 degrees of freedom.

Fiber sample size calculation:

Iteration	Degrees of freedom	t-value	Calculated N	Whole N
1	∞	1.960	31.191	32
2	31	2.040	33.789	34
3	33	2.035	33.624	34

Vessel sample size calculation:

Iteration	Degrees of freedom	t-value	Calculated N	Whole N
1	∞	1.960	31.935	32
2	31	2.040	34.595	35
3	34	2.032	34.324	35

APPENDIX II

VOLUME, RING RADIUS AND JUVENILE VOLUME PERCENTAGE

Species: Po
Total Height (m): 19.15
Stump Height (m): 0.15
Tip Length (m): 1.85

Part A: Bolt and Disc Information - Mean Aspects.

Disc No.	1	2	3	4	5	6	7	8	9	10	Tip
Bolt Length (m)*	0.15	1.15	2	2	2	2	2	2	2	2	1.85
Disc Height (m)	0.15	1.3	3.3	5.3	7.3	9.3	11.3	13.3	15.3	17.3	19.15
Ring Count	62	58	52	47	42	35	31	25	20	14	N/A

* at the top of each section

Part B: Radius Inside Bark (cm) - Mean Aspects.

	Height										
Age / Ring	0.15 m	1.3 m	3.3 m	5.3 m	7.3 m	9.3 m	11.3 m	13.3 m	15.3 m	17.3 m	Tip
62	18.53	13.76	12.93	11.63	10.37	9.58	9.61	6.36	3.32	1.04	
61	18.14	13.52	12.66	11.35	10.10	9.31	9.32	6.12	3.17	0.97	
60	17.66	13.20	12.39	11.04	9.84	9.07	9.06	5.91	3.00	0.92	
59	17.19	12.90	12.09	10.75	9.62	8.87	8.84	5.74	2.90	0.86	
58	16.68	12.58	11.78	10.43	9.36	8.63	8.56	5.53	2.77	0.80	
57	16.15	12.25	11.46	10.13	9.15	8.41	8.29	5.34	2.67	0.77	
56	15.60	11.99	11.22	9.88	8.93	8.19	8.01	5.12	2.49	0.69	
55	14.74	11.61	10.79	9.45	8.57	7.85	7.59	4.81	2.30	0.55	
54	13.89	11.22	10.38	9.04	8.23	7.48	7.18	4.48	2.05	0.46	
53	13.19	10.91	10.01	8.64	7.87	7.17	6.79	4.21	1.90	0.36	
52	12.52	10.42	9.60	8.18	7.47	6.85	6.45	3.95	1.75	0.29	
51	11.75	10.00	9.24	7.82	7.14	6.51	6.07	3.66	1.58	0.22	
50	11.02	9.53	8.88	7.42	6.74	6.16	5.72	3.38	1.42	0.17	
49	10.58	9.24	8.65	7.25	6.57	5.94	5.47	3.18	1.27	0.08	
48	10.20	9.03	8.46	7.05	6.41	5.77	5.25	3.03	1.17		
47	9.73	8.68	8.10	6.68	6.13	5.46	4.87	2.73	0.93		
46	9.39	8.39	7.80	6.41	5.87	5.17	4.53	2.47	0.75		
45	9.08	8.12	7.47	6.13	5.61	4.88	4.20	2.19	0.51		
44	8.76	7.92	7.25	5.91	5.41	4.65	3.89	1.94	0.30		
43	8.46	7.63	6.98	5.67	5.19	4.37	3.58	1.70	0.13		
42	8.06	7.32	6.70	5.40	4.94	4.08	3.27	1.46			
41	7.70	6.98	6.41	5.11	4.69	3.78	2.89	1.13			
40	7.36	6.70	6.14	4.83	4.42	3.49	2.57	0.82			
39	6.99	6.43	5.87	4.57	4.17	3.18	2.23	0.50			
38	6.65	6.23	5.72	4.33	3.94	2.95	1.99	0.26			
37	6.33	5.99	5.52	4.09	3.71	2.72	1.69				
36	6.06	5.72	5.25	3.82	3.37	2.43	1.40				
35	5.91	5.53	5.05	3.61	3.10	2.20	1.14				
34	5.77	5.35	4.88	3.40	2.85	1.94	0.91				
33	5.55	5.18	4.73	3.24	2.63	1.71	0.68				
32	5.31	5.00	4.56	3.05	2.36	1.48	0.41				
31	4.99	4.79	4.37	2.85	2.07	1.18					
30	4.81	4.58	4.17	2.62	1.72	0.81					
29	4.67	4.42	4.01	2.45	1.46	0.56					
28	4.50	4.23	3.86	2.27	1.17	0.24					
27	4.36	4.08	3.73	2.18	0.95						
26	4.21	3.89	3.57	2.04	0.72						
25	4.13	3.82	3.50	1.99	0.58						
24	4.00	3.75	3.44	1.93	0.49						
23	3.81	3.51	3.24	1.76	0.41						
22	3.60	3.28	3.05	1.57	0.32						
21	3.38	3.02	2.86	1.38	0.22						
20	3.19	2.81	2.68	1.16							
19	2.99	2.58	2.41	0.93							
18	2.87	2.44	2.19	0.69							
17	2.64	2.26	1.93	0.41							
16	2.50	2.13	1.76	0.23							
15	2.40	2.03	1.64								
14	2.31	1.95	1.52								
13	2.08	1.72	1.21								
12	1.91	1.48	0.84								
11	1.78	1.30	0.15								
10	1.70	1.18									
9	1.59	1.02									
8	1.38	0.83									
7	1.08	0.57									
6	0.88	0.44									
5	0.70	0.24									
4	0.56										
3	0.49										
2	0.36										
1	0.19										

Grey shaded area represents juvenile wood zone.

APPENDIX II

VOLUME, RING RADIUS AND JUVENILE VOLUME PERCENTAGE

Part C: Total Volume (dm^3) - Mean Aspects.

	Height											Total
Age / Ring	0.15 m	1.3 m	3.3 m	5.3 m	7.3 m	9.3 m	11.3 m	13.3 m	15.3 m	17.3 m	Tip	Vol. (dm^3)
62	16.18	96.23	111.96	94.97	76.29	62.63	57.85	41.71	16.16	3.80	0.21	578.00
61	15.50	92.40	107.70	90.77	72.48	59.23	54.46	39.04	14.94	3.46		549.98
60	14.70	87.81	102.93	86.46	68.69	56.26	51.63	36.75	13.79	3.09		522.12
59	13.92	83.39	98.12	82.17	65.33	53.73	49.21	34.86	12.98	2.87		496.58
58	13.11	78.85	93.31	77.75	61.65	50.89	46.40	32.62	12.03	2.62		469.25
57	12.29	74.22	88.40	73.50	58.54	48.50	43.77	30.54	11.20	2.42		443.38
56	11.47	69.91	84.67	70.20	55.69	46.11	41.20	28.36	10.17	2.09		419.88
55	10.24	63.60	78.92	64.60	51.11	42.42	37.42	25.37	8.94	1.75		384.38
54	9.09	57.59	73.37	59.48	46.91	38.81	33.73	22.48	7.63	1.39		350.47
53	8.19	52.89	68.84	54.94	42.94	35.60	30.60	20.04	6.70	1.18		321.91
52	7.39	47.93	63.06	49.95	38.50	32.25	27.79	17.94	5.85	0.98		291.64
51	6.50	42.98	58.21	45.98	35.19	29.30	24.86	15.78	5.00	0.80		264.60
50	5.72	38.32	53.28	42.05	31.58	26.17	22.16	13.86	4.23	0.64		238.01
49	5.27	35.64	50.33	40.02	30.06	24.62	20.45	12.57	3.69	0.51		223.16
48	4.90	33.51	48.07	38.10	28.50	23.33	19.09	11.53	3.31			210.35
47	4.46	30.71	44.26	34.61	25.81	21.16	16.82	9.80	2.62			190.25
46	4.15	28.63	41.23	32.03	23.73	19.20	14.83	8.36	2.09			174.25
45	3.89	26.80	38.24	29.33	21.69	17.38	13.01	7.03	1.58			158.95
44	3.62	25.19	36.22	27.50	20.18	15.97	11.53	5.94	1.21			147.36
43	3.37	23.42	33.57	25.41	18.55	14.44	10.02	4.94	0.91			134.62
42	3.06	21.40	30.94	23.26	16.82	12.88	8.57	4.02				120.94
41	2.79	19.50	28.19	21.12	15.12	11.39	7.11	3.03				108.25
40	2.55	17.88	25.91	19.15	13.45	9.94	5.89	2.29				97.07
39	2.30	16.29	23.81	17.37	12.00	8.63	4.74	1.64				86.80
38	2.08	14.99	22.43	16.15	10.75	7.60	3.97	1.26				79.25
37	1.89	13.70	20.81	14.82	9.58	6.64	3.22					70.65
36	1.73	12.52	18.92	13.23	8.13	5.41	2.47					62.41
35	1.65	11.82	17.60	12.10	7.11	4.54	1.93					56.74
34	1.57	11.18	16.47	11.10	6.17	3.72	1.44					51.66
33	1.45	10.40	15.46	10.32	5.46	3.10	1.06					47.25
32	1.33	9.60	14.39	9.46	4.68	2.43	0.74					42.62
31	1.17	8.62	13.19	8.55	3.89	1.77						37.20
30	1.09	7.95	12.03	7.60	3.08	1.13						32.88
29	1.03	7.45	11.16	6.92	2.55	0.77						29.89
28	0.95	6.88	10.28	6.28	2.05	0.45						26.89
27	0.90	6.43	9.59	5.86	1.77							24.55
26	0.84	5.94	8.76	5.31	1.47							22.32
25	0.80	5.70	8.42	5.09	1.34							21.35
24	0.75	5.42	8.12	4.88	1.24							20.41
23	0.68	4.84	7.17	4.27	1.02							17.98
22	0.61	4.28	6.30	3.69	0.80							15.69
21	0.54	3.71	5.43	3.17	0.61							13.46
20	0.48	3.26	4.72	2.67								11.13
19	0.42	2.81	3.90	2.09								9.22
18	0.39	2.55	3.36	1.65								7.95
17	0.33	2.18	2.77	1.22								6.51
16	0.29	1.94	2.39	0.98								5.61
15	0.27	1.78	2.14									4.19
14	0.25	1.64	1.91									3.80
13	0.20	1.32	1.39									2.91
12	0.17	1.05	0.90									2.13
11	0.15	0.88	0.54									1.56
10	0.14	0.77										0.90
9	0.12	0.64										0.76
8	0.09	0.47										0.56
7	0.05	0.27										0.32
6	0.04	0.17										0.21
5	0.02	0.10										0.12
4	0.01											0.01
3	0.01											0.01
2	0.01											0.01
1	0.00											0.00

Grey shaded area represents juvenile wood zone.

APPENDIX II

VOLUME, RING RADIUS AND JUVENILE VOLUME PERCENTAGE

Part D: Juvenile Wood Volume (dm^3) - Mean Aspects.

	Height											Juvenile Total Vol. (dm^3)
Age / Ring	0.15 m	1.3 m	3.3 m	5.3 m	7.3 m	9.3 m	11.3 m	13.3 m	15.3 m	17.3 m	Tip	
62	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.68	1.83	0.21	161.69
61	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.68	1.77		161.42
60	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.68	1.73		161.37
59	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.68	1.67		161.32
58	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.68	1.62		161.27
57	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.68	1.60		161.25
56	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.68	1.54		161.18
55	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.68	1.75		161.40
54	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.26	1.39		160.62
53	0.84	10.37	25.90	23.86	23.84	28.96	26.17	14.03	5.02	1.18		160.17
52	0.84	10.37	25.90	23.86	23.84	27.61	24.87	14.03	4.78	0.98		157.09
51	0.84	10.37	25.90	23.86	23.84	26.18	23.49	14.03	5.00	0.80		154.31
50	0.84	10.37	25.90	23.86	23.84	24.78	22.16	13.86	4.23	0.64		150.49
49	0.84	10.37	25.90	23.86	23.84	23.93	20.45	12.57	3.69	0.51		145.96
48	0.84	10.37	25.90	23.86	23.84	23.33	19.09	11.53	3.31			142.08
47	0.84	10.37	25.90	23.86	22.77	21.16	16.82	9.80	2.62			134.15
46	0.84	10.37	25.90	23.86	21.80	19.20	14.83	8.36	2.09			127.25
45	0.84	10.37	25.90	23.86	20.87	17.38	13.01	7.03	1.58			120.84
44	0.84	10.37	25.90	23.86	20.18	15.97	11.53	5.94	1.21			115.81
43	0.84	10.37	25.90	22.95	18.55	14.44	10.02	4.94	0.91			108.91
42	0.84	10.37	25.90	21.95	16.82	12.88	8.57	4.02				101.35
41	0.84	10.37	25.90	21.12	15.12	11.39	7.11	3.03				94.87
40	0.84	10.37	24.80	19.15	13.45	9.94	5.89	2.29				86.74
39	0.84	10.37	23.81	17.37	12.00	8.63	4.74	1.64				79.41
38	0.84	9.96	22.43	16.15	10.75	7.60	3.97	1.26				72.97
37	0.84	9.48	20.81	14.82	9.58	6.64	3.22					65.39
36	0.84	8.97	18.92	13.23	8.13	5.41	2.47					57.96
35	0.84	8.61	17.60	12.10	7.11	4.54	1.93					52.72
34	0.84	8.29	16.47	11.10	6.17	3.72	1.44					48.03
33	0.84	7.99	15.46	10.32	5.46	3.10	1.06					44.23
32	0.84	7.68	14.39	9.46	4.68	2.43	0.74					40.21
31	0.84	7.32	13.19	8.55	3.89	1.77						35.55
30	0.84	6.97	12.03	7.60	3.08	1.13						31.65
29	0.84	6.72	11.16	6.92	2.55	0.77						28.96
28	0.84	6.43	10.28	6.28	2.05	0.45						26.32
27	0.84	6.20	9.59	5.86	1.77							24.25
26	0.84	5.94	8.76	5.31	1.47							22.32
25	0.80	5.70	8.42	5.09	1.34							21.35
24	0.75	5.42	8.12	4.88	1.24							20.41
23	0.68	4.84	7.17	4.27	1.02							17.98
22	0.61	4.28	6.30	3.69	0.80							15.69
21	0.54	3.71	5.43	3.17	0.61							13.46
20	0.48	3.26	4.72	2.67								11.13
19	0.42	2.81	3.90	2.09								9.22
18	0.39	2.55	3.36	1.65								7.95
17	0.33	2.18	2.77	1.22								6.51
16	0.29	1.94	2.39	0.98								5.61
15	0.27	1.78	2.14									4.19
14	0.25	1.64	1.91									3.80
13	0.20	1.32	1.39									2.91
12	0.17	1.05	0.90									2.13
11	0.15	0.88	0.54									1.56
10	0.14	0.77										0.90
9	0.12	0.64										0.76
8	0.09	0.47										0.56
7	0.05	0.27										0.32
6	0.04	0.17										0.21
5	0.02	0.10										0.12
4	0.01											0.01
3	0.01											0.01
2	0.01											0.01
1	0.00											0.00

Grey shaded areas represents juvenile wood zone.

APPENDIX II

VOLUME, RING RADIUS AND JUVENILE VOLUME PERCENTAGE

Part E: Juvenile, Mature and Total Stem Volume and Percentage of Juvenile Wood - Mean Aspects.

	Wood Volume (dm^3)			Juvenile Wood
Age / Ring	Juvenile	Mature	Total	Percentage
62	161.69	416.31	578.00	27.97%
61	161.42	388.56	549.98	29.35%
60	161.37	360.75	522.12	30.91%
59	161.32	335.26	496.58	32.49%
58	161.27	307.98	469.25	34.37%
57	161.25	282.14	443.38	36.37%
56	161.18	258.70	419.88	38.39%
55	161.40	222.98	384.38	41.99%
54	160.62	189.85	350.47	45.83%
53	160.17	161.74	321.91	49.76%
52	157.09	134.55	291.64	53.86%
51	154.31	110.28	264.60	58.32%
50	150.49	87.53	238.01	63.23%
49	145.96	77.20	223.16	65.41%
48	142.08	68.27	210.35	67.54%
47	134.15	56.11	190.25	70.51%
46	127.25	47.00	174.25	73.03%
45	120.84	38.11	158.95	76.02%
44	115.81	31.55	147.36	78.59%
43	108.91	25.71	134.62	80.90%
42	101.35	19.59	120.94	83.80%
41	94.87	13.38	108.25	87.64%
40	86.74	10.33	97.07	89.36%
39	79.41	7.39	86.80	91.49%
38	72.97	6.28	79.25	92.08%
37	65.39	5.26	70.65	92.55%
36	57.96	4.45	62.41	92.87%
35	52.72	4.02	56.74	92.91%
34	48.03	3.62	51.66	92.98%
33	44.23	3.02	47.25	93.60%
32	40.21	2.41	42.62	94.34%
31	35.55	1.64	37.20	95.58%
30	31.65	1.23	32.88	96.26%
29	28.96	0.92	29.89	96.91%
28	26.32	0.58	26.89	97.86%
27	24.25	0.29	24.55	98.80%
26	22.32	0.00	22.32	100.00%
25	21.35	0.00	21.35	100.00%
24	20.41	0.00	20.41	100.00%
23	17.98	0.00	17.98	100.00%
22	15.69	0.00	15.69	100.00%
21	13.46	0.00	13.46	100.00%
20	11.13	0.00	11.13	100.00%
19	9.22	0.00	9.22	100.00%
18	7.95	0.00	7.95	100.00%
17	6.51	0.00	6.51	100.00%
16	5.61	0.00	5.61	100.00%
15	4.19	0.00	4.19	100.00%
14	3.80	0.00	3.80	100.00%
13	2.91	0.00	2.91	100.00%
12	2.13	0.00	2.13	100.00%
11	1.56	0.00	1.56	100.00%
10	0.90	0.00	0.90	100.00%
9	0.76	0.00	0.76	100.00%
8	0.56	0.00	0.56	100.00%
7	0.32	0.00	0.32	100.00%
6	0.21	0.00	0.21	100.00%
5	0.12	0.00	0.12	100.00%
4	0.01	0.00	0.01	100.00%
3	0.01	0.00	0.01	100.00%
2	0.01	0.00	0.01	100.00%
1	0.00	0.00	0.00	100.00%

APPENDIX III

JUVENILE WOOD BASAL AREA PERCENTAGES

	Percentages of Juvenile Wood										
	Basal Area (%) - Mean of Aspects										Volume
Age / Ring	0.15 m	1.3 m	3.3 m	5.3 m	7.3 m	9.3 m	11.3 m	13.3 m	15.3 m	17.3 m	(%)
62	5.16	21.84	24.60	25.85	38.13	55.94	35.37	33.17	47.88	100.00	27.97
61	5.39	22.64	25.66	27.15	40.24	59.29	37.64	35.75	52.49	100.00	29.35
60	5.68	23.73	26.79	28.69	42.37	62.40	39.79	38.42	58.64	100.00	30.91
59	6.00	24.86	28.13	30.26	44.38	65.32	41.84	40.73	62.86	100.00	32.49
58	6.37	26.13	29.61	32.15	46.88	68.93	44.60	43.79	68.67	100.00	34.37
57	6.80	27.55	31.29	34.07	49.00	72.67	47.55	46.99	74.19	100.00	36.37
56	7.28	28.78	32.64	35.83	51.47	76.54	50.97	51.16	85.51	100.00	38.39
55	8.16	30.67	35.29	39.19	55.82	83.42	56.73	57.83	100.00	100.00	41.99
54	9.19	32.84	38.17	42.80	60.64	91.88	63.44	66.78	100.00	100.00	45.83
53	10.20	34.77	41.01	46.80	66.19	100.00	70.89	75.70	100.00	100.00	49.76
52	11.31	38.08	44.58	52.31	73.62	100.00	78.63	86.11	100.00	100.00	53.86
51	12.85	41.34	48.18	57.24	80.53	100.00	88.72	100.00	100.00	100.00	58.32
50	14.61	45.52	52.17	63.45	90.31	100.00	100.00	100.00	100.00	100.00	63.23
49	15.83	48.43	54.91	66.51	95.11	100.00	100.00	100.00	100.00	100.00	65.41
48	17.04	50.76	57.41	70.33	100.00	100.00	100.00	100.00	100.00		67.54
47	18.72	54.88	62.70	78.34	100.00	100.00	100.00	100.00	100.00		70.51
46	20.12	58.74	67.53	85.01	100.00	100.00	100.00	100.00	100.00		73.03
45	21.50	62.71	73.63	93.11	100.00	100.00	100.00	100.00	100.00		76.02
44	23.10	65.91	78.17	100.00	100.00	100.00	100.00	100.00	100.00		78.59
43	24.79	71.11	84.33	100.00	100.00	100.00	100.00	100.00	100.00		80.90
42	27.32	77.16	91.53	100.00	100.00	100.00	100.00	100.00			83.80
41	29.89	84.98	100.00	100.00	100.00	100.00	100.00	100.00			87.64
40	32.72	92.24	100.00	100.00	100.00	100.00	100.00	100.00			89.36
39	36.28	100.00	100.00	100.00	100.00	100.00	100.00	100.00			91.49
38	40.08	100.00	100.00	100.00	100.00	100.00	100.00	100.00			92.08
37	44.30	100.00	100.00	100.00	100.00	100.00	100.00				92.55
36	48.34	100.00	100.00	100.00	100.00	100.00	100.00				92.87
35	50.74	100.00	100.00	100.00	100.00	100.00	100.00				92.91
34	53.24	100.00	100.00	100.00	100.00	100.00	100.00				92.98
33	57.64	100.00	100.00	100.00	100.00	100.00	100.00				93.60
32	62.98	100.00	100.00	100.00	100.00	100.00	100.00				94.34
31	71.32	100.00	100.00	100.00	100.00	100.00					95.58
30	76.77	100.00	100.00	100.00	100.00	100.00					96.26
29	81.44	100.00	100.00	100.00	100.00	100.00					96.91
28	87.53	100.00	100.00	100.00	100.00	100.00					97.86
27	93.24	100.00	100.00	100.00	100.00						98.80
26	100.00	100.00	100.00	100.00	100.00						100.00
25	100.00	100.00	100.00	100.00	100.00						100.00
24	100.00	100.00	100.00	100.00	100.00						100.00
23	100.00	100.00	100.00	100.00	100.00						100.00
22	100.00	100.00	100.00	100.00	100.00						100.00
21	100.00	100.00	100.00	100.00	100.00						100.00
20	100.00	100.00	100.00	100.00							100.00
19	100.00	100.00	100.00	100.00							100.00
18	100.00	100.00	100.00	100.00							100.00
17	100.00	100.00	100.00	100.00							100.00
16	100.00	100.00	100.00	100.00							100.00
15	100.00	100.00	100.00								100.00
14	100.00	100.00	100.00								100.00
13	100.00	100.00	100.00								100.00
12	100.00	100.00	100.00								100.00
11	100.00	100.00	100.00								100.00
10	100.00	100.00									100.00
9	100.00	100.00									100.00
8	100.00	100.00									100.00
7	100.00	100.00									100.00
6	100.00	100.00									100.00
5	100.00	100.00									100.00
4	100.00										100.00
3	100.00										100.00
2	100.00										100.00
1	100.00										100.00

Grey shaded area represents juvenile wood zone.

APPENDIX III

JUVENILE WOOD BASAL AREA PERCENTAGES

	Percentages of Juvenile Wood										
	Basal Area (%) - Mean of Aspects										Volume (%)
Age / Ring	0.15 m	1.3 m	3.3 m	5.3 m	7.3 m	9.3 m	11.3 m	13.3 m	15.3 m	17.3 m	
62	5.16	21.84	24.60	25.85	38.13	55.94	35.37	33.17	47.88	100.00	27.97
61	5.39	22.64	25.66	27.15	40.24	59.29	37.64	35.75	52.49	100.00	29.35
60	5.68	23.73	26.79	28.69	42.37	62.40	39.79	38.42	58.64	100.00	30.91
59	6.00	24.86	28.13	30.26	44.38	65.32	41.84	40.73	62.86	100.00	32.49
58	6.37	26.13	29.61	32.15	46.88	68.93	44.60	43.79	68.67	100.00	34.37
57	6.80	27.55	31.29	34.07	49.00	72.67	47.55	46.99	74.19	100.00	36.37
56	7.28	28.78	32.64	35.83	51.47	76.54	50.97	51.16	85.51	100.00	38.39
55	8.16	30.67	35.29	39.19	55.82	83.42	56.73	57.83	100.00	100.00	41.99
54	9.19	32.84	38.17	42.80	60.64	91.88	63.44	66.78	100.00	100.00	45.83
53	10.20	34.77	41.01	46.80	66.19	100.00	70.89	75.70	100.00	100.00	49.76
52	11.31	38.08	44.58	52.31	73.62	100.00	78.63	86.11	100.00	100.00	53.86
51	12.85	41.34	48.18	57.24	80.53	100.00	88.72	100.00	100.00	100.00	58.32
50	14.61	45.52	52.17	63.45	90.31	100.00	100.00	100.00	100.00	100.00	63.23
49	15.83	48.43	54.91	66.51	95.11	100.00	100.00	100.00	100.00	100.00	65.41
48	17.04	50.76	57.41	70.33	100.00	100.00	100.00	100.00	100.00		67.54
47	18.72	54.88	62.70	78.34	100.00	100.00	100.00	100.00	100.00		70.51
46	20.12	58.74	67.53	85.01	100.00	100.00	100.00	100.00	100.00		73.03
45	21.50	62.71	73.63	93.11	100.00	100.00	100.00	100.00	100.00		76.02
44	23.10	65.91	78.17	100.00	100.00	100.00	100.00	100.00	100.00		78.59
43	24.79	71.11	84.33	100.00	100.00	100.00	100.00	100.00	100.00		80.90
42	27.32	77.16	91.53	100.00	100.00	100.00	100.00	100.00			83.80
41	29.89	84.98	100.00	100.00	100.00	100.00	100.00	100.00			87.64
40	32.72	92.24	100.00	100.00	100.00	100.00	100.00	100.00			89.36
39	36.28	100.00	100.00	100.00	100.00	100.00	100.00	100.00			91.49
38	40.08	100.00	100.00	100.00	100.00	100.00	100.00	100.00			92.08
37	44.30	100.00	100.00	100.00	100.00	100.00	100.00				92.55
36	48.34	100.00	100.00	100.00	100.00	100.00	100.00				92.87
35	50.74	100.00	100.00	100.00	100.00	100.00	100.00				92.91
34	53.24	100.00	100.00	100.00	100.00	100.00	100.00				92.98
33	57.64	100.00	100.00	100.00	100.00	100.00	100.00				93.60
32	62.98	100.00	100.00	100.00	100.00	100.00	100.00				94.34
31	71.32	100.00	100.00	100.00	100.00	100.00					95.58
30	76.77	100.00	100.00	100.00	100.00	100.00					96.26
29	81.44	100.00	100.00	100.00	100.00	100.00					96.91
28	87.53	100.00	100.00	100.00	100.00	100.00					97.86
27	93.24	100.00	100.00	100.00	100.00						98.80
26	100.00	100.00	100.00	100.00	100.00						100.00
25	100.00	100.00	100.00	100.00	100.00						100.00
24	100.00	100.00	100.00	100.00	100.00						100.00
23	100.00	100.00	100.00	100.00	100.00						100.00
22	100.00	100.00	100.00	100.00	100.00						100.00
21	100.00	100.00	100.00	100.00	100.00						100.00
20	100.00	100.00	100.00	100.00							100.00
19	100.00	100.00	100.00	100.00							100.00
18	100.00	100.00	100.00	100.00							100.00
17	100.00	100.00	100.00	100.00							100.00
16	100.00	100.00	100.00	100.00							100.00
15	100.00	100.00	100.00								100.00
14	100.00	100.00	100.00								100.00
13	100.00	100.00	100.00								100.00
12	100.00	100.00	100.00								100.00
11	100.00	100.00	100.00								100.00
10	100.00	100.00									100.00
9	100.00	100.00									100.00
8	100.00	100.00									100.00
7	100.00	100.00									100.00
6	100.00	100.00									100.00
5	100.00	100.00									100.00
4	100.00										100.00
3	100.00										100.00
2	100.00										100.00
1	100.00										100.00

Grey shaded area represents juvenile wood zone.