VARIATION OF WOOD PROPERTIES IN A SINGLE STEM OF JACK PINE (*Pinus banksiana* Lamb.)

by

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ABSTRACT

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Keywords: tracheid length, relative density, ring width, radial and tangential shrinkage, juvenile and mature wood, juvenile and mature wood volume.

Radial and axial variation of tracheid length, relative density, ring width, radial and tangential shrinkage, and juvenile and mature wood volume were studied in a single stem of jack pine, 37 km north of Thunder Bay. The tree was 60-year-old and was from a naturally grown stand in the Jack Haggerty Forest of Lakehead University, Thunder Bay, Ontario. Specimens were taken from the tree stem at heights of 0.15, 1.4, 3.4, 5.4, 7.4, 9.4, 11.4, 13.4, 15.4 m along west and east aspect. Juvenile and mature wood boundary was demarcated by using the radial variation pattern of tracheid length as the criterion.

Tracheid length increased from pith outward in the juvenile wood, reaching a maximum, then remained constant or leveled off towards the bark in the mature wood. The rate of increase in tracheid length with ring age increased with increasing height with an exception at 13.4 m. The mean tracheid length in the juvenile and mature wood increased from the base upward, reaching a maximum at 3.4 m and 5.4 m for the juvenile and mature wood, respectively, followed by a decrease further to the top. Relative density decreased from the pith outward with ring age in the juvenile wood and remained less variable in the mature wood, with an exception at 0.15 m. Relative density decreased with increasing height with an exception at 13.4 m in both juvenile and mature wood. Ring width increased with ring age from the pith outward in the juvenile wood and fluctuated in the mature wood. Ring width decreased with increasing height in the juvenile wood. No axial trend for ring width variation in the mature wood was found. Tangential shrinkage was greater than radial shrinkage. The mean tracheid length of the west aspect was significantly different from that of the east aspect. Relative density of both juvenile and mature wood in the east aspect was significantly higher than that in the west aspect. Ring width in the west aspect was significantly wider than that in the east aspect for mature wood. For both tracheid length and ring width, there was no difference between west and east aspects in the juvenile wood. Radial, tangential shrinkage (overall and the two outermost wood strips) increased from pith outward to the bark, reaching a maximum then followed by a leveling off. Radial, tangential shrinkage (overall and the two outermost wood strips) decreased with increasing height with an exception at 0.15 m. The percentage of juvenile wood accounted for 16% and 30%, respectively, of the entire stem volume based on ring age and stem diameter as criteria. The juvenile wood zone was conical in shape. There was a strong negative correlation between juvenile wood width and cambial initial age. The values for percentage of juvenile wood volume at breast height can be used to predict the entire stem value.

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INTRODUCTION

Wood is a product of the metabolic activity of cambium in a living tree (Panshin and de Zeeuw 1980) and a product of forestry operations (Zobel and van Buijtenen 1989). The wood produced by a living tree varies both radially (across the radius of the bole) and longitudinally (along the tree height). Moreover, the wood properties vary with different geographic location, seed source, species and other environmental factors. Such variation should be fully understood if we want to successfully convert wood into end products and use wood efficiently. The knowledge about variation of wood properties will also benefit the tree grower, the breeder, and the harvester for regeneration and wood quality improvement.

The greatest cause of wood variation among conifers is the presence of juvenile wood and its relative proportions to mature wood (Zobel and van Buijtenen 1989). Forest plantations and intensively managed stands represent an ever-increasing portion of the wood needed to supply the world's expanding human population. However, the short rotations and rapid tree growth associated with plantations increase the percentage of juvenile wood in harvested timber. Properties of juvenile wood are undesirable for some end products compared to that of mature wood. For example, in the juvenile wood, cells are shorter and cell walls are thinner, resulting in a lower relative density of wood; the micorfibril angels are flatter, resulting in greater longitudinal shrinkage of boards (Zobel and Spargue 1998). Forest management can be used to influence the proportion of juvenile wood by selection of the growth regime for the tree (Panshin and de Zeeuw

1980; Yang 1994; Zobel and Sprague 1998). However, before the forester modifies existing practices, research is needed to increase the fundamental knowledge on the juvenile wood properties, and its impacts on other wood properties.

Jack pine (*Pinus banksiana* Lamb.) is a common species found in the Boreal Forest and currently represents more than one-third of the total volume of softwood timber in Ontario (Ontario Ministry of Natural Resources 1997). The wood of jack pine has a coarse texture and is generally resinous and knotty, light in weight, and low in strength, resistance and stiffness compared to other pines. The wood of jack pine is used for pulpwood, poles, lumber posts and mine timbers (Panshin and de Zeeuw 1980). Jack pine is a very important species for forest utilization. However, the variation of wood properties in the stem of jack pine has not been studied adequately to date.

In this study, a single jack pine stem was studied with the following objectives: 1) to demarcate juvenile/mature wood boundary; 2) to investigate the variation of tracheid length, relative density and ring width, with respect to ring age, height and aspect; 3) to investigate the variation of radial and tangential shrinkage; 4) to find out the vertical distribution of juvenile wood and the percentage of juvenile wood.

LITERATURE REVIEW

TRACHEID LENGTH

It is generally accepted that most coniferous species have a general pattern of radial variation (Panshin and de Zeuuw 1980). According to Panshin and de Zeeuw (1980), tracheid length is very short near the pith, and thereafter, tracheid length follows one of the following patterns (Figure 1):

(1) Tracheid length increases rapidly from the pith outward in the juvenile wood until a maximum is reached at a certain range of ring age. After that, tracheid length remains constant in the mature wood (Dadswell 1958; Schmidt and Smith 1961; Zobel and Blair 1976; Barrichelo and Brito 1979).

(2) Tracheid length shows a rapid increase in the juvenile wood followed by continuously slow increase in the mature wood (Elliott 1960; Panshin and de Zeuuw 1980; Plumotre 1983; Zobel *et al.* 1983).

(3) Tracheid length shows a rapid increase in the juvenile wood until a maximum is reached at a certain range of ring age. After that, tracheid length showed a leveling off in the mature wood (Panshin and de Zeuuw 1980; Megraw 1985).

Tracheid length is primarily affected by the cambial initial length from which it developed (Schmidt and Smith 1961; Panshin and de Zeuuw 1980; Megraw 1985). The cambial initials divide periclinally in the tangential-longitudinal plane and anticlinally in the radial plane. Bannan (1967) emphasized that it was the cambial initials which

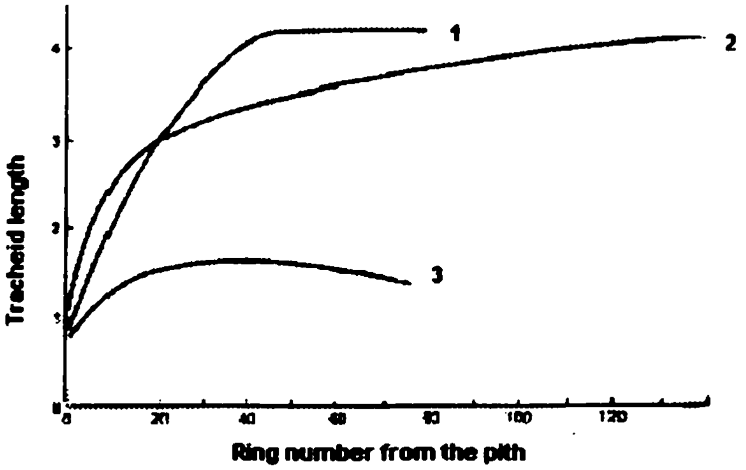


Figure 1. Typical curves for tracheid length variation from pith to bark (Revised from Panshin and de Zeeuw, 1980).

controlled tracheid length variation, that is, very short near the pith with rapid increase outward followed by a leveling off. According to Megraw (1985), the rate of anticlinal division has a major effect on the variation of tracheid length in *Pinus taeda* L. The author stated "when tree growth is rapid, a greater frequency and survival rate of cambial anticlinal division is required to keep up with girth expansion. ... This tends to reduce average fiber length during periods of rapid growth."

According to tracheid length variation, the cross section of the stem can be divided into two zones from the pith outward: (1) juvenile wood or core wood zone where rapid increase in tracheid length occurs; (2) mature wood or adult wood where tracheid length is relatively constant (Rendle 1959a). Wheeler *et al.* (1966) further emphasized that these two types of woods must be recognized and taken into consideration when any variation studies are conducted within and between trees.

Regression analysis of tracheid length over ring age was used to demarcate the juvenile and mature wood boundary by Yang *et al.* (1986) in *Larix laricina* (DuRoi) K. Koch. Bendtsen and Senft (1986) used a more usual method by examining graphic plots of tracheid length over rings from pith to bark in *Pinus taeda* L. Also a logarithmic formula was reported by Shiokura (1982) to describe the radial variation of tracheid length with ring number in coniferous trees.

Longitudinally from the stump upwards, the tracheid length tends to increase with increasing height up to a maximum, thereafter the tracheid length decreases with further increasing height (Panshin and de Zeuuw 1980). The same trend was described by Kribs (1928) for *Pinus banksiana* Lamb., by Wheeler *et al.* (1966) for *Pinus taeda* L., and by Megraw (1985) for *Pinus taeda* L. Another trend in axial variation of tracheid length is that tracheid length shows a constant decrease in the upward direction (Webb 1964). However, Wang and Micko (1984) found that the tracheid length at the top of the tree was longer than from the lower heights in *Picea glauca* (Moench) Voss. Moreover, Taylor (1973) showed no trend of tracheid length with stem height at all in hardwood of *Eucalyptus grandis* Hill ex Maiden. The variation of the proportion of juvenile wood from the base to the top of the tree is assumed to be the reason for the variation in tracheid length along the tree trunk by Zobel (1975a).

RELATIVE DENSITY

Relative density of wood is the ratio of the dry weight of wood substance based on green volume to the weight of an equal volume of water. It indicates the amount of actual substance in a unit volume of wood on the green volume base (Zobel and Jett

1995). Wood density is defined as the ratio of the dry weight of wood to its volume and is normally expressed as grams per cubic centimeter ($g \cdot cm^{-3}$) based on the green volume. Using the metric system, wood density and relative density are easily converted. Because of the numerous efforts investigating wood density and relative density, its variation can be well understood. It is affected by the cell wall thickness, the cell diameter, and the earlywood to latewood ratio (Panshin and de Zeeuw 1980).

Relative density within a tree varies from pith to bark and with height in the stem. Variation of relative density from pith to bark can be categorized into three groups (Panshin and de Zeeuw 1980):

(1) Relative density increases from pith outward, then remains constant in the mature wood (Cooper 1960; Gilmore and Pearson 1969; Barrichelo and Brito 1979; Bunn 1981; Roody 1983; Kellison *et al.* 1983; Megraw 1985).

(2) Relative density decreases from pith outward, then increases toward the bark (Tajima 1967; Olesen 1977; Kromhout and Toon 1978; Falkenhagen 1979; Lewark 1979).

(3) Relative density decreases linearly or curvilinearly from the pith to bark (Krahmer 1966; Taylor and Wooten 1973).

Low relative density near the pith followed by a density increase from pith to bark is the predominant variation in relative density for about two-third of the softwood and hardwood species (Panshin and de Zeeuw 1980). Relative density near the pith is low because there are relatively few latewood cells and a high proportion of cells have thin cell wall layers (Haygreen and Bowyer 1996). Some species exhibit greater density variation than others. For example, in *Picea sitchensis* (Bong.) Carr., relative density is very high in the innermost rings and then decreases from the pith outward until a minimum is reached about ring 8 to 12, after which it increases gradually towards the bark (Harvald and Olesen 1987). This is in agreement with Petty *et al.* (1990) who also found relative density in *Picea sitchensis* (Bong.) Carr. to be relatively high near the pith, falling to a minimum further out and then gradually increasing with distance from the pith. This trend in relative density variation was also found for *Pinus caribaea* Dougl. by Kromhout and Toon (1978), for *Pinus caribaea* Dougl. by Falkenhagen (1979). High relative density near the pith in *Pinus banksiana* Lamb. was not found in the literature.

In a study done by Harvald and Olesen (1987) on the variation of relative density within the juvenile wood of *Picea sitchensis* (Bong.) Carr., it was found that relative density decreased with increasing height in the stem. Megraw (1985) found that wood relative density was slightly greater at breast height than higher up in *Pinus taeda* L. Donaldson *et al.* (1995) also reported a similar pattern in *Pinus radiata* D. Don. grown in New Zealand. However, in contrast, Ward (1975) found that for *Picea sitchensis* (Bong.) Carr., relative density does not markedly decrease with height in the stem, but rather increases with increasing height.

Compression wood in conifers has an indistinct and sharp latewood band and is deeper in color than normal wood (Panshin and de Zeeuw 1980). Compression wood has different microscopic structures from normal wood, *e.g.*, short tracheid, round shape cell, flat fibril angel, and thick cell wall. Compression wood tends to have a higher relative density than normal wood due to its thicker cell wall (Panshin and de Zeeuw 1980; Haygreen and Bowyer 1996).

RING WIDTH

Ring width or growth rate is often used as the most important criterion for tree selection in tree improvement programs. Radially, ring width decreases from the pith outward to the bark. This decreasing trend reaches a minimum at a certain age and then levels off and fluctuates with environmental conditions. Axially, ring width increases with increasing height.

Seth and Agrawal (1984) found that the ring width increased at the pith and then slowly decreased to the bark in *Pinus wallichiana* A.B. Jackson. Taras (1965) and Perng (1983) stated that ring width decreased from pith to bark with fluctuation in the mature wood of *Pinus elliottii* Engelm. and *Picea rubens* Sarg., respectively. Kozlowski (1971) reported an axial pattern of ring width variation as ring width narrowed down with decreasing height. Larson (1969) emphasized that environmental factors such as climate changes and thinning led to fluctuation of ring width. Ring width can also be increased by thinning in southern pine as reported by Martin (1984). Fast-grown plantation trees tend to have wider rings than trees grown in a natural location (Bendtsen 1978; Zobel 1981; Zobel 1984; Megraw 1985). Though much research has been done about ring width variation, reports on variation of ring width in jack pine are scarce.

SHRINKAGE

Wood is subject to dimensional changes when its moisture fluctuates below the fiber saturation point. The amount of shrinkage is generally proportional to the amount of water removed from the cell wall below the fiber saturation point. Dimensional changes caused by shrinkage are anisotropic: *i.e.*, different in axial, radial, and tangential directions. Axial shrinkage of wood can be negligible: *i.e.*, 0.3% in practice. For jack pine, mean values for radial and tangential shrinkage are roughly 3.7% and 6.6%, respectively (Forest Products Laboratory 1999). These values refer to changes from green to oven-dry conditions and are expressed in percentage of green dimensions.

Shrinkage of wood is affected by a number of factors, such as relative density, the size and shape of the measured wood, and the anatomic structure of the wood (Siau 1984; Skaar 1988, Desch and Dinwoodie 1996). Radial and tangential shrinkage variations are reported by Yao (1969) in *Pinus taeda L.*, Wilcox and Pong (1971) in *Abies balsamia* (L.) Mill., Choong and Foggy (1989) in *Pinus echinata* Mill., and Koubaa *et al.* (1998) in *Populus x euramericana* (Dode) Guinier. They all found (1) radial and tangential shrinkage increased from the pith outward followed by a leveling off near the bark; and (2) radial and tangential shrinkage tended to decrease with increasing height. There is lack of information in regard to shrinkage variation in jack pine.

VOLUME OF JUVENILE WOOD

Zobel *et al.* (1959) defined juvenile wood as wood formed near the tree center. Juvenile wood is sometimes referred to as core wood because it is produced near the pith during the early period of tree growth (Yang 1986). Generally, the period of juvenile wood varies from 5 to 20-year-of-age (Panshin and de Zeeuw 1980). Corson (1991) reported juvenile wood was the first 15 annual growth rings from the pith in *Pinus* *radiata* D. Don., while Cown (1992) defined it within 10 rings for the same species. In fact, there is no clear demarcation between juvenile and mature wood. The term "transition zone" always refers to the region between the two types of woods. This means no distinct line can be drawn where juvenile wood ends and where mature wood begins. However, relative density, tracheid length, growth rate and cell diameter can be used as criteria for defining the juvenile wood zone. While using these as criteria, different results may be obtained (Yang *et al.* 1994).

Juvenile wood has an important impact on wood properties. According to Zobel and Sprague (1998), the "juvenile wood zone is the area of rapid change in properties near the pith; mature wood is more uniform towards the bark." Compared with mature wood, juvenile wood has shorter tracheid length, smaller cell diameter, larger microfibrillar angels, and low relative density which lead to poor physical properties and mechanical strength, and different chemical properties in the end products. Because of the "undesirable" properties of juvenile wood, the percentage of juvenile wood in a whole tree is a concern for many researchers due to its impact on wood strength and wood product qualities (Pansin and de Zueew 1980; Yang 1994; Zobel and Sprague 1998).

The proportion of juvenile wood is related to tree age. Zobel and Blair (1976) have demonstrated that juvenile wood volume in plantation loblolly pine (*Pinus taeda* L.) at 15, 25 and 40-year-of-age contain 85%, 55% and 19% of juvenile wood, respectively. Kellison (1981) stated that *Pinus taeda* L. contained 19% by volume of juvenile wood at age 45 and 85% at age 15. Senft (1986) found that a naturally grown 50-year-old Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) may be expected to contain about 16% juvenile wood, while a plantation grown tree of a similar size but younger age may be expected to contain about 55% juvenile wood. The percentage of juvenile wood is largely dependent on species and environmental conditions (Yang 1986).

MATERIALS AND METHODS

SAMPLE COLLECTION AND PREPARATION

One jack pine tree was selected and felled at the Lakehead University Jack Haggerty Forest, Thunder Bay, Ontario. The tree was 60-year-old and in a naturally grown stand. Appendices I and II show the field data of the stand and diameter and number of growth rings at various heights of the tree, respectively. Figure 2 illustrates the sample collection in the field and preparation in the laboratory.

Nine pith-to-bark wood discs, 3 cm thick each, were sectioned from the tree stem at heights of 0.15, 1.4, 3.4, 5.4, 7.4, 9.4, 11.4, 13.4, and 15.4 m. The wood discs were cut into strips, 1.5 cm thick, in an east-west orientation.

The wood strips were used for ring width measurements and shrinkage studies. The shrinkage was studied first. After which the strips were made into further specimens for relative density, tracheid length and juvenile/mature wood boundary determination.

DETERMINATIONS AND MEASUREMENTS

Ring Width

The central wood strips of the disc that contained the pith-to-bark section were smoothed with a sander to expose the growth rings on cross-section. The cross-sections of each strip were placed on a photo copy machine (Konica 7033) according to their location in the stem and the images were copied. The image of growth ring was magnified 10 times and copied in order to measure the ring width easily. After the magnified copy of growth ring of each strip was measured and recorded, the actual width of each ring width was obtained by dividing 10.

Shrinkage

The central wood strips from each wood disc were used for radial shrinkage measurements. Others left were used for tangential shrinkage measurements. Each strip was immersed in water for seven days until saturated to represent the green condition. Two lines were drawn at each end of the strip and the distance between these two lines was measured and recorded as the distance of green condition.

These strips were dried in an oven at 100±3 °C for approximately 2 weeks until a constant weight was obtained. The distance of each strip as marked was then re-measured as the oven-dry distance of the strip. The shrinkage percentage of each strip from a green condition to an oven-dry condition was calculated using the following formula:

$$\text{Shrinkage \%} = \frac{Lm - Lo}{Lm} \times 100 \qquad \text{Equation (1)}$$

Where Lm = the green condition distance of the sample

Lo = the oven-dry distance of the sample

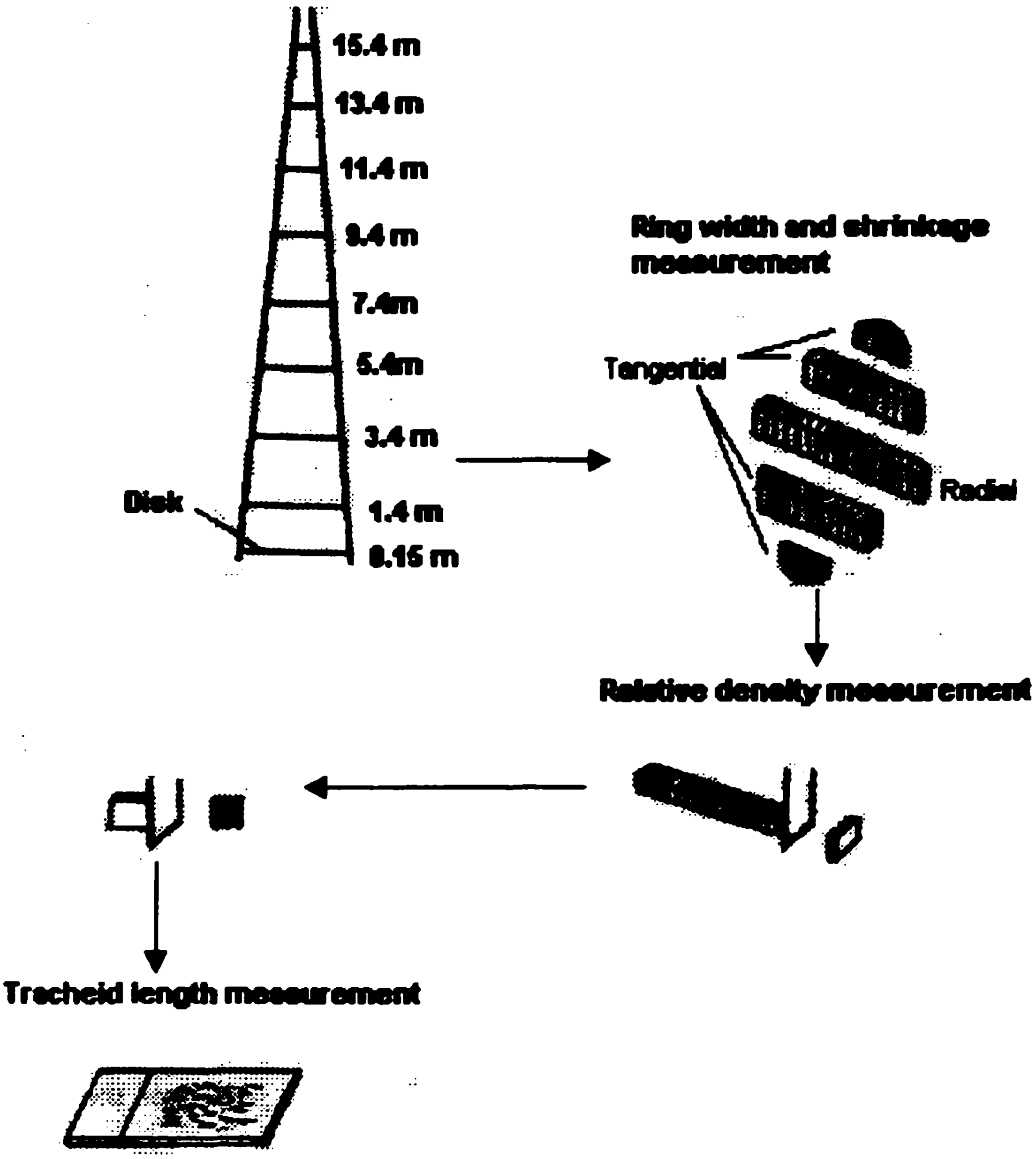


Figure 2. Illustration of sample collection and preparation.

Relative Density

Relative density is defined as the wood substance present in a given green volume of wood. The maximum moisture content method (Smith 1954) for small sample was used to determine the relative density of growth ring.

To determine the relative density, each wood strip was cut into small chips that contained one growth ring. Each chip was numbered and placed in beakers with distilled water. The beakers were then placed in a dessicator and a vacuum was applied to draw the air out of the wood. The vacuum was applied for 14 days to ensure complete saturation, *i.e.*, no more water intake, of the samples. Once the chips reached their maximum weights, they were removed from the dessicator and weighed on an automatic semi-micro-balance as maximum moisture contents (*Wm*). The water saturated chips were dried in an oven at $100 \pm 3\,^{\circ}$C for approximately 1 week until a constant weight was obtained. The dried chips were then weighed as the oven dry weight (*Wo*).

The relative density of the growth rings was calculated using the following formula from Smith (1954).

$$\text{Relative density} = \frac{1}{(Wm - Wo)/Wo + 1/G} \qquad \text{Equation (2)}$$

Where Wm = the maximum moisture content of the chip

Wo = the ovendry weight of the chip

G = the density of the cell wall substance =1.53

Tracheid Length

After the relative density measurements were completed, the wood chips were cut into small wood sticks and placed in labeled test tubes. The wood sticks were macerated for tracheid length measurement according to Franklin (1945). The maceration solution was prepared with an equal part of glacial acetic acid and hydrogen peroxide. After the solution was placed in the test tubes, they were covered by parafilm and placed on a heater at 60 °C for 48 to 72 hours until the wood sticks turned white. Then the wood sticks were rinsed three times with distilled water and shaken into individual tracheids. The tracheids from each tube were placed on a microscopic slide and viewed through a light microscope with 2.5×10 magnification.

A preliminary measurement was made to determine the number of tracheids required at a given confidence level and allowable error. Growth ring ages 9 and 18 counted from the pith of 15.4 m wood disc were randomly selected for tracheid length preliminary measurement. Twenty-five tracheids from growth ring ages 9 and 18 were randomly measured to represent the tracheid length of the growth ring. The result of the preliminary measurement used to determine the number of tracheid length measurement required for a given confidence level and an allowable error was calculated using the following formula:

$$N = \frac{t_\alpha{}^2 \bullet s^2}{E^2} = \frac{t_\alpha{}^2 \bullet s^2}{(\bar{x} \bullet 10\%)^2} = \frac{t_\alpha{}^2 \bullet (s/x \bullet 100)^2}{10\%} = \frac{t_\alpha{}^2 \bullet (CV)^2}{(10\%)^2} \qquad \text{Equation (3)}$$

Where N = number of tracheids to be measured

t = the student's t

α = the confidence level at 95% (*i.e.* $\alpha \leq 0.05$)

s = standard deviation of the samples

$\bar{x}$ = mean of the samples

CV = coefficient of variation, $\frac{s}{\bar{x}} \times 100$

E = allowable error at 10% of the mean

In this study, 25 tracheid lengths were required at 95% confidence level and allowable error at 10% of the mean.

Volume of Juvenile Wood

The juvenile wood in this study was defined as the zone where the tracheid length increased progressively from the pith outwards to the bark, while mature wood was defined as the zone where the tracheid length became constant or leveled off.

The following formulae were used to calculate the volume of juvenile wood and mature wood.

Volume of juvenile wood for each section = Juvenile wood basal area × Height of the section = $\pi \times r^2 \times$ Height of the section = $\frac{\pi(r_t^2 + r_b^2)}{2} \times (H_t - H_b)$ Equation (4)

Volume of total juvenile wood = Sum of the 9 sections Equation (5)

Where r = radius of the juvenile wood

r_t = radius of the juvenile wood of the top section

r_b = radius of the juvenile wood of the base section

Height of the section = $H_t - H_b$ = height of the top section (H_t) - height of the base section (H_b)

In this study, the tree bole was divided into nine conical sections. The volume of total juvenile wood equals the sum of volume of juvenile wood of the nine sections.

Cambial initial age was defined as the number of years between the formation of the cambium initials and the year the seed germinated (Yang *et al.* 1986). At a given tree height, the cambial initial age is calculated by taking the difference between the number of growth rings at 0.15 m height and the number of growth rings at the upper level, plus one. The relationship between juvenile wood width and cambial initial age was analyzed.

DATA ANALYSIS

Variation of the three variables (*i.e.*, tracheid length, relative density and ring width) were analyzed with respect to several factors such as ring age, height in stem, and aspect. Radial and tangential shrinkage were analyzed with respect to wood strip number (from the pith to bark instead of ring age) and height in stem. Tangential shrinkage of the two outermost wood strips from wood disc was analyzed with respect to height in stem. The data were entered into Microsoft Excel and then analyzed with the SPSS program.

Juvenile and Mature Wood Boundary

In this study, tracheid length was used as a criterion for determining the boundary of juvenile and mature wood. The determination of juvenile/mature wood boundary was based on Yang *et al.* (1986) method. The initial boundary of juvenile and mature wood was determined by examining the plot of tracheid length over ring age counted from the pith for all heights and aspects. The juvenile wood zone was defined as where the tracheid length stopped increasing rapidly, while the mature wood was defined as the zone where the tracheid length became constant or leveled off. Then the data became separated into two parts, pith to boundary and boundary to bark. Two regression lines were calculated by using tracheid length of these two sets of data, respectively. The intersection of these two lines was considered the secondary boundary between juvenile and mature wood for all the heights and aspects. However, this method could not be applied for the upper two heights (15.4 m and 13.4 m) of the tree stem because there were no distinct points where the tracheid length increased rapidly and where the tracheid length became constant. Also the radial variations of tracheid length between two aspects were not consistent due to its nature. Therefore, an adjusted tracheid length as boundary point of juvenile and mature wood at various heights was used. The adjusted tracheid length was determined by using the mean of tracheid length in the west and east aspects for all heights except for the upper two heights (15.4 m and 13.4 m). Then an axial trend from the base to the top of the stem for all height except the upper two heights (15.4 and 13.4 m) was obtained. The upper two tracheid lengths as boundary points were derived by examining the extended axial trend of other heights. After the tracheid length of boundary point was determined for all heights, horizontal lines were drawn on the radial variation pattern curves and crossed with the curves at both west and east aspects. The intersections between the horizontal lines and the radial variation curves at the west and east aspects were considered the new boundaries of the juvenile and mature wood for west and east aspect, respectively.

Tracheid length, relative density and ring width of juvenile and mature wood were analyzed separately.

Table 1. Tracheid length of boundary point for demarcating boundary of juvenile and mature wood at various heights.

Height (m)	Tracheid length of the new boundary (mm)
15.4	2.00
13.4	2.10
11.4	2.50
9.4	2.70
7.4	2.80
5.4	3.20
3.4	3.20
1.4	3.15
0.15	3.00

Radial Variation

Radial variations of the variables in the juvenile wood were examined using linear regression. The linear equation $Y=a+bX$ was used to determine the fitness of the model to the data. Y is the wood property variable, X is the ring age counted from the pith, a and b are the intercept and slope of the regression line, respectively. The slope (b) represented the general variation trend of the wood property variable with ring age in the juvenile wood. The correlation coefficient of the regression (r) between X and Y of the model was also calculated for the data set for each height and aspect.

Axial Variation

Multiple comparison procedures are methods to determine which means are significantly different from each other (Norusis 1982). Axial variations of the variables were tested with the multiple comparison method on the series of height means for the juvenile wood and mature wood. Each height mean was calculated from the data of two aspects of a given height. Juvenile and mature wood were tested separately. In this study multiple comparison was used to identify the height means which were significantly different from others. Those height means that were significantly different from others were classified into one of the subsets. The height means of different subsets were significantly different from each other.

Differences between Two Aspects

The differences between the means of west and east aspects were tested with student's t test. For the null hypothesis of no difference, the test was as follows:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s_{\bar{x}_1 - \bar{x}_2}} = \frac{\bar{d}}{s_{\bar{d}}}$$

Note that $\bar{d}$ is used to replace the difference of the two means, $s_{\bar{d}}$ is the standard deviation appropriate to a difference between two means.

The test of difference between the two aspects for the variables was based on the means at each height from west and east aspects. Juvenile wood and mature wood were separated for analysis.

Correlations between Variables

Correlations between each pair of the following variables were tested: tracheid length, relative density, ring width and ring age. The tests were to examine the strength of linear association (Norusis 1982) between every two of the above variables. The correlations were based on the data from the juvenile and mature wood of the entire stem, respectively.

RESULTS

The results in the following section are in accordance to the sequence of data analysis.

TRACHEID LENGTH

Radial Variation

In the jack pine stem, tracheid length increased progressively from the pith outward for all heights, then remained constant (11.4, 9.4, 7.4, 5.4, 3.4, 1.4 m) or leveled off (0.15 m) at ring age of juvenile and mature wood boundary (Table 2) towards the bark (Figure 3). In the juvenile wood, tracheid length was shorter than that in the mature wood.

The radial variation of tracheid length with ring age could be expressed by the linear regression equation $Y= a+bX$ (Table 2). The linear regression equations were all significant at the 5% level in both juvenile and mature wood for all heights and aspects.

The boundaries between juvenile and mature wood at each height are shown in Figure 3. The slope of the regression line represents the rate at which tracheid length increased with ring age from the pith outward. In both west and east aspects, the slope increased with increasing height from the base up to the top with an exception low value at 13.4 m (Figure 4).

Table 2. Linear equations Y=a+bX representing the variation of juvenile wood tracheid length (Y) with ring age (X), and ring age of the juvenile/mature wood boundary (X_{jm}) for each heights of the west and east aspects.

Height (m)	Total ring age (yrs)	West			East		
		a+bX	r	X_{jm}	a+bX	r	X_{jm}
15.4	18	0.73+0.21X	0.99**	7	0.88+0.23X	0.96**	6
13.4	26	0.78+0.14X	0.99**	9	0.83+0.10X	0.99**	12
11.4	33	0.84+0.18X	0.96**	11	0.95+0.13X	0.98**	13
9.4	39	0.99+0.16X	0.98**	13	1.00+0.14X	0.98**	15
7.4	42	1.11+0.13X	0.96**	16	1.00+0.12X	0.98**	16
5.4	49	1.01+0.13X	0.99**	19	0.89+0.12X	0.99**	21
3.4	52	1.02+0.12X	0.93**	21	1.00+0.12X	0.96**	22
1.4	56	0.98+0.12X	0.97**	21	0.99+0.10X	0.97**	25
0.15	59	1.12+0.07X	0.99**	28	0.97+0.07X	0.99**	30

** Significant at $\alpha \leq 0.01$.

Axial Variation

The mean tracheid length increased from base upward and reached a maximum at 3.4 m and 5.4m height for juvenile and mature wood, respectively. Thereafter, the mean tracheid length of the west and east aspects decreased toward to the top for both juvenile and mature wood (Figure 5). Mean tracheid length of the west and east aspects at various heights are listed in Appendix III.

In the juvenile wood, the mean tracheid length at the 13.4 m was significantly different from that at the 3.4 m (Table 3). No significant differences were found between all other heights in the juvenile wood. In the mature wood, the mean tracheid length of the 5.4 m and 3.4 m height were in the subsets of the highest value, and those of the 15.4 m and 13.4 m were in the subsets of the lowest value (Table 3). Impact of height is more

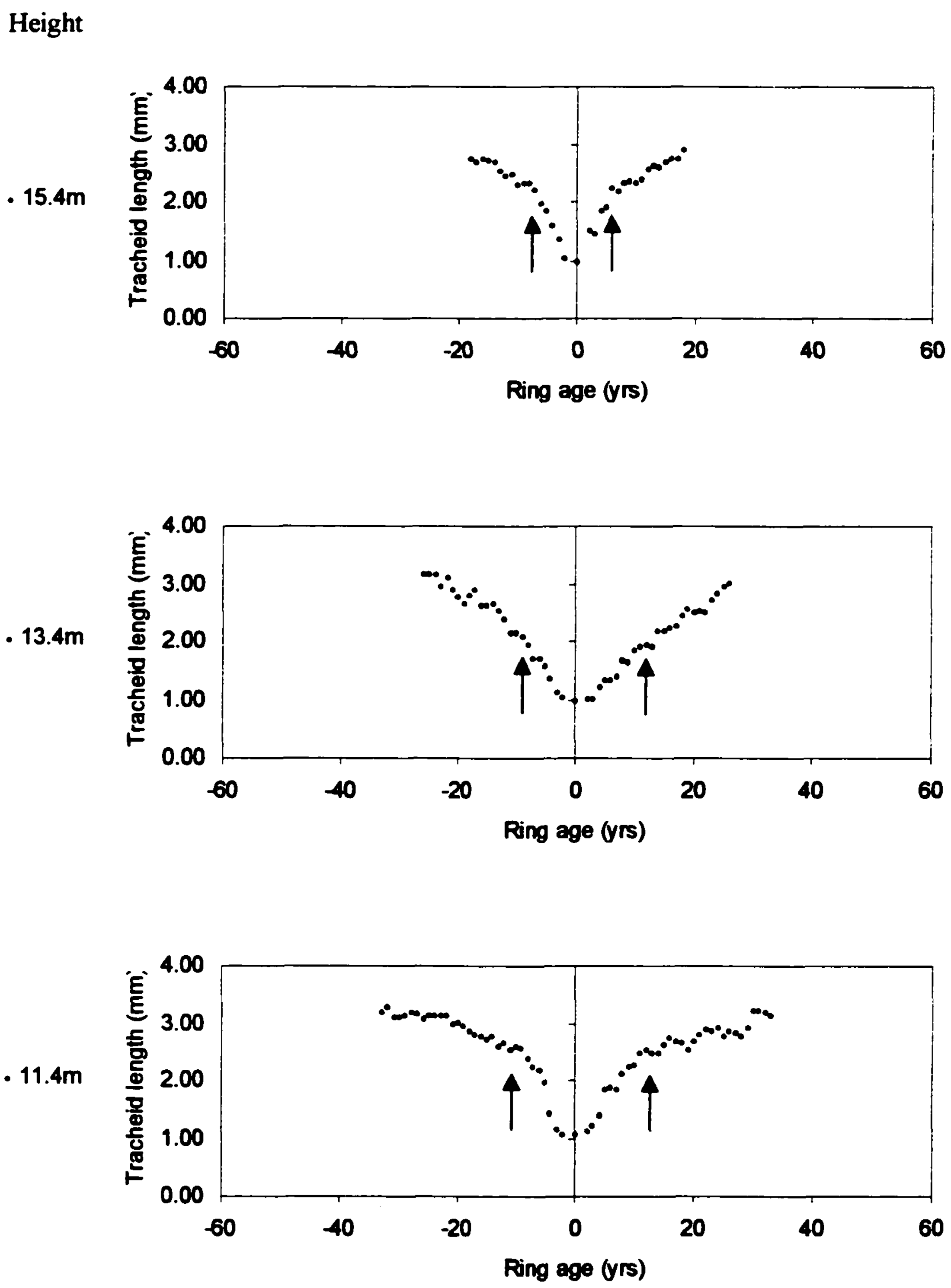


Figure 3. Radial variation of tracheid length at various heights of the tree at west and east aspects. Arrows indicate the boundary of the juvenile and mature wood. Note that negative ring ages represent west aspect and positive ring ages represent east aspect.

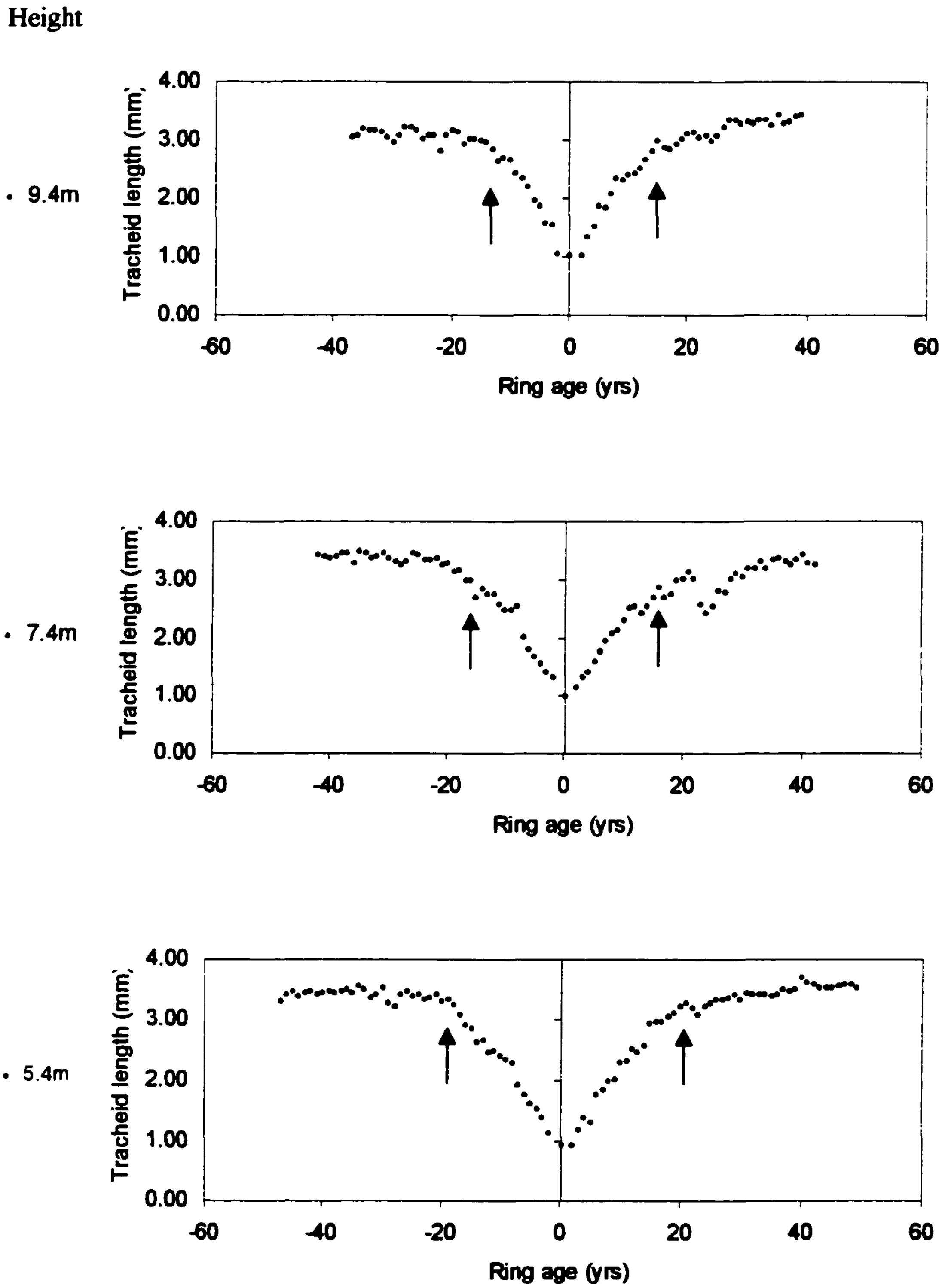


Figure 3. (Continued) Radial variation of tracheid length at various heights of the tree at west and east aspects.

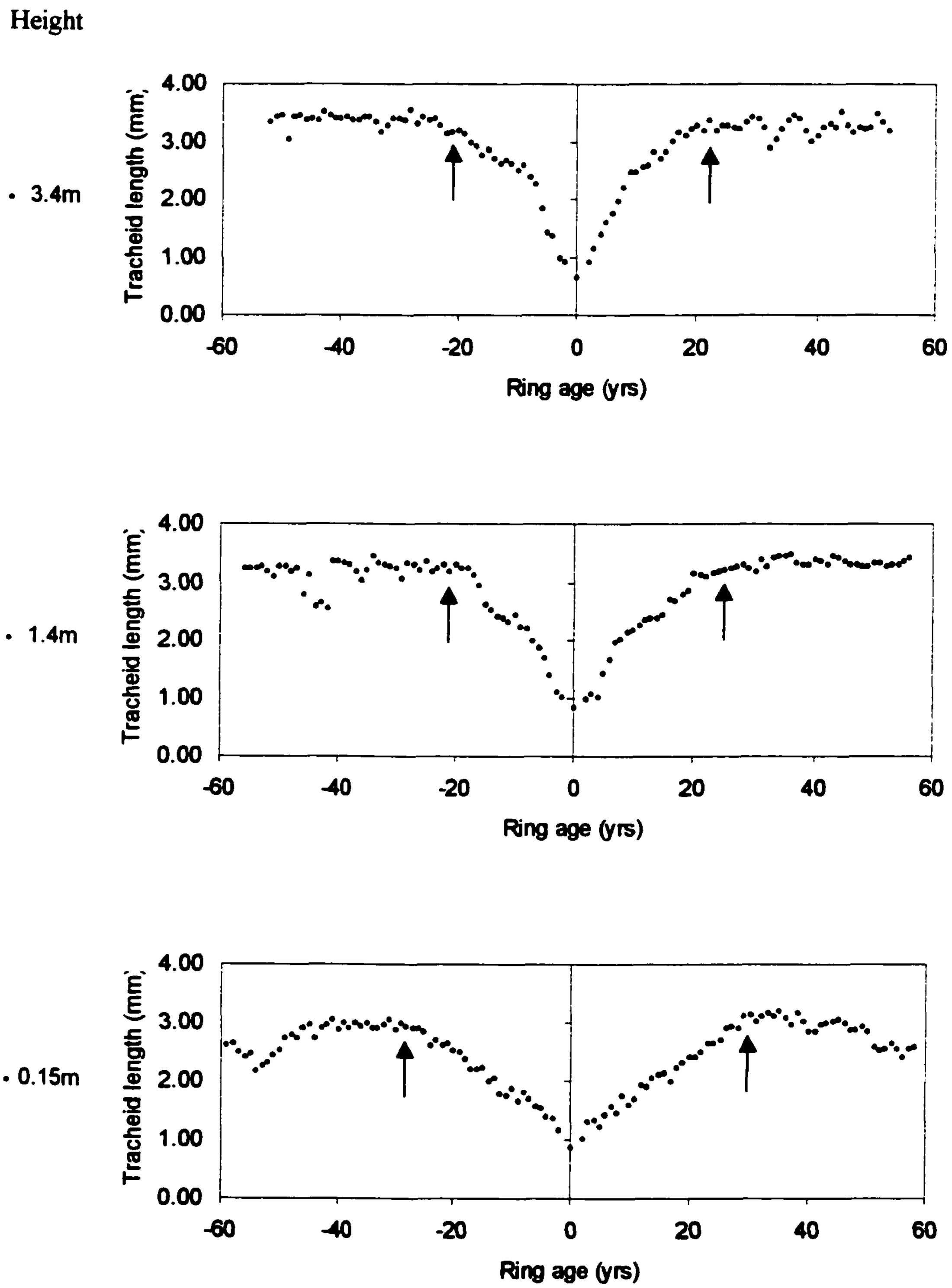


Figure 3. (Continued) Radial variation of tracheid length at various heights of the tree at west and east aspects.

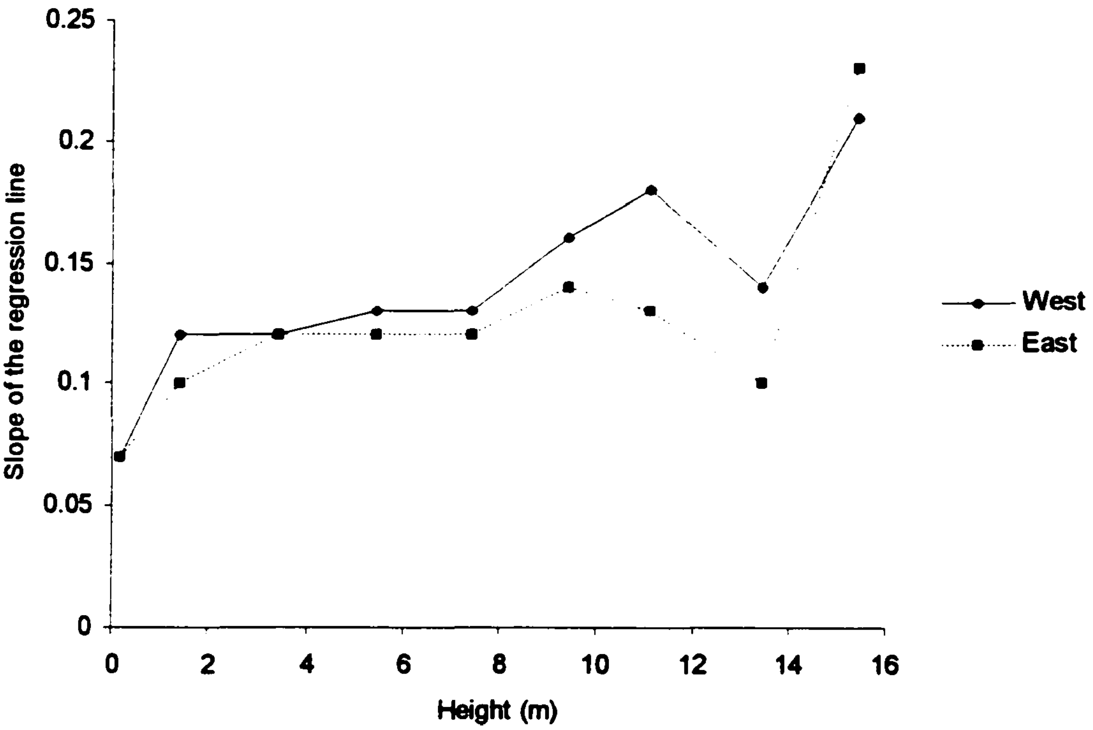


Figure 4. Relationship between the rate of tracheid length increase (slope of the regression line) and height in the jack pine studied.

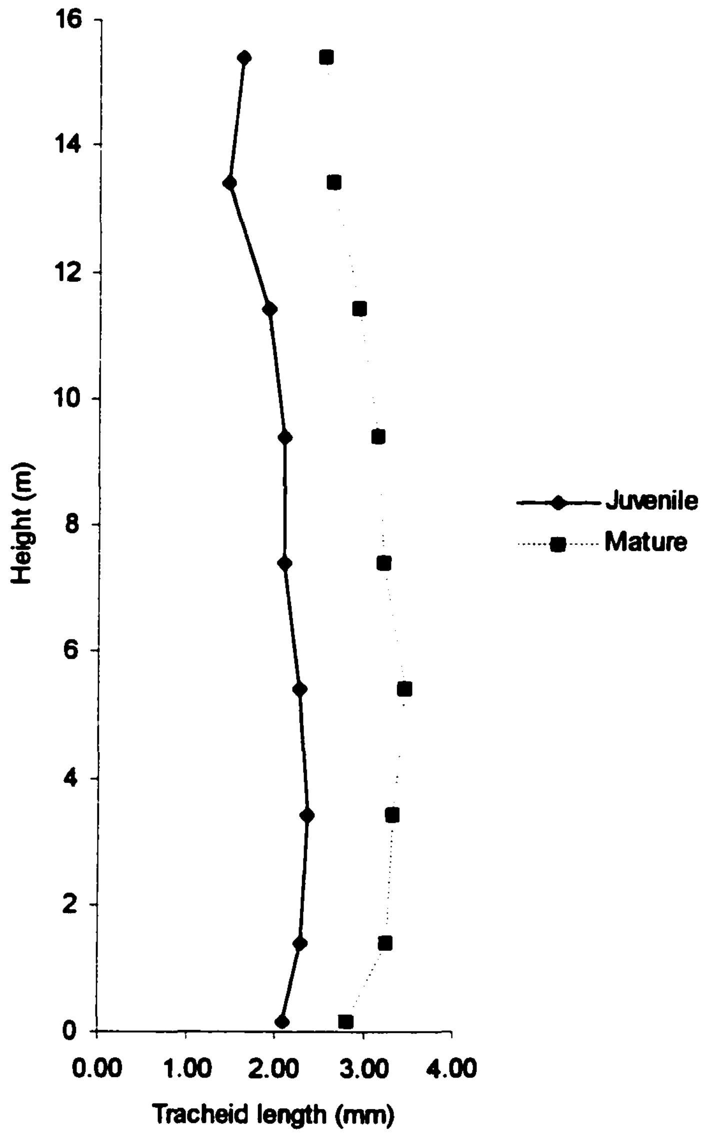


Figure 5. Axial variation of the mean tracheid length with height in the juvenile and mature wood.

significant in the mature wood than in the juvenile wood. For both juvenile and mature wood, the shortest tracheid length occurred at the upper tree heights, *i.e.*, 13.4 m and 15.4 m in the juvenile and mature wood, respectively.

Table 3. Multiple comparisons of the means of tracheid length of heights for testing axial variation in the juvenile and mature wood.

	Juvenile wood				Mature wood				
Height	Mean	Subset[a]			Mean	Subset[a]			
(m)	(mm)	1	2	3	(mm)	1	2	3	4
15.4	1.62	1.62	1.62		2.54	2.54			
13.4	1.47	1.47			2.63	2.63			
11.4	1.90	1.90	1.90	1.90	2.93		2.93		
9.4	2.08	2.08	2.08	2.08	3.15			3.15	
7.4	2.10	2.10	2.10	2.10	3.21			3.21	
5.4	2.26		2.26	2.26	3.45				3.45
3.4	2.36			2.36	3.32			3.32	3.32
1.4	2.29		2.29	2.29	3.26			3.26	
0.15	2.09	2.09	2.09	2.09	2.82		2.82		

[a] Subsets 1, 2, 3, ... for juvenile and mature wood denote subsets significantly different from each other; the height means within the subsets are not significantly different. For example, in the mature wood, subset 1 contains mean tracheid length 2.54 and 2.63 of 15.4 and 13.4 m heights and they are significantly different from subset 2 which contains the mean of 2.93 and 2.82 of height 11.4 and 0.15 m; the mean 2.54 and 2.63 in subset 1 are not significantly different. (Significant at α = 0.05)

Difference between Two Aspects

The mean tracheid length of the west and east aspect at each height were not significantly different from each other in the juvenile wood (Table 4). In the mature wood, the mean tracheid length of the west aspect was significantly longer than that of the east aspect at 13.4 m, 11.4 m, 7.4 m and 3.4 m, while the mean tracheid length of the west aspect was significantly shorter than that of the east aspect at 9.4 m and 1.4 m. At all other heights in the mature wood, the mean tracheid length of the west and east aspects were not significantly different.

Table 4. Number of measurements, mean tracheid length, standard deviation and t value for testing the differences between west and east aspects in tracheid length at various heights.

		Mature wood				Juvenile wood			
Height (m)	Aspect	N	Mean (mm)	s	t	N	Mean (mm)	s	t
15.4	West	11	2.54	0.182		7	1.58	0.463	
	East	12	2.54	0.216	ns	6	1.67	0.437	ns
13.4	West	17	2.75	0.209		9	1.50	0.398	
	East	14	2.50	0.207	2.16*	12	1.44	0.350	ns
11.4	West	22	3.00	0.223		11	1.78	0.604	
	East	20	2.85	0.225	2.42*	13	1.84	0.525	ns
9.4	West	24	3.09	0.102		13	2.08	0.618	
	East	24	3.20	0.177	-2.77*	15	2.09	0.623	ns
7.4	West	26	3.35	0.122		16	2.19	0.629	
	East	26	3.06	0.284	4.85**	16	2.02	0.586	ns
5.4	West	28	3.44	0.077		19	2.27	0.719	
	East	28	3.46	0.140	ns	21	2.25	0.777	ns
3.4	West	31	3.37	0.106		21	2.32	0.787	
	East	30	3.26	0.140	3.57*	22	2.39	0.816	ns
1.4	West	35	3.19	0.213		20	2.30	0.762	
	East	31	3.35	0.073	-3.81*	28	2.29	0.759	ns
0.15	West	31	2.77	0.254		28	2.11	0.572	
	East	28	2.88	0.233	ns	30	2.08	0.636	ns

* Significant at $\alpha \leq 0.05$.

** Significant at $\alpha \leq 0.01$.

ns - not significant

RELATIVE DENSITY

Radial Variation

In the juvenile wood, relative density was generally high near the pith and decreased outward to a certain ring age, then increased further outward. The higher relative density near the pith was more obvious in the juvenile wood at the heights of 15.4 m, 13.4 m, 5.4 m and 3.4 m. In the mature wood, the variation of relative density became relatively constant for all heights (Figure 6). Table 5 shows the linear equations expressing the radial variation of relative density with ring age in the juvenile wood. The slopes (b) were all negative indicating the general decreasing pattern of relative density (Y) with ring age (X) with an exception of a positive slope at 0.15 m. At some heights of both aspects, there was no correlation between relative density and ring age in the juvenile wood. The ranges of relative density variation were 0.32-0.69 and 0.35-0.53 for the juvenile and mature wood, respectively. The highest relative density 0.69 occurred in the juvenile wood of the east aspect at 13.4 m.

Axial Variation

In the juvenile wood, mean relative density decreased from the base up to the top with an exception of a relatively high relative density at 13.4 m height. Relative density in the mature wood followed the same variation pattern as shown in the juvenile wood. Figure 7 shows the axial variation of relative density with height for juvenile and mature wood. Mean relative density of the west and east aspects at various heights are listed in Appendix IV.

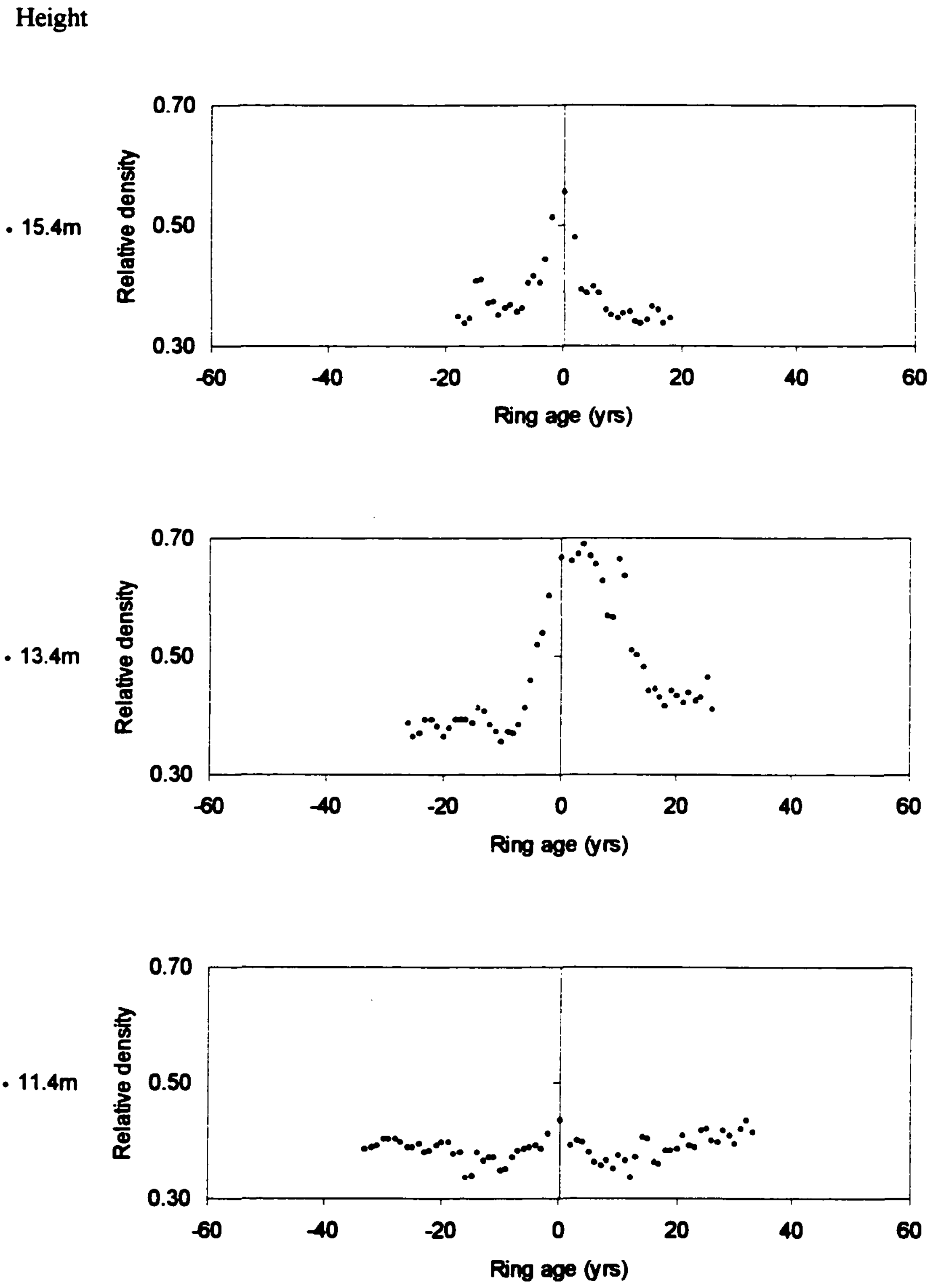


Figure 6. Radial variation of relative density at various heights of the tree at west and east aspects. Note that negative ring ages represent west aspect and positive ring ages represent east aspect.

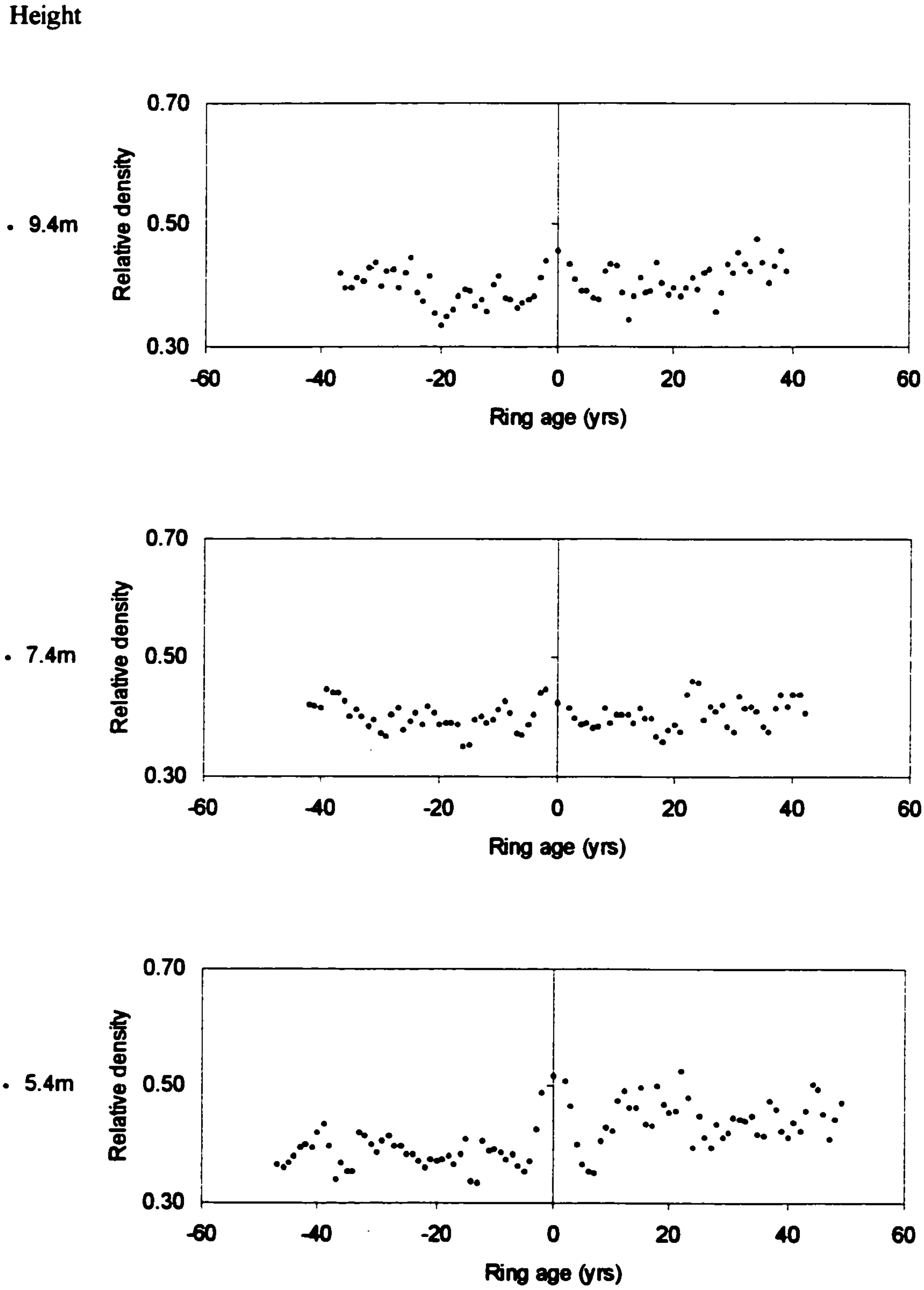


Figure 6. (Continued) Radial variation of relative density at various heights of the tree at west and east aspects.

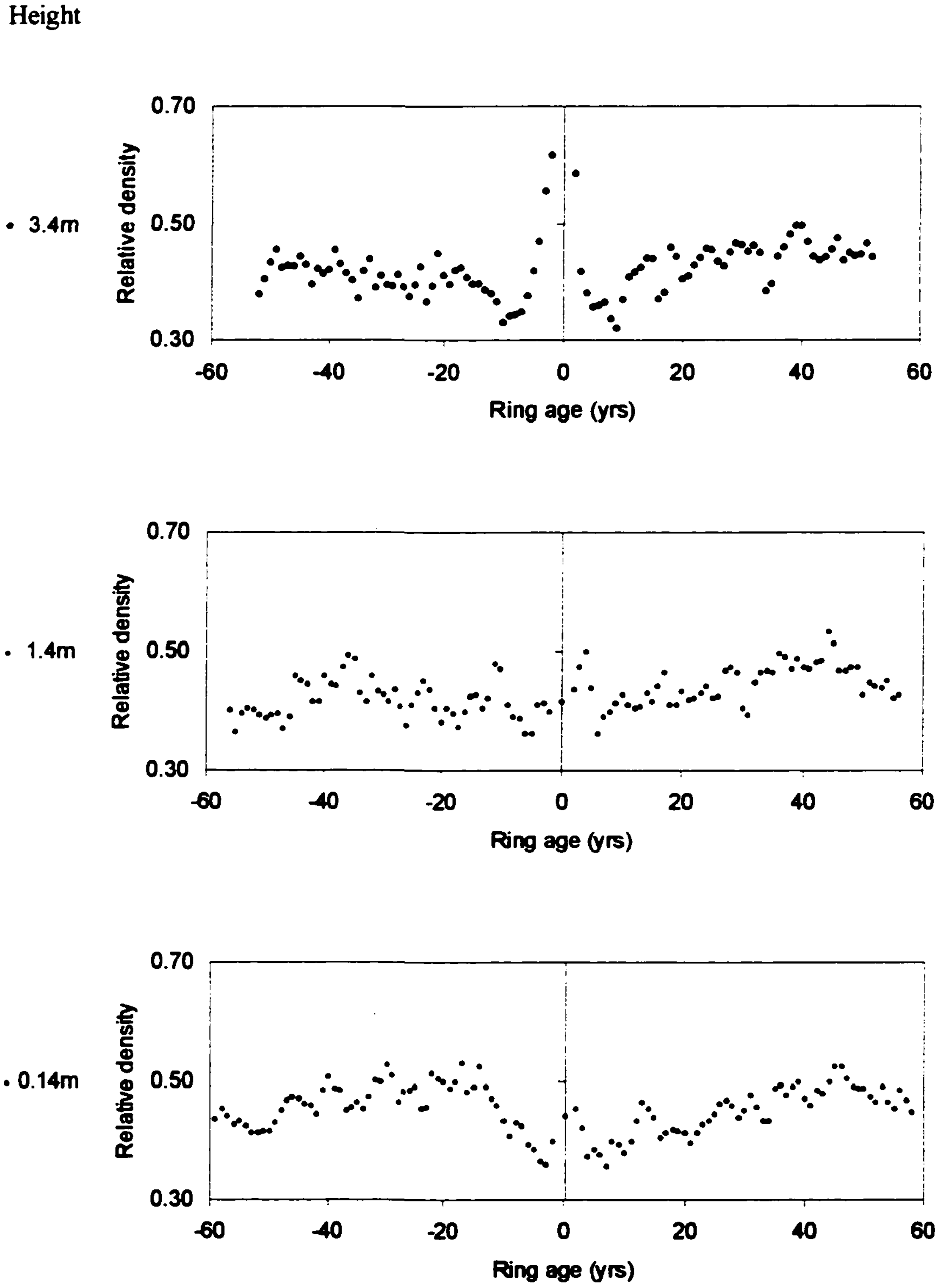


Figure 6. (Continued) Radial variation of relative density at various heights of the tree at west and east aspects.

The mean relative density of juvenile wood at 13.4 m height was significantly different from that at other heights. The mean relative density at 13.4 m is the highest value (0.517) of relative density in the juvenile wood (Table 6). Relative density of mature wood showed a decreasing pattern with increasing height. The lowest and highest relative density occurred at 15.4 m and 0.15 m, respectively (Table 6).

Table 5. Linear equations Y=a+bX representing the variation of juvenile wood relative density (Y) with ring age (X) for each heights of the west and east aspects.

Height (m)	Total ring age (yrs)	West		East	
		a+bX	r	a+bX	r
15.4	18	0.56-0.0294X	0.93*	0.54-0.0311X	0.84*
13.4	26	0.67-0.0382X	0.97**	0.72-0.0160X	0.68*
11.4	33	0.42-0.0065X	0.88**	0.41-0.0049X	0.76*
9.4	39	0.43-0.0046X	0.59*		ns
7.4	42	0.43-0.0037X	0.64*	0.40-0.0001X	0.53*
5.4	49	0.43-0.0043X	0.52*		ns
3.4	52	0.51-0.0074X	0.46*		ns
1.4	56		ns		ns
0.15	59	0.40+0.0041X	0.70**	0.40+0.0017X	0.50*

* Significant at $\alpha \leq 0.05$.
** Significant at $\alpha \leq 0.01$.
ns - not significant

Difference between Two Aspects

The mean relative density of the west aspect was significantly lower than that of the east aspect in the juvenile wood at 13.4 m, 5.4 m, 1.4 m, while a higher relative density occurred at the west aspect of 0.15 m (Table 7). At all other heights, there were

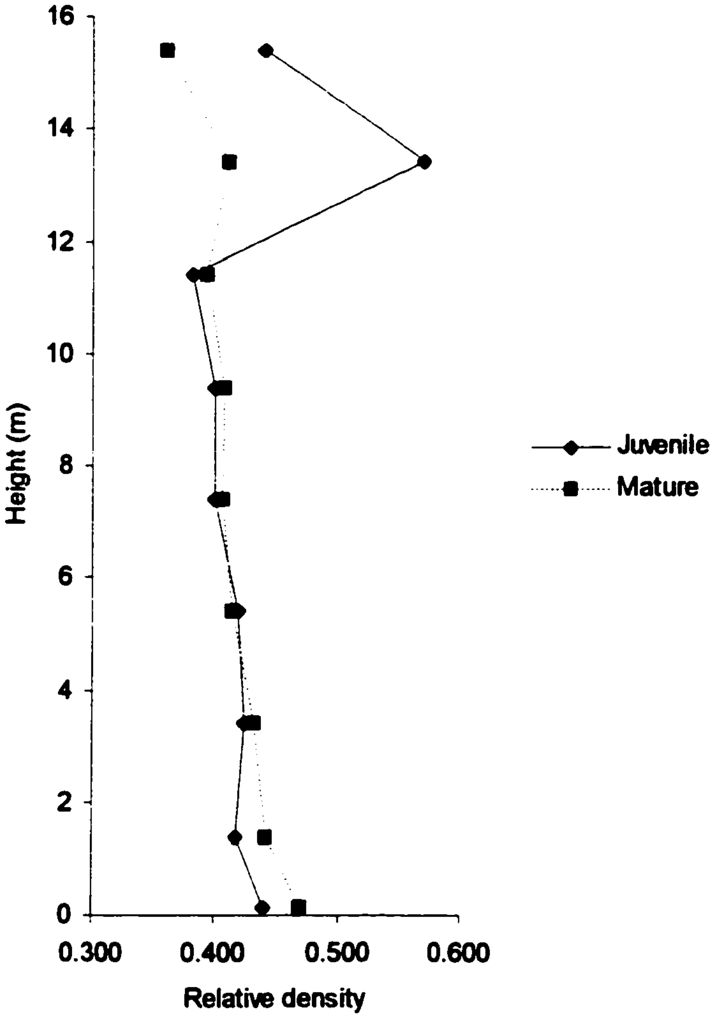


Figure 7. Axial variation of the mean relative density with height in the juvenile and mature wood.

no significant differences of mean relative density between these two aspects in the juvenile wood. In the mature wood, the mean relative density of the west aspect was significantly lower than that of the east for all heights, with an exception at 15.4 m (Table 7). No difference of relative density from west and east aspects was found for 7.4 m in the mature wood.

Table 6. Multiple comparisons of the means of relative density of heights for testing axial variation in the juvenile and mature wood.

Height	Juvenile wood			Mature wood					
		Subset[a]					Subset[a]		
(m)	Mean	1	2	Mean	1	2	3	4	5
15.4	0.44	0.44		0.36	0.36				
13.4	0.57		0.57	0.41		0.41	0.41		
11.4	0.38	0.38		0.39		0.39			
9.4	0.40	0.40		0.41		0.41	0.41		
7.4	0.40	0.40		0.41		0.41	0.41		
5.4	0.42	0.42		0.41		0.41	0.41		
3.4	0.42	0.42		0.43			0.43	0.43	
1.4	0.42	0.42		0.44				0.44	
0.15	0.44	0.44		0.47					0.47

[a] Subsets 1, 2, 3, ... for juvenile and mature wood denote subsets significantly different from each other; the height means within the subsets are not significantly different (Significant at $\alpha=0.05$).

RING WIDTH

Radial Variation

Ring width increased from the pith outward and reached a maximum at ring age of 4 to 12 for various heights followed by a leveling off in the remainder of the juvenile wood. In the mature wood the ring width fluctuated (Figure 8). The ring width of the east aspect at ring ages of 10 to 13 at 13.4 m was relatively wide and deviated from the general pattern.

Table 7. Number of measurements, mean relative density, standard deviation and t value for testing the differences between west and east aspects in relative density at various heights.

Height		Mature wood				Juvenile wood			
(m)	Aspect	N	Mean	s	t	N	Mean	s	t
15.4	West	11	0.37	0.024		7	0.45	0.068	
	East	12	0.35	0.010	2.24*	6	0.44	0.070	ns
13.4	West	17	0.39	0.015		19	0.48	0.108	
	East	14	0.44	0.026	-7.66**	12	0.63	0.055	-4.22*
11.4	West	22	0.38	0.018		11	0.39	0.024	
	East	20	0.40	0.020	-2.75*	13	0.38	0.025	ns
9.4	West	24	0.40	0.029		13	0.39	0.030	
	East	24	0.42	0.027	-2.40*	15	0.40	0.029	ns
7.4	West	26	0.40	0.021		16	0.40	0.028	
	East	26	0.41	0.028	ns	16	0.40	0.012	ns
5.4	West	28	0.39	0.023		19	0.39	0.046	
	East	28	0.44	0.033	-7.43**	21	0.45	0.049	-3.61*
3.4	West	31	0.41	0.024		21	0.43	0.098	
	East	30	0.45	0.023	-6.60**	22	0.42	0.089	ns
1.4	West	35	0.42	0.032		21	0.41	0.029	
	East	31	0.46	0.030	-5.03**	25	0.43	0.027	-2.18*
0.15	West	31	0.46	0.031		28	0.46	0.047	
	East	28	0.48	0.023	-2.79*	30	0.42	0.030	3.57*

* Significant at $\alpha \leq 0.05$.

** Significant at $\alpha \leq 0.01$.

ns - not significant

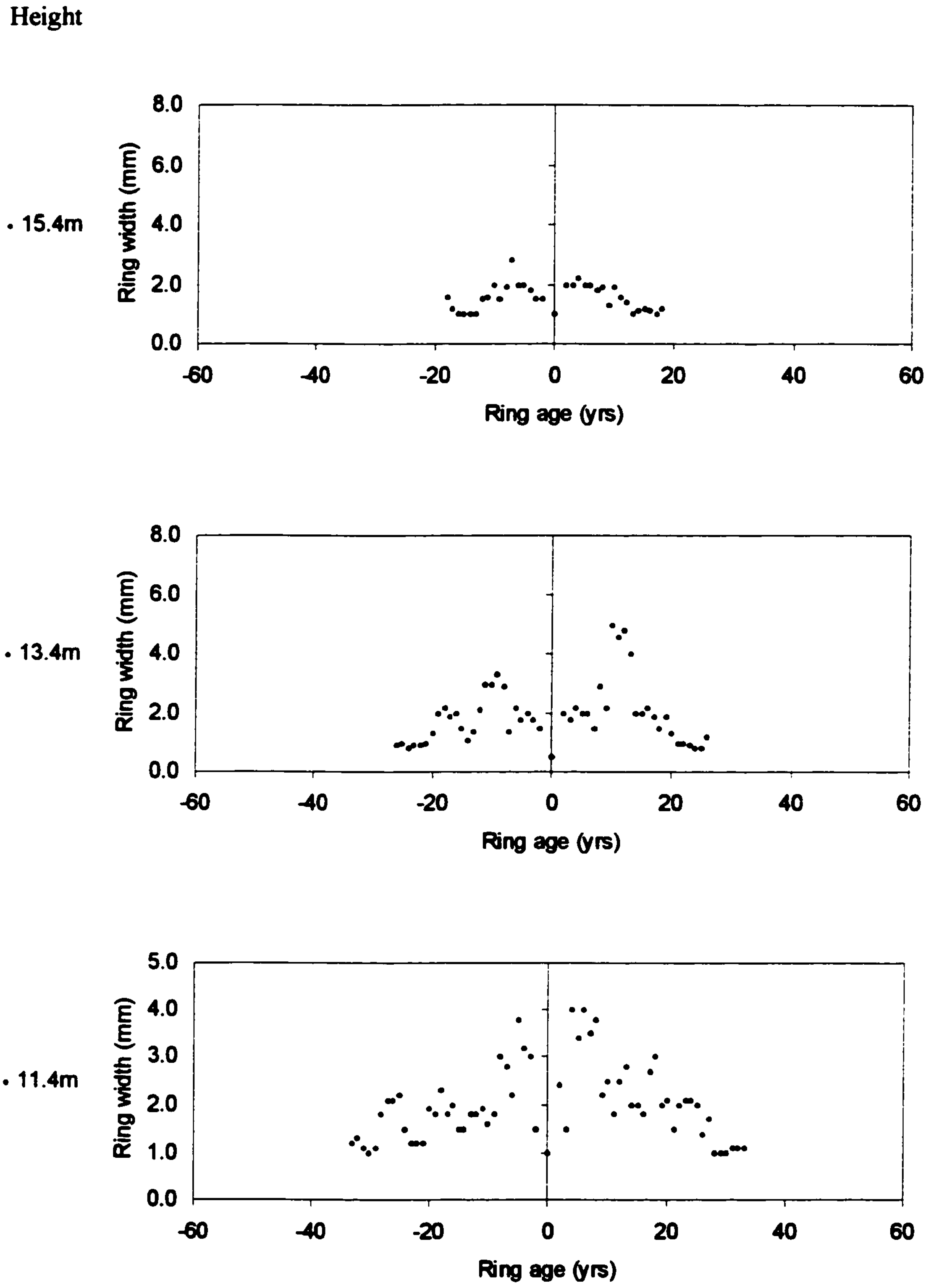


Figure 8. Radial variation of ring width at various heights of the tree at west and east aspects. Note that negative ring ages represent west aspect and positive ring ages represent east aspect.

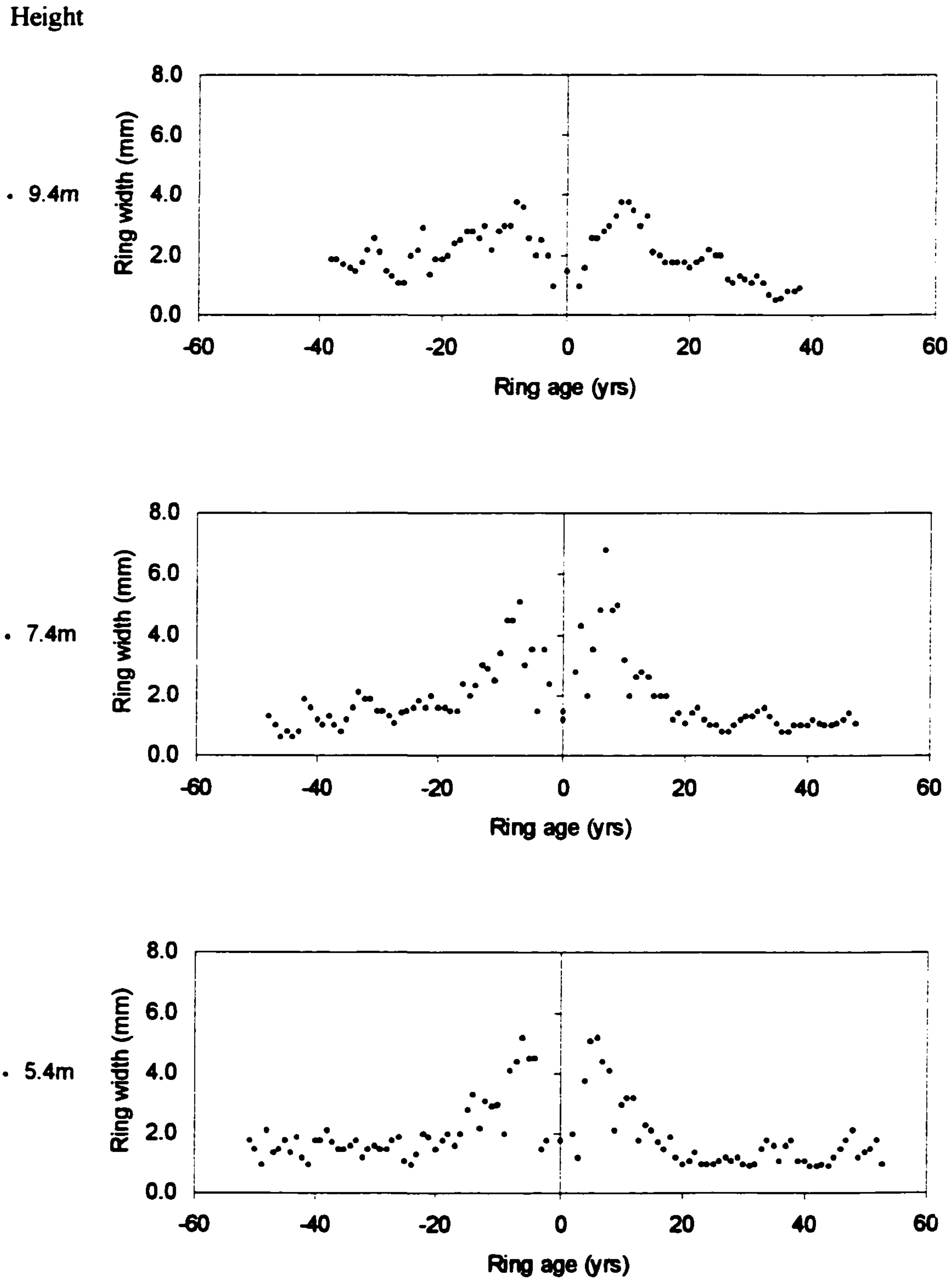


Figure 8. (Continued) Radial variation of ring width at various heights of the tree at west and east aspects.

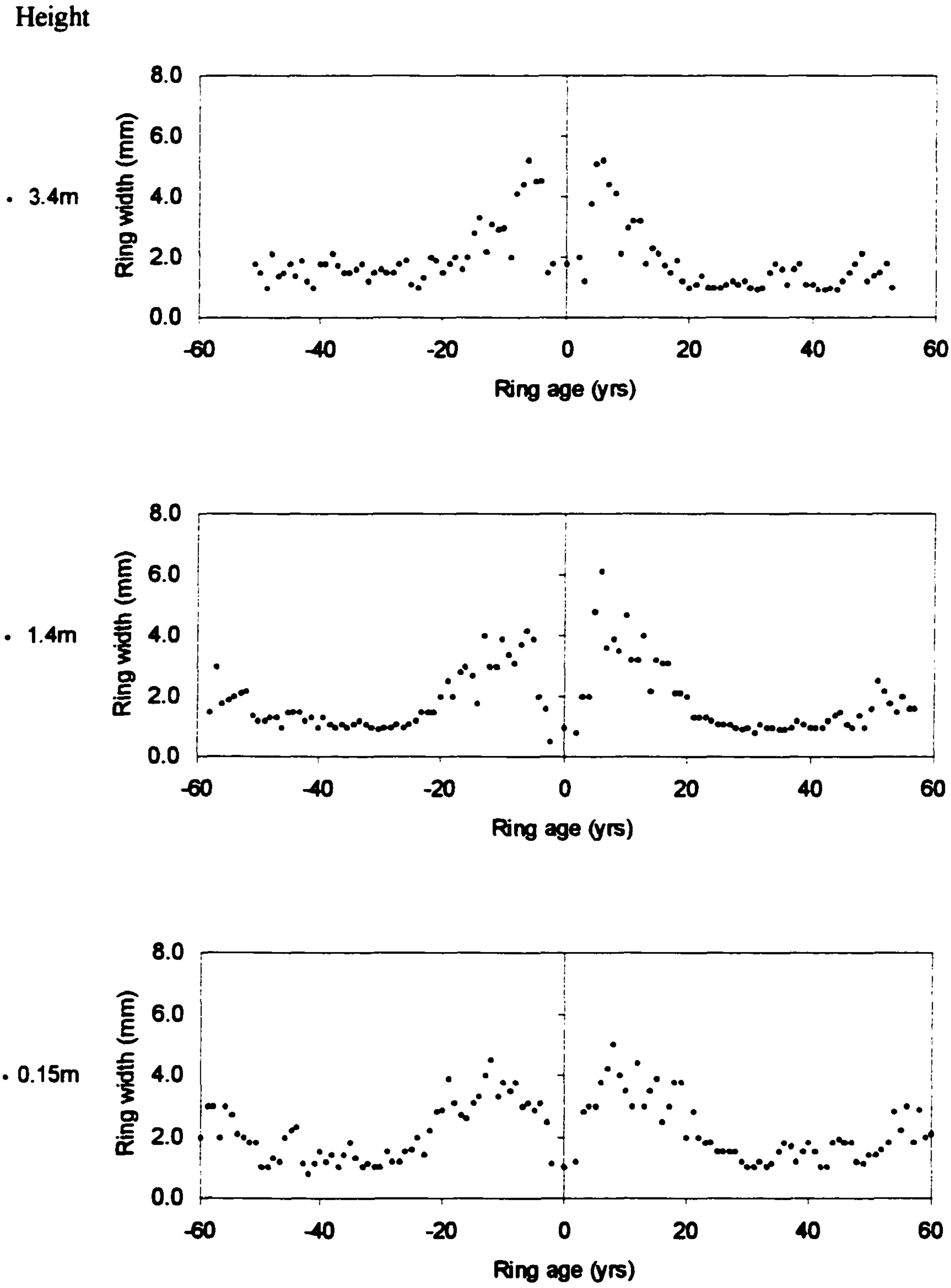


Figure 8. (Continued) Radial variation of ring width at various heights of the tree at west and east aspects.

Table 8 shows the linear equations expressing the radial variation of ring width with ring age in the juvenile wood. The slope (b) which was positive or negative indicated the increase or decrease of ring width (Y) with ring age (X). At some heights of both aspects, there was no correlation between ring width and ring age in the juvenile wood.

Table 8. Linear equations $Y=a+bX$ representing the variation of juvenile wood ring width (Y) with ring age (X) for each heights of the west and east aspects.

Height (m)	Total ring age (yrs)	West		East	
		a+bX	r	a+bX	r
15.4	18	0.81+0.246X	0.95*		ns
13.4	26	0.70+0.247X	0.82*	0.46+0.333X	0.84*
11.4	33		ns		ns
9.4	39	1.66+0.126X	0.62*		ns
7.4	42		ns		ns
5.4	49		ns	4.20-0.125X	0.51*
3.4	52		ns	3.75-0.108X	0.54*
1.4	56		ns		
0.15	59		ns	3.65-0.062X	0.48*

* Significant at $\alpha \leq 0.05$.
ns - not significant

Axial variation

In juvenile wood, ring width decreased from the base of the tree to the top with the narrowest ring at the top. There was no apparent trend for ring width variation in the mature wood. Figure 9 shows the axial variation of ring width with height for juvenile and mature wood. It is evident that ring width in the juvenile wood is wider than that in

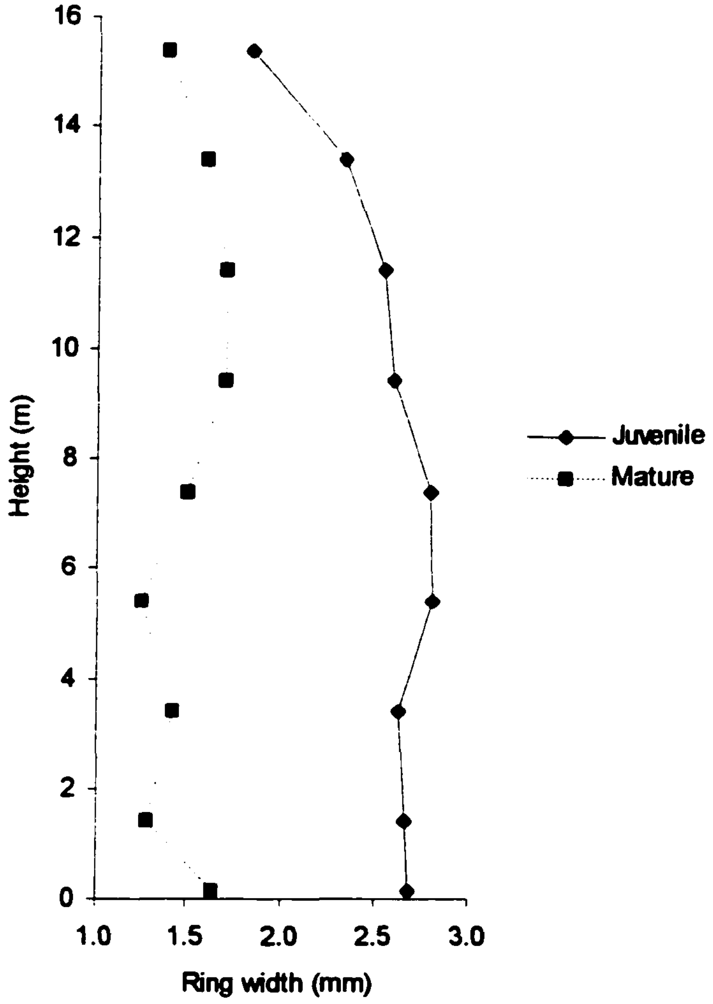


Figure 9. Axial variation of the mean ring width of with height in the juvenile and mature wood.

the mature wood (Figure 9). Mean ring width of the west and east aspects at various heights are listed in Appendix V.

In the juvenile wood, the differences among the height means of ring width were not significant. In the mature wood, the ring widths at 11.4 m and 9.4 m (wide ring subsets) were significantly different from that at 5.4 m (narrow ring subset) (Table 9).

Table 9. Multiple comparisons of the means of ring width of heights for testing axial variation in the juvenile and mature wood.

Height (m)	Juvenile wood Mean (mm)	Juvenile wood Subset[a] 1	Mature wood Mean (mm)	Mature wood Subset[a] 1	Mature wood Subset[a] 2
15.4	1.8	1.8	1.4	1.4	1.4
13.4	2.3	2.3	1.6	1.6	1.6
11.4	2.6	2.6	1.7		1.7
9.4	2.6	2.6	1.7		1.7
7.4	2.8	2.8	1.5	1.5	1.5
5.4	2.8	2.8	1.2	1.2	
3.4	2.6	2.6	1.4	1.4	1.4
1.4	2.7	2.7	1.3	1.3	1.3
0.15	2.7	2.7	1.6	1.6	1.6

[a] Subsets 1, 2, 3, ... for juvenile and mature wood denote subsets significantly different from each other; the height means within the subsets are not significantly different (Significant at $\alpha=0.05$).

Difference between Two Aspects

There was no significant differences in the ring width between the west and east aspects in the juvenile wood for all heights (Table 10). The ring width in the west aspect was significantly wider than that in the east aspect at 9.4 m, 5.4 m, and 3.4 m in the mature wood. At other heights in the mature wood, ring width at the west aspect was not significantly different from that at the east aspect (Table 10).

Table 10. Number of measurements, mean ring width, standard deviation and t value for testing the differences between west and east aspects in ring width at various heights.

Height (m)	Aspect	Mature wood N	Mature wood Mean (mm)	Mature wood s	Mature wood t	Juvenile wood N	Juvenile wood Mean (mm)	Juvenile wood s	Juvenile wood t
15.4	West	11	1.4	0.373		7	1.8	0.563	
	East	12	1.4	0.342	ns	6	1.9	0.432	ns
13.4	West	17	1.6	0.714		9	1.9	0.825	
	East	14	1.6	0.849	ns	12	2.6	1.425	ns
11.4	West	22	1.6	0.390		11	2.3	0.866	
	East	20	1.8	0.607	ns	13	2.7	0.970	ns
9.4	West	24	2.0	0.536		13	2.5	0.794	
	East	24	1.3	0.511	4.33**	15	2.7	0.860	ns
7.4	West	26	1.5	0.459		16	2.7	0.606	
	East	26	1.5	0.356	ns	16	2.9	0.778	ns
5.4	West	28	1.4	0.430		19	2.8	1.102	
	East	28	1.1	0.222	2.62*	21	2.8	1.532	ns
3.4	West	31	1.6	0.313		21	2.8	1.163	
	East	30	1.3	0.340	3.47*	22	2.5	1.301	ns
1.4	West	35	1.3	0.340		21	2.6	1.034	
	East	31	1.3	0.411	ns	25	2.7	1.373	ns
0.15	West	31	1.6	0.656		28	2.7	0.982	
	East	28	1.6	0.555	ns	30	2.7	1.139	ns

* Significant at $\alpha \leq 0.05$.

** Significant at $\alpha \leq 0.01$.

ns - not significant

SHRINKAGE

Radial and Axial Variation

Mean tangential shrinkage (5.6%) was greater than mean radial shrinkage (4.0%) in the jack pine studied. Mean radial tangential shrinkages at various heights of the west and east aspect are listed in Appendix VI.

Radial shrinkage was at the pith section while tangential shrinkage was at the various tangential sections from pith to the bark. Tangential shrinkage increased from the pith outward to the bark, reaching a maximum and then leveled off near the bark for all heights except in the east aspect at 15.4 m and 13.4 m (Figure 10). Shrinkage in the east aspect at 15.4 m decreased from the pith outward, reaching a minimum and then increased to the bark, while shrinkage in the east aspect of 13.4 m remained constant from pith outward to the bark. The tangential shrinkage values in the east aspect at 13.4 m and 15.4 m were lower than expected.

Both radial and tangential shrinkage were relatively low at 0.15 m and increased at 1.4 m. Thereafter, radial and tangential shrinkage showed a decreasing trend with increasing height (Figure 11). Tangential shrinkage at the top (15.4 m) height was significantly lower than at other height levels excluding that at 13.4 m (Table 11). The tangential shrinkage value at the top was the lowest with a value of 3.4%. No significant differences were found for tangential shrinkage at all other heights below 13.4 m.

Axial tangential shrinkage variation of the two outermost wood strips is shown in Figure 12. It was relatively low at 0.15 m and increased at 1.4 m. After that it decreased with increasing height. Tangential shrinkage of the two outermost wood strips at the top (15.4 m) height was significantly lower than those at other heights, excluding that at

13.4 m (Table 12). The tangential shrinkage value at the top was 3.4%. No significant differences were found for tangential shrinkage of the outermost two wood strips at various heights below 13.4 m. Mean tangential shrinkage of the two outermost wood strips at various heights of the west and east aspect is listed in Appendix VII.

Relationship between Shrinkage and Relative Density

Generally, there is a close relationship between shrinkage and relative density, that is, wood with a higher relative density shrinks more than the one with a lower density (Haygreen and Bowyer 1996). In this study, no correlation was found between radial shrinkage and relative density, nor between tangential shrinkage and relative density (Figures 13).

VOLUME OF JUVENILE WOOD

Vertical variation of juvenile and mature wood, expressed by the ring age and the tree diameter, is shown in Figures 14, 15 and Table 13.

The juvenile wood core in this 60-year-old jack pine is conical in shape when expressed both by ring age and tree diameter (Figures 14 and 15). No mature wood was found when the tree is less than 26-year-old. Based on ring age or tree diameter as criteria, the percentage of juvenile wood volume accounted for approximately 16% and 30%, respectively of the total tree stem volume.

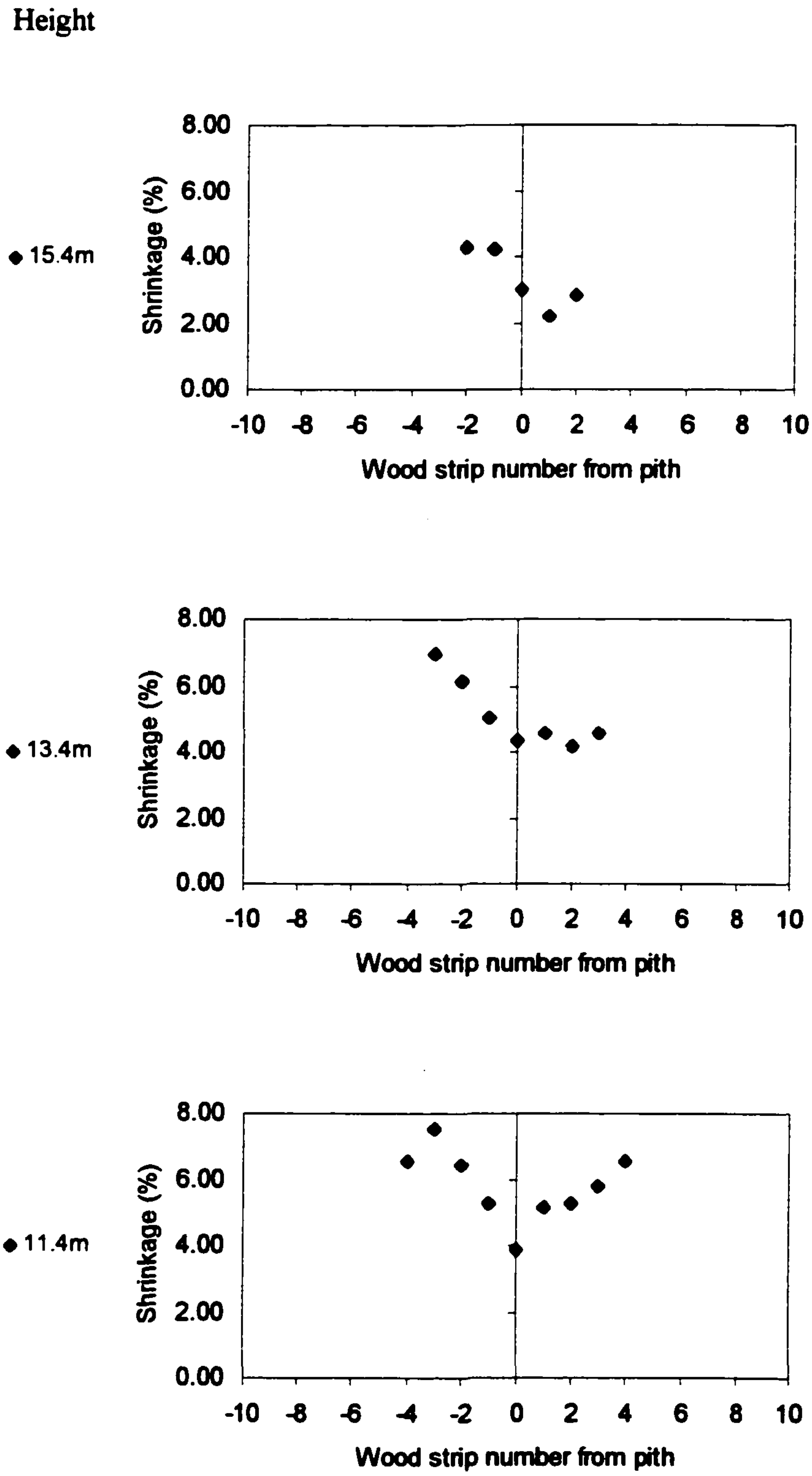


Figure 10. Radial variation of radial and tangential shrinkage at various heights of the tree at west and east aspects. Note that negative wood strip numbers represent west aspect and positive wood strip numbers represent east aspect.

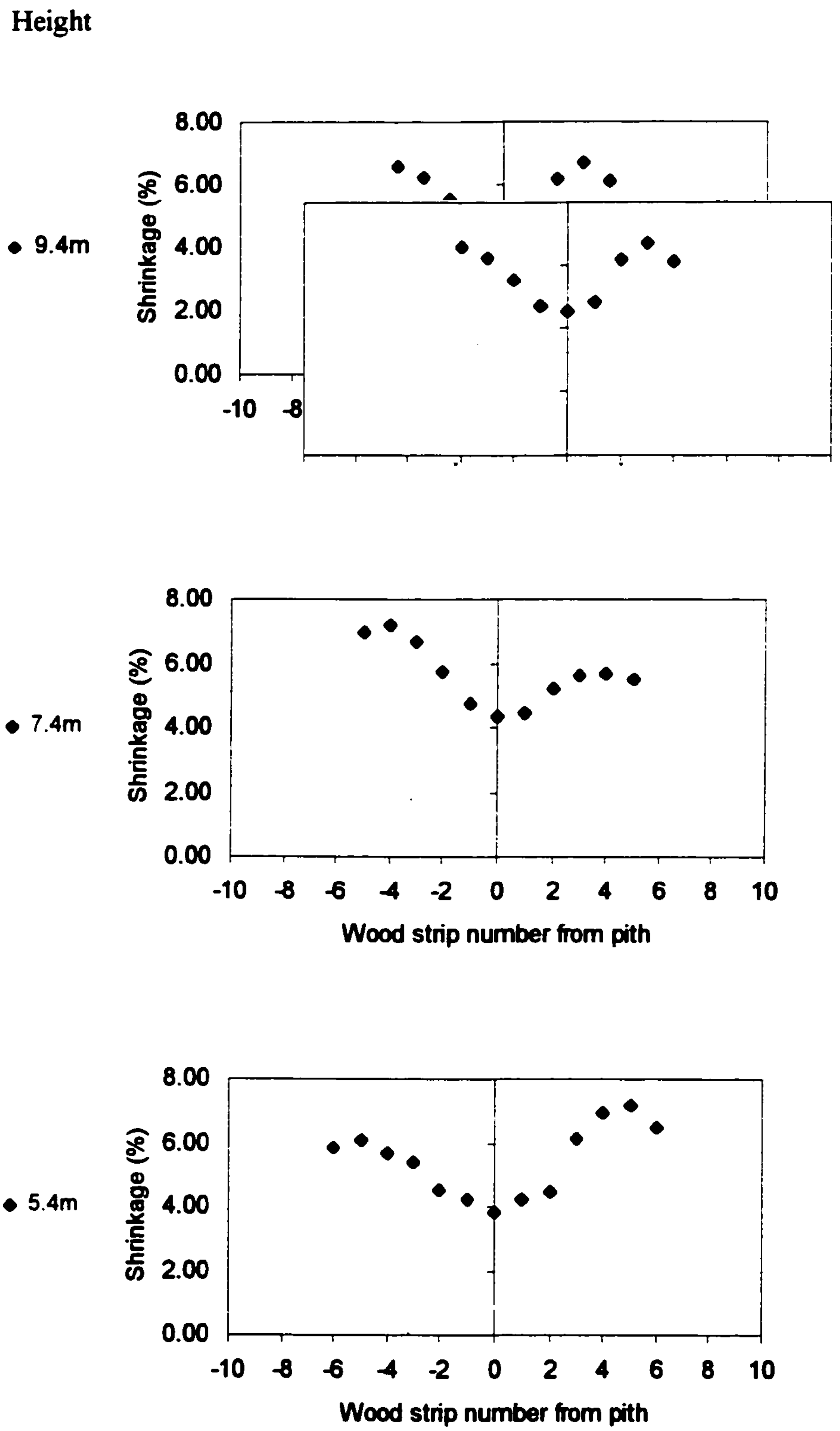
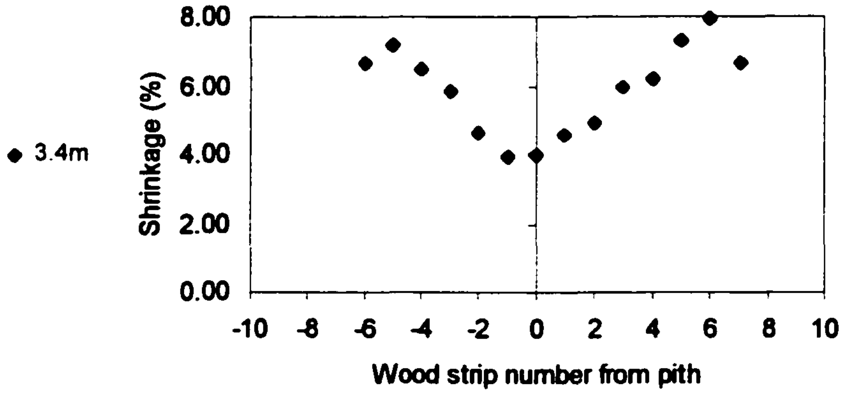
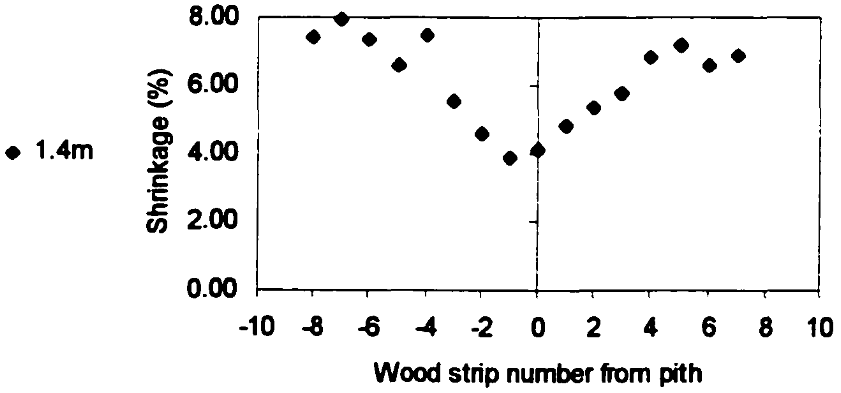


Figure 10. (Continued) Radial variation of radial and tangential shrinkage at various heights of the tree at west and east aspects.

Height





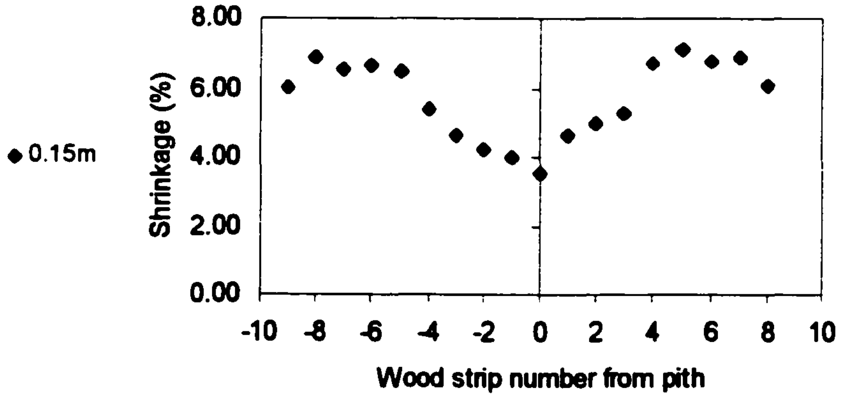


Figure 10. (Continued) Radial variation of radial and tangential shrinkage at various heights of the tree at west and east aspects.

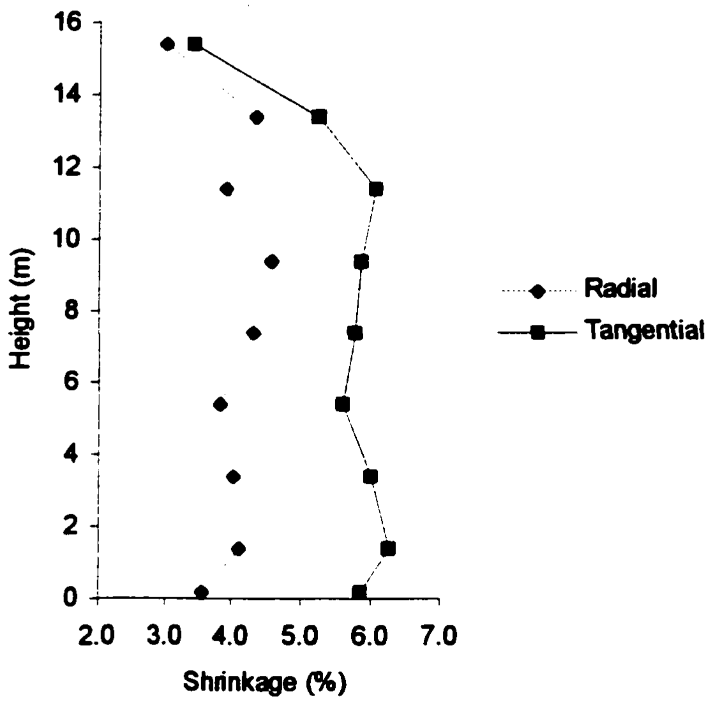


Figure 11. Axial variation of radial and tangential shrinkage at various heights.

Table 11. Multiple comparisons of the means of tangential shrinkage at various heights for testing axial variation.

Height (m)	Mean (%)	Subset[a] 1	2
15.4	3.4	3.4	
13.4	5.3	5.3	5.3
11.4	6.1		6.1
9.4	5.9		5.9
7.4	5.8		5.8
5.4	5.6		5.6
3.4	6.0		6.0
1.4	6.3		6.3
0.15	5.9		5.9

[a] Subsets 1, 2 denote subsets significantly different from each other; the height means within the subsets are not significantly different (Significant at α=0.05).

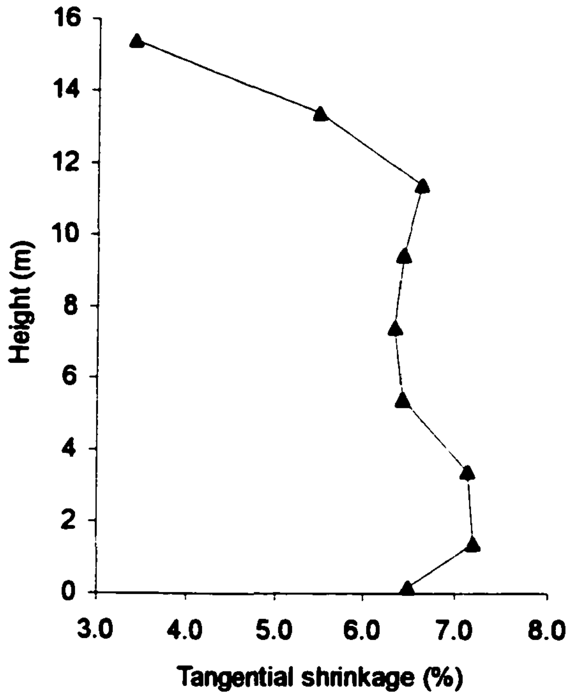


Figure 12. Axial tangential shrinkage variation of the two outermost wood strips at various heights.

Table 12. Multiple comparisons of the means of tangential shrinkage of the two outermost wood strips at various heights for testing axial variation.

Height (m)	Mean (%)	Subset[a] 1	2
15.4	3.4	3.4	
13.4	5.5	5.5	5.5
11.4	6.6		6.6
9.4	6.4		6.4
7.4	6.3		6.3
5.4	6.4		6.4
3.4	7.1		7.1
1.4	7.2		7.2
0.15	6.5		6.5

[a] Subsets 1, 2 denote subsets significantly different from each other; the height means within the subsets are not significantly different (Significant at α=0.05).

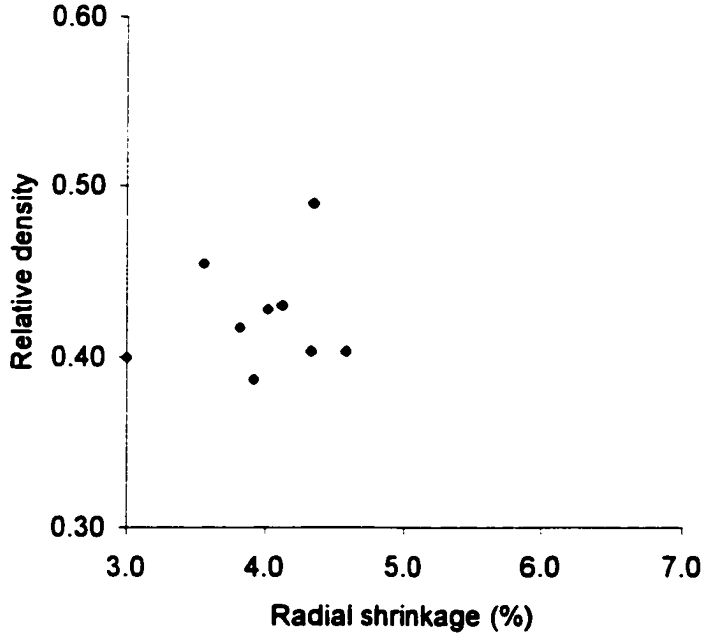


Figure 13.a. Relationship between and radial shrinkage and relative density.

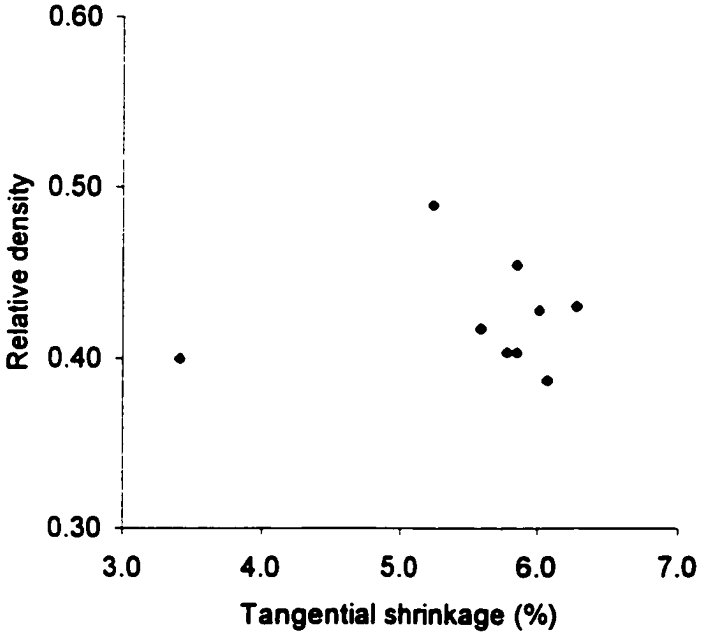


Figure 13.b. Relationship between tangential shrinkage and relative density.

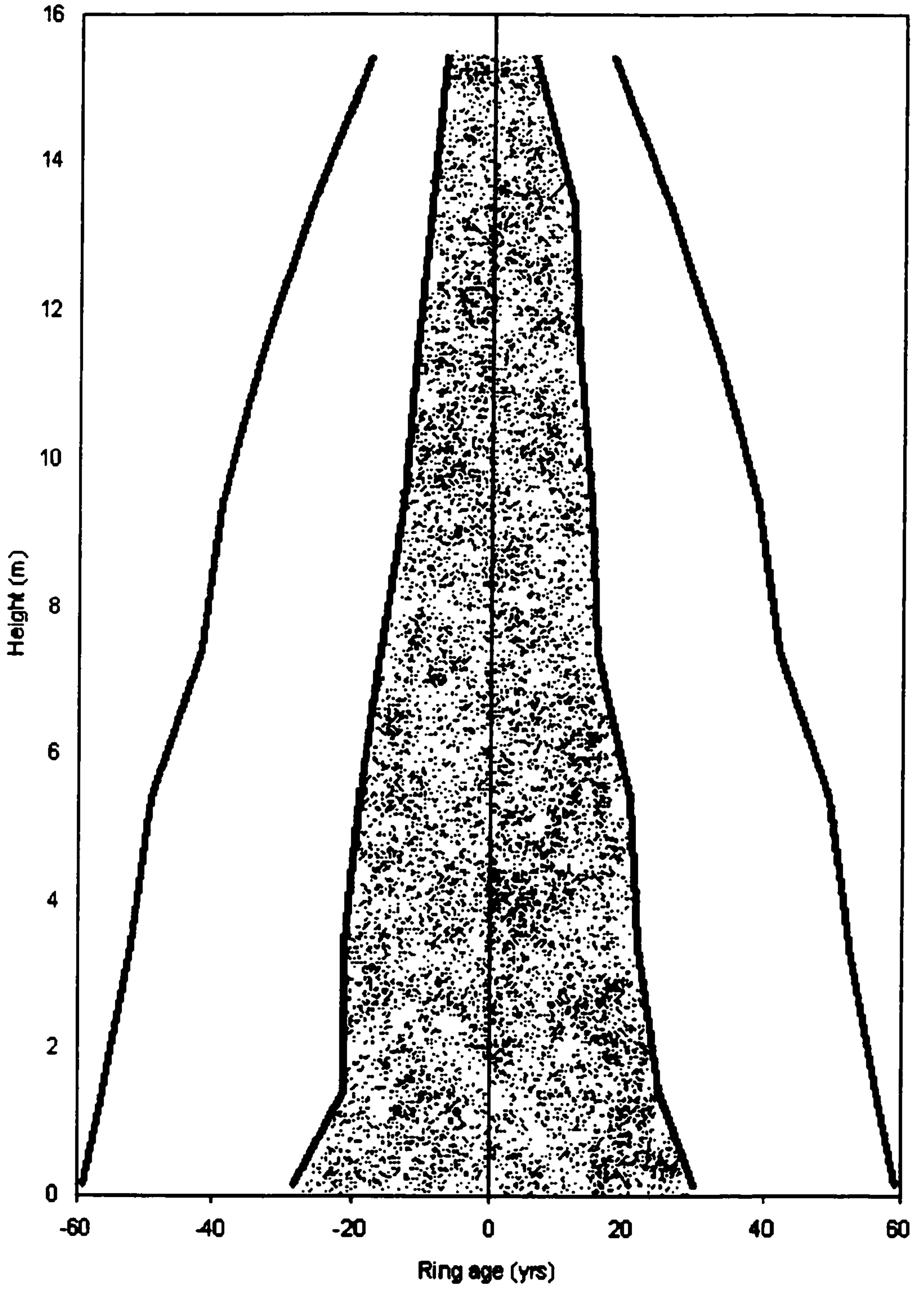


Figure 14. Vertical distribution of juvenile wood (the shaded zone) in the entire stem expressed by ring age. Note that negative ring ages represent west aspect and positive ring ages represent east aspect.

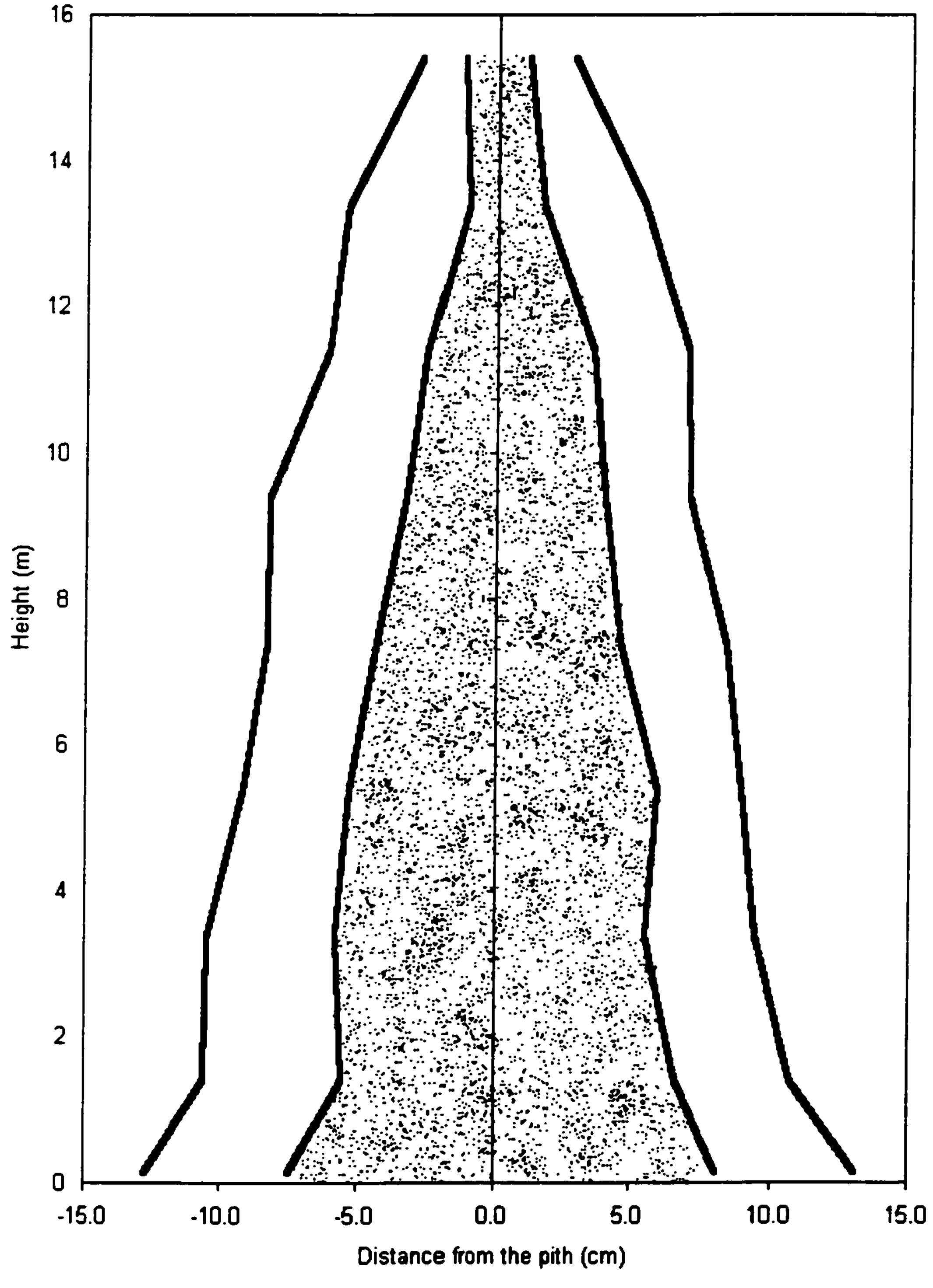


Figure 15. Vertical distribution of juvenile wood (the shaded zone) in the entire stem expressed by distance from the pith. Note that negative distances represent west aspect and positive distances represent east aspect; the actual stem diameter equals the sum of distances (absolutely value) of west and east aspects.

Relationship between Ring Age, Stem Diameter and Percentage of Juvenile Wood Volume

A strong linear correlation exists between percentage of juvenile wood volume and ring age (r = -0.830**), as well as percentage of juvenile wood and stem diameter (r = -0.927**). The percentage of juvenile wood volume, when expressed by ring age, remained 100% when the ring age is less than 26 years. The percentage of juvenile wood volume decreased rapidly with increasing ring age after 26 years (Figures 14 and 16). The percentage of juvenile wood volume, when expressed by stem diameter, remained 100% when the stem diameter was less than 15.2 cm at ring age 26. The percentage of juvenile wood volume decreased rapidly with increasing stem diameter when the tree diameter was greater than 15.2 cm (Figures 15 and 17).

Relationship between Juvenile Wood Zone Width and Cambial Initial Age

There is a strong negative correlation between juvenile wood zone width and cambial initial age. When expressed in ring age (Figure 18.a.), the correlation coefficients between juvenile wood zone width and cambial initial age were -0.97** and -0.98** for the west and east aspect, respectively. When expressed in centimeters (Figure 18.b.), the correlation coefficients between juvenile wood zone width and cambial initial age were -0.96** and -0.97** for the west and east aspect, respectively. The increasing cambial initial age led to the narrower juvenile wood zone width. This indicated that the cambial initial age plays an important role in juvenile wood formation.

Breast Height to Entire Stem Correlation

In order to determine if the breast height values can be used to indicate the characteristics of wood for the entire stem, percentage of juvenile wood volume at the breast height and at the entire stem was studied. The coefficient of determination between breast height and the entire stem for percentage of juvenile wood volume was $r^2 = 0.99$ (Figure 17). The result implies that one can predict the juvenile wood volume for entire stem by using the values at breast height.

Table 13. Gross characteristics of juvenile wood and mature wood at various tree heights determined by tracheid length as juvenile/mature wood boundary in a 60-year-old jack pine.

Height (m)	Total ring age (yrs)	Cambial initial age (yrs)	Tree diameter (mm)	Tree radius (mm)		Juvenile wood Radius (mm)		Juvenile wood No. of rings		Mature Wood Radius (mm)		Mature Wood No. of rings	
				W	E	W	E	W	E	W	E	W	E
15.4	18	42	55.6	27.9	27.7	12.6	11.2	7	6	15.3	16.5	11	12
13.4	26	34	108.0	54.0	54.0	10.4	17.1	9	12	43.6	36.9	17	14
11.4	33	27	131.3	61.2	70.1	25.8	35.4	11	13	35.4	34.7	22	20
9.4	39	21	153.9	82.7	71.2	33.0	39.9	13	15	49.7	31.3	26	24
7.4	42	18	167.4	83.5	83.9	43.7	45.9	16	16	39.8	38.0	26	26
5.4	49	11	182.0	92.1	89.9	52.6	59.5	19	21	39.5	30.4	30	28
3.4	52	8	199.1	104.7	94.4	57.9	55.1	21	22	46.8	39.3	31	30
1.4	56	4	213.0	105.7	107.3	55.6	66.8	21	25	50.1	40.5	35	31
0.15	59	1	258.6	127.7	130.9	75.1	81.0	28	30	52.6	49.9	31	29

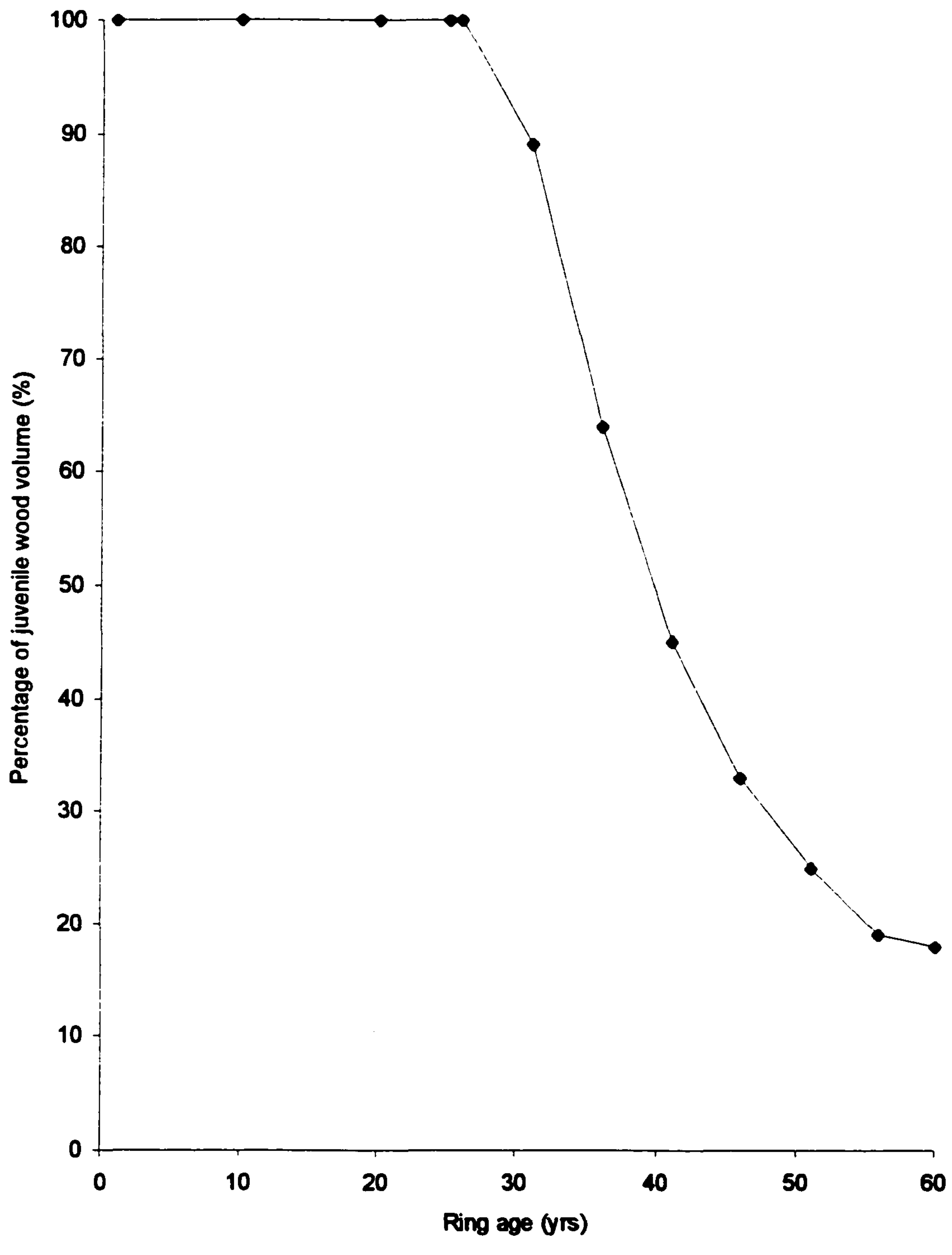


Figure 16. Relationship between percentage of juvenile wood volume and ring age.

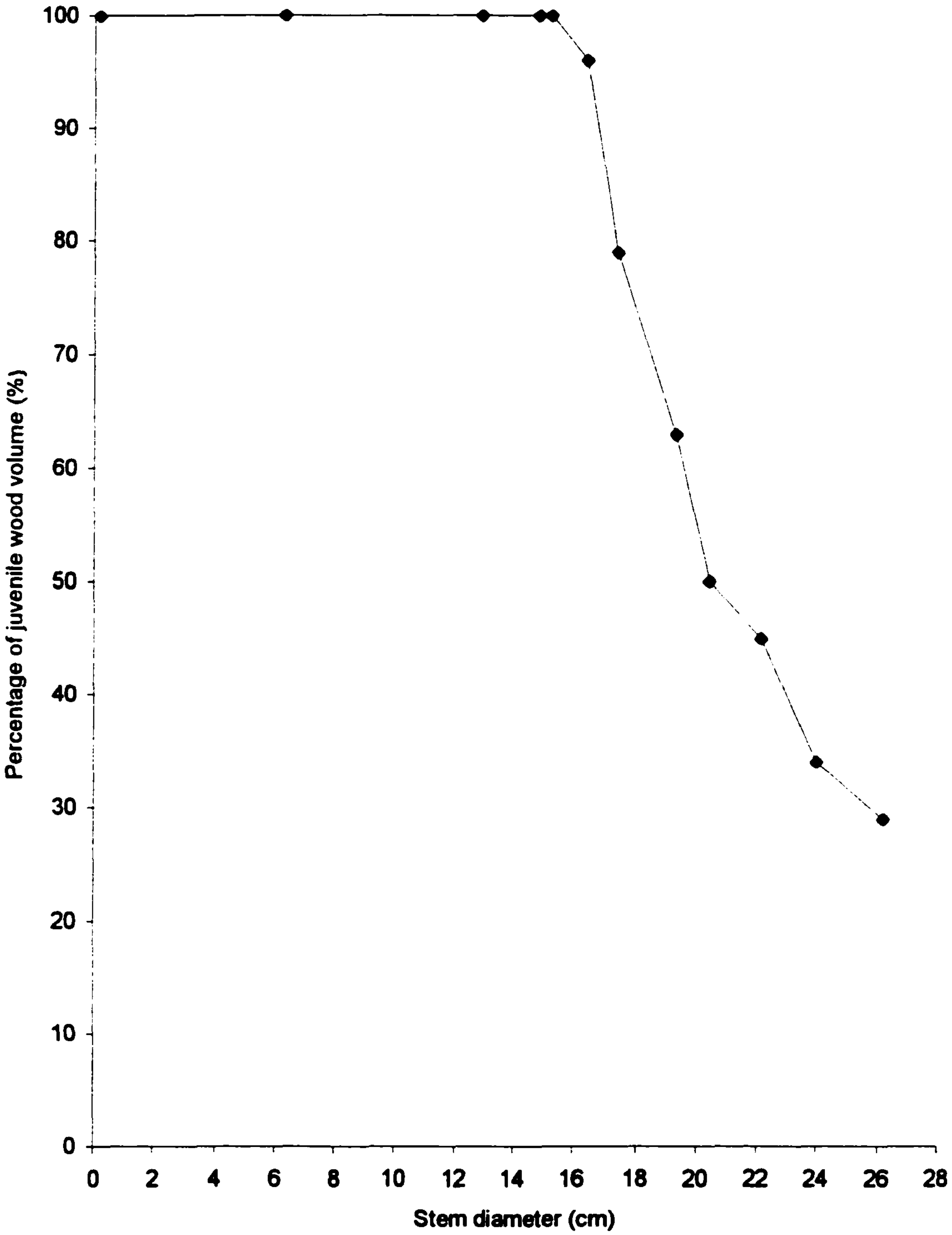


Figure 17. Relationship between percentage of juvenile wood volume and stem diameter.

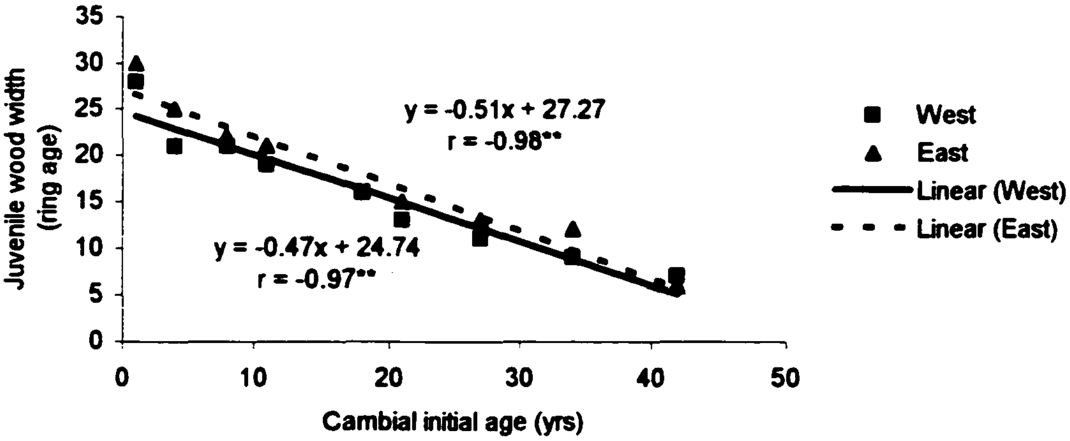


Figure 18.a. Relationship between juvenile wood zone width expressed in ring age and cambial initial age.

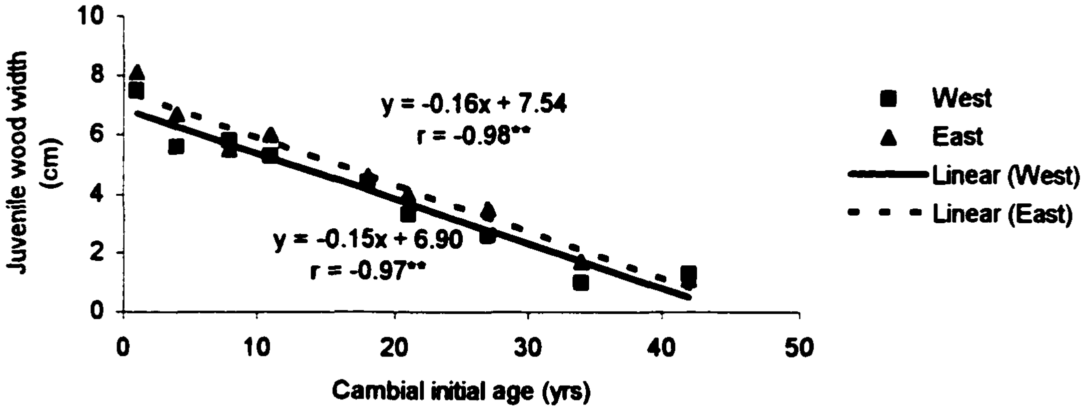


Figure 18.b. Relationship between juvenile wood zone width expressed in centimeters and cambial initial age.

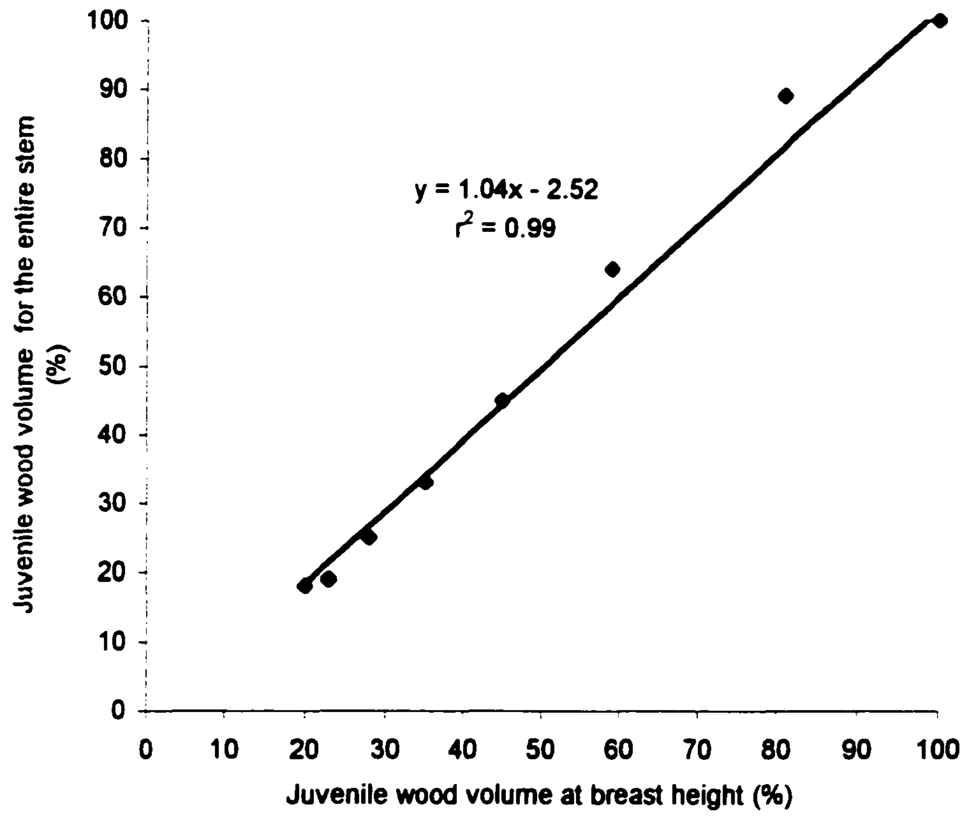


Figure 19. Relationship between entire stem to breast height for percentage of juvenile wood volume.

CORRELATIONS BETWEEN VARIABLES

Table 14 shows the correlation coefficients of the ring age, the tracheid length, the relative density and the ring width in the juvenile and mature wood based on the entire stem.

In the juvenile wood, the tracheid length and the ring age were positively correlated, and the correlation coefficient was 0.884**. The relative density and the ring width were correlated negatively with the ring age. The correlation coefficients were -0.140** for the relative density and -0.318** for the ring width. In the mature wood, the relative density and the ring width were correlated positively with ring age with r = 0.269** and 0.178**, respectively. The tracheid length was correlated negatively with the ring age in the mature wood (r = -0.176**).

In both juvenile and mature wood, the tracheid length was correlated negatively with the relative density and the ring width with r = -0.360** and -0.223** in the juvenile wood, and r = -0.261* and -0.378** in the mature wood, respectively.

The relative density was negatively correlated with the ring width (r = -0.117*) in the juvenile wood, but no correlation was found in the mature wood.

Table 14. Correlation coefficients (r) for the relationship between ring age (RA), tracheid length (TL), relative density (RD), and ring width (RW) in the juvenile and mature wood.

	Juvenile wood (n=305)			
	RA	TL	RD	RW
RA		0.884**	-0.140**	-0.318**
TL	-0.176**		-0.360**	-0.223**
RD	0.269**	-0.261*		-0.117*
RW	0.178**	-0.378**	ns	
	Mature wood (n=438)			

* Significant at α ≤ 0.05.
** Significant at α ≤0.01.

DISCUSSION

TRACHEID LENGTH

Radial Variation

The pattern of tracheid length variation (Figure 3) generally conforms to "Sanio's law", *i.e.*, tracheid length increased rapidly with increasing growth rings from the pith until a maximum was reached, and then increased or decreased slightly in subsequent growth rings (Bailey and Shepard 1915). This radial variation pattern has also been reported by Dadswell (1958) in *Pinus radiata* D. Don, Schmidt and Smith (1961) in *Pinus caribaea* Dougl., and Megraw (1985) in *Pinus taeda* L. This trend was also generalized by Panshin and de Zeeuw (1980), and Zobel and Sprague (1998).

The variation of the slope (increasing rate at which tracheid length increased with ring age from pith outward) from the base up to the top (Figure 4) is in agreement with the results of Kribs (1928) in *Pinus banksiana* Lamb., Megraw (1985) in *Pinus taeda* L., and Yang *et al.* (1986) in *Larix laricina* (DuRoi) K. Koch. They all reported the slope increased with increasing height. That means the rate at which tracheid length increases with ring age from pith is slower at the base than higher in the stem. This also indicates that there is a shorter period for juvenile wood at the top. Yang *et al.* (1986) explained it as "the tree ages, the most recently formed cambium forms mature fibers in a shorter period of time than cambium developed earlier in the life of the tree".

In this study, radial variation of tracheid length was generally consistent for all heights. It is suitable for demarcating the juvenile and mature wood boundary. Though many researchers reported methods for juvenile and mature wood boundary determination by growth ring width (Paul 1957; Zobel *et al.* 1959; Bendtsen and Senft 1986), relative density (Loo *et al.* 1985; Bendtsen and Senft 1986; Di Lucca 1989; Cook and Barbour 1993; Abdel-Gadir and Krahmer 1993ab; Sauter *et al.* 1999), and longitudinal shrinkage (Ying *et al.* 1994). Yang and Benson (1997) summarized four advantages of using cell length as an criterion for demarcating the juvenile and mature wood boundary as: " (1) it can be applied in both natural and plantation grown trees; (2) it can be used in both conifers and hardwoods; (3) it has a high degree of heredity in nature; and (4) it is not greatly affected by growth ring width. "

Axial Variation

In this study, tracheid length in both juvenile and mature wood generally increases from ground level to a certain height and then decreases to the top of the tree (Figure 5). This agrees with Sanio's law (Bailey and Shepard 1915) and Panshin and de Zueew (1980). A similar pattern was also presented by Kribs (1928) in *Pinus banksiana* Lamb., Jackson (1959), Wheeler *et al.* (1966) and Megraw (1985) in *Pinus taeda* L. Taylor *et al.* (1982a) stated that for *Pinus contorta* Dougl. ex Loud. the average tracheid length for top logs was shorter than for butt logs because top logs would contain a higher proportion of juvenile wood with shorter tracheids. Cambial initial age was reported to have a major effect on the axial variation of tracheid length (Yang *et al.* 1986). Bannan (1967) stated a reduced rate of anticlinal division of cambial initials with increasing height, while a reduced rate of anticlinal division of cambial initials led to the increase in tracheid length.

RELATIVE DENSITY

Radial Variation

The general radial pattern of relative density is that relative density is low at the pith, followed by a rapid increase through the juvenile wood and then remains constant near the bark (Panshin and De Zeeuw 1980; Zobel and Sprague 1989). Similar results have been reported in pines by Copper (1960) in *Pinus resinosa* Ait., Manwiller (1972) in *Pinus clausa* (Chapm. ex Engelm.) Vasev ex Sarg., Brown (1973) in *Pinus caribaea* Dougl., Bunn (1981) in *Pinus radiata* D. Don, Zobel *et al.* (1983), Megraw (1985) in *Pinus taeda* L., and in other species by Wilcox and Pong (1971) in *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr., Olesen (1977) in *Picea abies* (L.) Karst., Taylor *et al.* (1982b) in *Picea glauca* (Moench.) Voss.

In this study, relative density was generally high near the pith and decreased outward to a certain ring age, then increased further outward in the juvenile wood. In the mature wood, the variation of relative density became less variable (Figure 6). The variation of relative density found in this study does not agree with the general results reported by the above authors as relative density increased from pith outward and remained constant near the bark. However, there are exceptions to the general pattern. High relative density near the pith followed by a falling off was reported by Krahmer (1966) in *Tsuga heterophylla* (Raf.) Sarg., Tajima (1967) in *Pinus densiflora* Sieb. & Zucc., Kromhout and Toon (1978) and Falkenhagen (1979) in *Pinus caribaea* Dougl., and Lewark (1979) in *Picea abies* (L.) Karst, Keith and Chauret (1986), Villeneuve *et al.* (1987) in *Pinus banksiana* Lamb., and Yang and Hazenberg (1994) in *Picea mariana* (Mill.) B.S.P. According to Kromhout and Toon (1978) and Falkenhagen (1979), the cause of the high relative density at the center was thought to be resin infiltration at the heart of the tree. The relative proportion of earlywood to latewood (latewood percentage) has been reported to be the dominant factor determining the overall relative density (Megraw 1985). Megraw (1985) stated the variation of the whole average relative density depends on the combination of earlywood relative density, latewood relative density, and the percentage of each. According to Zobel and Talbert (1984), the cell size and cell wall thickness have a primary influence on relative density and amount of latewood. The high relative density near the pith in this study may be due to the reason of small cell size, thick cell wall, and a high proportion of latewood. It should be pointed out here that radial variation of relative density varies greatly from tree to tree, from species to species and from site to site (Panshin and de Zeeuw 1980; Zobel and Sprague 1998).

Axial Variation

Usually the axial variation in relative density shows a considerable decrease with increasing height (Panshin and De Zeeuw 1980; Zobel and Spargue 1989). This pattern was also reported in *Pinus resinosa* Ait. by Jayne (1958) and Cooper (1960), in *Pinus caribaea* Dougl. by Brown (1971), in *Pinus resinosa* Ait., *Pinus banksiana* Lamb., *Larix laricina* (DuRoi) K. Koch, *Picea glauca* (Moench) Voss. by Provin (1971), in *Pinus banksiana* Lamb. by Roddy (1983), in *Pinus taeda* L. by Megraw (1985). The axial variation of relative density of this study (Figure 7) both in the juvenile and mature wood is consistent with the above results with exception at the top of the stem. Relative density in both juvenile and mature wood decreased from the base to 11.4 m height, followed by a fluctuation at the upper height.

Relative density both in the juvenile and mature wood at the top of the stem in this study was relatively higher than expected for both aspects. Compression wood could be observed visually from the cross section of disc 8 (13.4 m) where the high relative density occurred. The relative density of compression wood is generally higher than that of normal wood (Haygreen and Bowyer 1996). Another cause of the high relative density was the resin streak around the pith at discs 8 and 9 (13.4 m and 15.4 m). The growth rings near the pith of these two discs were dark-colored and filled with resin. These two reasons may explain the high relative densities at the top two sampling heights.

Zobel (1975b) discussed that the differences in overall relative density with height were a direct result of the proportion of juvenile wood. The percentage of juvenile wood increased with increasing stem height (van Buijtenen 1969). The effect of ring width (growth rate) on relative density has been reported for many conifers (Zobel and van Buijtenen 1989). Paul (1932) and van Buijtenen (1969) found a negative relationship between relative density and ring width in *Pinus taeda* L.: i.e., lower relative density always associates with faster growth. However, Zobel (1970), Pearson and Gilmore (1980) and Megraw (1985) reported that there was no relationship within the same species. MacPeak *et al.* (1987) indicated that fast grown *Pinus tadae* L. had a larger core of juvenile wood

RING WIDTH

Radial Variation

Ring width increased outward from the pith and reached maximum followed by a leveling off in the juvenile wood and remained relatively constant in the mature wood (Figure 8). The radial variation of ring width does not follow the pattern reported by Taras (1965) in *Pinus elliottii* Engelm and Perng (1983) in *Picea rubens* Sarg., as ring width was wider in the juvenile wood and decreased from pith outward followed by a fluctuation in the mature wood. In this study, the first few rings in the juvenile wood had relatively narrow width. This was also found by Paul (1957) as trees did not have wide-ringed wood in the early stage of tree growth. He mistakenly termed the narrow-ringed type of juvenile wood as mature wood. Zobel and Blair (1976) indicated that the physical properties of the narrow-ringed juvenile wood were different from those of mature wood. However, mean ring width in the juvenile wood in this study was wider than that of mature wood (Figure 8). Large environmental variations can often have a greater influence on the ring width of juvenile wood because juvenile wood is more sensitive to growth conditions (Zobel and Sprague 1998).

Comparing radial variation of ring width and relative density in the juvenile wood of this study, relative density has the reversed variation pattern as ring width, decreasing from pith in the juvenile wood. This trend (i.e., high relative density near the pith) appears to be related to narrow rings in the juvenile wood, and was also found by Polge and Illy (1968) in *Pinus pinaster* Ait., van Buijtenen (1969) in *Pinus taeda* L., Burley (1973) in *Pinus patula* Schiede & Deppe., and Nicholls and Wright (1976) in *Pinus radiata* D. Don.

Axial Variation

Kozlowski (1971) and Borgaonkar *et al.* (1996) reported a trend of decreasing ring width from the base to the top of a stem. A similar radial variation of ring width in the juvenile wood was found in this study, but the axial variation pattern of ring width in the mature wood was not found. Studies on the axial variation of ring width with respect to tree height are relatively scarce. Mean ring width of juvenile wood was wider than that of mature wood in this study (Figure 9). This has been reported by others (Rendle 1959b; Panshin and de Zeeuw 1980; Senft *et al.* 1985; Zobel and Sprague 1998).

Compression wood tends to have wide rings on the compression side and narrower rings to the opposite side of the pith (Haygreen and Bowyer 1996). In this study, compression wood was found to have a major effect on ring width as wider rings appeared at the east side of tree trunk at 13.4 m height. However, since it accounted for a small portion from ring 10 to 12 at 13.4 m height, the mean ring width was not affected greatly.

DIFFERENCE BETWEEN WEST AND EAST ASPECTS FOR TRACHEID LENGTH, RELATIVE DENSITY AND RING WIDTH

Tracheid length showed irregular variation between west and east aspects at different height in the mature wood. No significant differences were found in the juvenile wood (Table 4). According to Bannan (1967), exposure to the sun always causes more cambial activity and consequently shorter tracheids.

At most heights, relative density of both juvenile and mature wood in the east aspect was significantly higher than that in the west aspect (Table 7). Ward and Gradiner (1976) also found that relative density in the west aspect was significant lower than that in the east in *Picea sitchensis* (Bong.) Carr. Similarly, Schütt (1962) found that relative density from the east side were always higher than those from the north or south side in *Pinus contorta* Dougl. ex Loud. grown in Europe. Polge and Illy (1968) also found a higher relative density on the east compared to the west side of the tree. On the other hand, Zobel and Rhodes (1955), Walters and Bruckman (1965), and Perng (1983) studied *Pinus taeda* L., *Populus deltoides* Bartr. ex Marsh. and *Picea rubens* Sarg., respectively, and found no significant differences between the aspects. The aspect difference is affected by sunlight, prevailing winds which are indirect cause of the variation (Olesen 1973). More sunlight, and the influence of winds tended to have high relative density according to Olesen (1973).

Ring width in the west aspect was significantly wider than that in the east aspect for mature wood. No significant differences were found between these two aspects in the juvenile wood (Table 10). No relevant literature was found for ring width variation between aspects.

For both tracheid length and ring width, there was no difference between west and east aspects in the juvenile wood (Tables 4 and 10). The significant differences were found for relative density in the juvenile wood at some heights (Table 7). Studies made by Cown *et al.* (1991) show that juvenile wood was less responsive to environmental differences than was mature wood in *Pinus radiata* D. Don.

SHRINKAGE

Mean tangential shrinkage (5.56%) was greater than mean radial shrinkage (3.96%) in this study. This was in agreement with many authors' results (Panshin and de Zeeuw 1980; Desch and Dinwoodie 1996; Haygreen and Bowyer 1996; Forest Products Laboratory 1999). Differences in shrinkage between tangential and radial directions result from many factors (Boyd 1974; Skaar 1988; Desch and Dinwoodie 1998). Desch and Dinwoodie (1998) stated that several anatomical characteristics should be responsible for such a differential radially and tangentially as: " (1) the restricting effect of the ray on the radial plane; (2) the difference in degree of lignification between the radial and tangential walls; (3) small differences in microfibrillar angle between the radial and tangential walls; and (4) the increased thickness of the middle lamella in the tangential direction compared with that in the radial direction".

The radial and tangential shrinkage in this study increased from pith outward and then showed a tendency to level off near the bark (Figure 10). This pattern of variation was also observed by Wilcox and Pong (1971) in *Abies concolor* (Gord & Glend.) Lindl ex Hildebr. and Koubaa *et al.* (1998) in *Populus x euramericana* (Dode) Guinier. No reports of radial variation of shrinkage were found in the *Pinus* species. The relationship between radial and tangential shrinkage and moisture content was reported to be linear at or below the fiber saturation point (Haygreen and Bowyer 1996). Choong and Foggy (1988) reported in *Pinus echinata* Mill. that moisture content was low near the pith and increase outward to a maximum followed by a leveling off. This radial variation pattern of moisture content is the same as that of shrinkage.

Tangential shrinkages in the east aspect at 15.4 m and 13.4 m did not follow the general pattern and were lower than expected values (Figure 10). This was caused by the presence of compression wood in the east aspect at the top of the stem. Compression wood was reported to have smaller tangential shrinkage than normal wood (Panshin and de Zeeuw 1980; Haygreen and Bowyer 1996). This may be due to the differences in both anatomical and submicroscopic structure between compression wood and normal wood (Wardrop and Dadswell 1950; Panshin and de Zeeuw 1980; Haygreen and Bowyer 1996).

Radial and tangential shrinkage generally tends to decrease with increasing height (Wilcox and Pong 1971; Yao 1969). In this study, radial, overall tangential and tangential shrinkage of the two outermost wood strips showed a pattern of decreasing with increasing stem height (Figures 11 and 12). The relationship between shrinkage and relative density has been documented and discussed (Siau 1984; Skaar 1988; Desch and Dinwoodie 1996; Haygreen and Bowyer 1996). It is believed that there is a relationship between shrinkage and relative density: the higher the relative density, the more it will tend to shrink (Desch and Dinwoodie 1996; Haygreen and Bowyer 1996). In this study, relative density and tangential shrinkage have the same axial trend. However, the correlation was weak for relative density and tangential shrinkage (Figure 13). Yao (1969) stated that even for the same species, shrinkage of samples having the same relative density but representing different trees is not necessarily the same. Variation in the shrinkage may be affected by not only relative density alone, but also by microfibril angle, lumen diameter, and presence of extractives (Haygreen and Bowyer 1996; Koubaa *et al.* 1998).

The sizes of the two outermost wood strips are almost the same as the normal size of commercial lumber (*i.e.*, 2×4 inches), so the axial tangential shrinkage variation of the outermost two wood strips has the practical implication in lumber manufacture. In this study, tangential shrinkage of the two outermost wood strips along the tree height did not vary greatly from the base up to 13.4 m. Only the tangential shrinkage value at the very top was significantly lower than those at other heights. This indicates that when lumber is cut along the tree bole, the dimensional changes will be almost the same longitudinally and will not cause serious problems such as warping, checking, splitting, and distortion of the end products (Forest Products Laboratory 1999).

VOLUME OF JUVENILE WOOD

The shape of juvenile wood in this study was conical (Figures 14 and 15) by using ring age and stem diameter as criteria, that is, juvenile wood is wider at the base than at the top. This finding of a conical shape of the juvenile wood agrees with the observations of Zobel and McElwee (1958) for *Pinus taeda* L., and Yang *et al.* (1986 and 1994) for *Larix laricina* (DuRoi) K. Koch and *Cryptomeria japonica* D. Don. While Rendle (1958) however, summarized that juvenile wood formed a cylinder-like column at the center of the tree. A similar cylindrical shape of the juvenile wood in *Pinus taeda* L. and *Pinus elliottii* Engelm. was reported by Zobel *et al.* (1959).

The top zone of this jack pine studied consists of both juvenile and mature wood. A similar report was made by Yang *et al.* (1986) in *Larix laricina* (DuRoi) K. Koch. However, this is not in agreement with the results of Zobel *et al.* (1959) in *Pinus taeda*

L. and *Pinus elliottii* Engelm. and Yang *et al.* (1994) in *Cryptomeria japonica* D. Don. They all reported no mature wood was found at the top of the stem.

In the jack pine studied, the percentage of juvenile wood expressed either by ring age or by stem diameter in the entire stem decreased considerably with increasing age of the tree (Figures 16 and 17). Based on the concept that juvenile wood is cylindrical in shape, Zobel and Blair (1976) found in a 15-year-old *Pinus taeda* L., 85% of the volume was juvenile wood, while in a 40-year-old one it only accounted for 19% of the volume. Kellison (1981) stated that stems of *Pinus taeda* L. contained 19% by volume of juvenile wood at age 45 and as much as 85% by volume at age 15 based on the same concept as Zobel and Blair (1976). In an 81-year-old dominant *Larix laricina* (DuRoi) K. Koch, Yang *et al.* (1986) preferred to consider the juvenile wood as conical in shape instead of cylindrical, and reported the percentage of juvenile wood volume accounted for approximately 44% and 66% of the total stem volume, based on tracheid length and growth ring width as criteria, respectively. In this 60-year-old jack pine, based on ring age or tree diameter as criteria, juvenile wood was 16% and 30% of the total stem volume, respectively. The discrepancy in the percentage of juvenile wood volume may be due to different species or different criteria used to determine the juvenile and mature wood boundary (Yang *et al.* 1986). More rapid growth would probably produce an even larger percentage of juvenile wood (Senft *et al.* 1985; Yang and Hazenberg 1994) and the amount of juvenile wood is greater in plantation grown trees than in natural stands (Zoble and van Buijtenen 1989). Martin (1984) stated "tight spacing and intermediate thinning" were effective ways to reduce the percentage of juvenile wood. Some researchers also reported that silvicultural treatments and genetic manipulations could change the amount and properties of juvenile wood (Rendle 1959b; Zobel *et al.* 1960b;

Schmidt and Smith 1961; Zobel and Blair 1976; Kellison 1981; Zobel and Talbert 1984; Briggs and Smith 1986; Clark and Saucier 1991; Yang 1994; Lindstrom 1997).

The cambial initial age of both west and east aspects has a strong negative relationship with width of juvenile wood in this study (Figure 18). This is in agreement with Yang *et al.* (1986) results for a 45-year-old *Larix laricina* (DuRoi) K. Koch. Yang *et al.* (1994) also found a similar relationship in *Crytomeria japonica* D. Don between these two variables. It was believed by many authors that large tree crowns produce a large amount of juvenile wood (Trendenlenburg 1935; Zobel *et al.* 1959; Knigge 1962; Brunden 1964; Larson 1969; Bendtsen 1978; Panshin and de Zeeuw 1980; Haygreen and Bowyer 1996). In this study, cambial initial age plays an important role in the formation of juvenile wood. It was reported that the formation of juvenile wood was primarily under the influence of cambial initial age (Yang *et al.* 1986 and 1994). Yang *et al.* (1986) further indicated that tree vigor and the size of the tree crown play a minor role in juvenile wood formation.

The coefficient of determination ($r^2 = 0.99$) was very high for the relationship between percentage of juvenile wood volume for entire stem and at the breast height (Figure 19). This indicates that the percentage of the juvenile wood volume at the breast height can be an indicator for that of the entire stem. Many researchers have reported the relationship between breast height wood properties and wood properties of the entire stem (Zobel *et al.* 1960a; Taras and Saucier 1970; Echols 1971; Cown 1981; Brito *et al.* 1984). However, most reports used the relative density to predict the relationship between breast height and entire tree. No reports were found using percentage of juvenile wood volume at the breast height in predicting the entire stem values.

CORRELATIONS BETWEEN VARIABLES

Ring Age and Other Variables

In the juvenile wood, ring age was positively correlated with tracheid length (r = 0.884) and negatively correlated with relative density (r = -0.140) and ring width (r = -0.318) (Table 14).

The strong positive correlation (r= 0.877) between ring age and tracheid length in the juvenile wood indicates that tracheid length is short near the pith and increases with ring age. This was similar to the results of Foelkel *et al.* (1975) in *Pinus oocarpa* Schiede ex Schltdl. and Ladrach (1984) in *Pinus patula* Schiede & Deppe. The negative correlation between ring age and ring width showed that in the juvenile wood, the first number of rings in the juvenile wood was expected to be wider than the later ones. Actually in this study, ring width showed narrow rings near the pith and became wider after few rings in the juvenile wood. However, the correlation was based on the ring widths for the whole stem. The first few narrow rings did not affect the relationship between ring width and ring age.

In the mature wood, ring age was correlated negatively with tracheid length but correlated positively with relative density and ring width (Table 14). Ring age and the other three variables were only weakly correlated. Many authors reported that radial variation of wood properties with ring age become less as trees become older (Cooper 1960; Roddy 1983; Talbert and Jett 1981).

Tracheid Length and Ring Width

In both juvenile and mature wood, tracheid length was correlated negatively with ring width (Table 15). This indicated that shorter tracheid length tends to be related to wider ring width. The same relationship was found by Bisset *et al.* (1951) in *Pinus radiata* D. Don, Echols (1958) in *Pinus ponderosa* Dougl. ex Laws., and Megraw (1985) in *Pinus taeda* L. From Megraw's (1985) point of view, tracheids were always shorter in faster growing trees which always have wider rings. Megraw further explained: "when tree growth is rapid, a greater frequency and survival rate of cambial anticlinal division is required to keep up with girth expansion. More cambial initials are therefore still in some stage of partial elongation from dividing anticlinally by the time they are already dividing periclinally and produing new xylem and phloem cells. This tends to reduce the average fiber length during periods of rapid growth".

Relative Density and Ring Width

In this study, relative density and ring width in the juvenile wood had a negative, but weak correlation (r = -0.117*). There was no correlation between these two variables in the mature wood (Table 14). Zobel (1956), Goddard and Strickland (1964), Bannister and Vine (1981) reported a weak negative correlation between ring width and relative density in *Pinus taeda* L., *Pinus elliottii* Engelm., and *Pinus radiata* D. Don, respectively. Stonecypher and Zobel (1966) found a strong negative correlation between ring width and relative density in the juvenile wood within the same species. A strong negative correlation was also found between ring age and relative density by van Buijtenen (1969) in *Pinus taeda* L. However, Tajima (1967) in *Pinus densiflora* Sieb. & Zucc., Larson (1972) in *Pinus taeda* L., *Pinus echinata* Mill., *Pinus resinosa* Ait., *Pinus* *banksiana* Lamb., Bamber and Burley (1983) in *Pinus radiata* D. Don obtained no relationship between ring age and relative density. Zobel and van Buijtenen (1989) cited 59 studies and summarized the ring width and relative density relationship as "there is generally little or no relationship between wood relative density and ring width of the individual tree". Megraw (1985) also stated that in *Pinus taeda* L. the correlation between relative density and ring width might be positive, negative or nonexistent, depending on circumstances. According to Megraw (1985), if there was a correlation between relative density and ring width, it should be weak to negligible in most cases. These results reflect the effects of different trees, environments and genetics which will result in different relationship between ring width and relative density (Zobel and van Buijtenen 1989).

Tracheid Length and Relative Density

In both juvenile and mature wood of the jack pine stem studied, tracheid length and relative density were correlated negatively with correlation coefficients of -0.360** and -0.261*, respectively (Table 14).

Zobel *et al.* (1960b) and Strickland and Gooddard (1966) found that relative density was negatively correlated to tracheid length in *Pinus taeda* L. and *Pinus elliottii* Engelm., respectively. Goddard and Strickland (1964) reported a negative but weak correlation between these two variables in *Pinus elliottii* Engelm. and it was of little practical significance. No relationship between relative density and tracheid length was reported by Schmidt and Smith (1961) in *Pinus caribaea* Dougl and Megraw (1985) in *Pinus taeda* L. Though relative density and tracheid length were correlated in this study, they are genetically independent from one another (Dadswell 1960; Wellwood and

Smith 1962; Zobel *et al.* 1962; Goggans 1964; Keller 1973; Allen 1985). Zobel and van Buijtenen (1989) stated that both relative density and tracheid length were genetically inherited.

CONCLUSIONS

Tracheid length increased from the pith outward in the juvenile wood and remained constant or leveled off at a certain ring age for different heights towards the bark in the mature wood. The rate of increase in tracheid length with ring age from pith outward increased with increasing height except at 13.4 m due to the presence of compression wood. The mean tracheid length increased from the base upward, reaching a maximum at 3.4 m and 5.4 m for juvenile and mature wood, respectively, followed by a decrease further to the top. The mean tracheid lengths of west and east aspects were not significantly different from each other in the juvenile wood. In the mature wood, the mean tracheid length of the west aspect was significantly longer than that of the east aspect at 7.4 m and 3.4 m, while the mean tracheid length of the west aspect was significantly shorter than that of the east aspect at 9.4 m and 1.4 m. At all other heights in the mature wood, the mean tracheid length of the west and east aspects were not significantly different.

Relative density generally decreased with ring age from the pith outward in the juvenile wood and remained less variable in the mature wood, with an exception of a reversed pattern at 0.15 m height. Relative density decreased with increasing height with the exception of relatively high values at 13.4 m height in both juvenile and mature wood due to the presence of compression wood. The mean relative density of the west aspect was significantly different from that of the east aspect in the juvenile wood at 13.4 m, 5.4 m, 1.4 m and 0.15 m. In the mature wood, the mean relative density of the west aspect was significantly different than that of the east aspect for all heights with an exception at 7.4 m.

Ring width increased with ring age from pith outward in the juvenile wood and fluctuated in the mature wood. Ring width decreased with increasing height in the juvenile wood. No axial trend was found of ring width variation in the mature wood. Ring width in the juvenile wood was wider than that in the mature wood. Ring width of the west aspect was significantly wider than that of the east aspect in the mature wood. There was no significant difference between ring width in the west and east aspects in the juvenile wood.

Tangential shrinkage was greater than radial shrinkage. Radial and tangential shrinkage generally increased from the pith outward to the bark, reaching a maximum followed by a leveling off. Radial, tangential shrinkage for both entire stem and the two outermost wood strips decreased with increasing height with an exception at 0.15 m. The lowest shrinkage occurred at the top for both juvenile and mature wood. There was no close relationship between radial or tangential shrinkage, and relative density.

The percentage of juvenile wood was 16% and 30%, respectively, of the entire stem volume based on ring age and stem diameter as criteria. The juvenile wood core was conical in shape. Ring age and stem diameter had strong negative correlation with percentage of juvenile wood volume. There was a strong negative correlation between juvenile wood width and cambial initial age. The values at breast height can be used to predict the entire stem for percentage of juvenile wood volume.

Ring age was correlated positively with tracheid length, and correlated negatively with ring width and relative density in the juvenile wood. In the mature wood, ring age was correlated negatively with tracheid length, and correlated positively with ring width and relative density Tracheid length and relative density were negatively correlated in both juvenile and mature wood. Relative density was negatively correlated with ring width in the juvenile wood, but no correlation was found in the mature wood.

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APPENDICES

Appendix I. Field data of the sampled stand.

Date	Oct. 29, 2000
Location	Longitude 89°22' Latitude 48°39' Jack Haggerty Forest
Elevation	536 m (Above Sea Level)
Stocking	0.7
Site index	11

Appendix II. Numbers of growth rings and diameter at various height sampled in the jack pine studied.

Height (m)	Number of rings	Diameter (cm)
15.4	18	5.6
13.4	26	10.8
11.4	33	13.1
9.4	39	15.4
7.4	42	16.7
5.4	49	18.2
3.4	52	19.9
1.4	56	21.3
0.15	59	25.9

Appendix III. Mean tracheid length (mm) at various heights in the juvenile and mature wood of the west and east aspect.

Height (m)	West		East		Mean		Overall mean
	Mature	Juvenile	Mature	Juvenile	Mature	Juvenile	
15.4	2.54	1.58	2.54	1.67	2.54	1.63	2.08
13.4	2.75	1.50	2.41	1.35	2.58	1.42	2.00
11.4	2.96	1.78	2.83	1.84	2.9	1.81	2.35
9.4	3.09	2.08	3.20	2.09	3.15	2.09	2.62
7.4	3.35	2.19	3.06	2.02	3.21	2.11	2.66
5.4	3.44	2.27	3.46	2.25	3.45	2.26	2.86
3.4	3.36	2.23	3.26	2.39	3.31	2.31	2.81
1.4	3.19	2.25	3.35	2.40	3.27	2.33	2.80
0.15	2.78	2.01	2.88	2.08	2.83	2.05	2.44

Appendix IV. Mean relative density at various heights in the juvenile and mature wood of the west and east aspect.

Height (m)	West		East		Mean		Overall mean
	Mature	Juvenile	Mature	Juvenile	Mature	Juvenile	
15.4	0.37	0.45	0.35	0.44	0.36	0.44	0.40
13.4	0.39	0.45	0.43	0.56	0.41	0.51	0.46
11.4	0.37	0.39	0.40	0.38	0.38	0.38	0.38
9.4	0.40	0.39	0.42	0.40	0.41	0.40	0.40
7.4	0.40	0.40	0.42	0.42	0.41	0.41	0.41
5.4	0.39	0.39	0.44	0.45	0.41	0.42	0.42
3.4	0.41	0.43	0.45	0.42	0.43	0.42	0.43
1.4	0.42	0.41	0.46	0.43	0.44	0.42	0.43
0.15	0.46	0.46	0.48	0.42	0.47	0.44	0.46

Appendix V. Mean ring width (mm) at various heights in the juvenile and mature wood of the west and east aspect.

Height (m)	West		East		Mean		Overall mean
	Mature	Juvenile	Mature	Juvenile	Mature	Juvenile	
15.4	1.4	1.8	1.4	1.9	1.9	1.0	1.4
13.4	1.3	2.1	1.0	2.4	2.3	1.2	1.7
11.4	1.6	2.5	1.8	2.7	2.6	1.4	2.0
9.4	2.0	2.5	1.4	2.7	2.6	1.4	2.0
7.4	1.4	2.7	1.3	2.5	2.6	1.3	1.9
5.4	1.6	2.9	1.3	2.5	2.7	1.3	2.0
3.4	1.5	2.7	1.5	2.9	2.8	1.5	2.1
1.4	1.4	2.8	1.1	2.8	2.8	1.4	2.1
0.15	1.6	2.8	1.7	2.7	2.8	1.4	2.1

Appendix VI. Mean radial tangential shrinkage (%) at various heights of the west and east aspect.

Height (m)	Radial	Tangential		
		West	East	Mean
15.4	3.0	4.3	2.5	3.4
13.4	4.3	6.0	4.5	5.3
11.4	3.9	6.4	5.7	6.1
9.4	4.6	5.8	6.0	5.9
7.4	4.3	6.3	5.3	5.8
5.4	3.8	5.3	5.9	5.6
3.4	4.0	5.8	6.2	6.0
1.4	4.1	6.3	6.2	6.3
0.15	3.6	5.7	6.1	5.9
Mean	4.0	5.8	5.4	5.6

Appendix VII. Mean tangential shrinkage (%) of the two outermost wood strips at various heights of the west and east aspect.

Height (m)	West			East			Overall mean
	Strip #1	Strip #2	Mean	Strip #1	Strip #2	Mean	
15.4	4.3	4.2	4.3	2.9	2.2	2.5	3.4
13.4	6.9	6.2	6.5	4.6	4.2	4.4	5.5
11.4	6.6	7.5	7.0	6.6	5.8	6.2	6.6
9.4	6.6	6.3	6.4	6.1	6.7	6.4	6.4
7.4	6.9	7.2	7.1	5.5	5.7	5.6	6.3
5.4	5.8	6.1	6.0	6.5	7.2	6.9	6.4
3.4	6.7	7.2	6.9	6.7	7.9	7.3	7.1
1.4	7.4	7.9	7.7	6.9	6.6	6.7	7.2
0.15	6.0	6.9	6.5	6.1	6.9	6.5	6.5

Appendix VIII. Percentage (%) of juvenile wood volume expressed by ring age (yrs) (entire stem and breast height) or stem diameter (cm) (entire stem only).

Entire stem		Breast height		Entire stem	
Ring age	Percentage	Ring age	Percentage	Diameter	Percentage
1	100	1	100	0.2	100
10	100	10	100	6.3	100
20	100	20	100	12.9	100
25	100	25	100	14.8	100
26	100	26	100	15.2	100
31	89	31	81	16.4	96
36	64	36	59	17.4	79
41	45	41	45	19.3	63
46	33	46	35	20.4	50
51	25	51	28	22.1	45
56	19	56	23	24.0	34
60	18	60	20	26.2	29

Appendix IX. Juvenile wood zone width expressed in ring age and centimeters and cambial initial age (yrs) at various heights.

Height (m)	Cambial initial age	Juvenile wood width expressed in ring age		Juvenile wood width expressed in centimeters	
		West	East	West	East
15.4	42	7	6	1.3	1.1
13.4	34	9	12	1.0	1.7
11.4	27	11	13	2.6	3.5
9.4	21	13	15	3.3	4.0
7.4	18	16	16	4.4	4.6
5.4	11	19	21	5.3	6.0
3.4	8	21	22	5.8	5.5
1.4	4	21	25	5.6	6.7
0.15	1	28	30	7.5	8.1

Appendix X. Images of entire stem growth ring variation (next page).