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Structure, density and shrinkage variation within silver maple

El-Sayed A. Ezzat Kandeel
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STRUCTURE, DENSITY AND SHRINKAGE VARIATION
WITHIN SILVER MAPLE

by

El-Sayed A. Ezzat Kandeel

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Wood Science

Approved:

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1968
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INTRODUCTION

More complete information on the sources and patterns of variation in properties of hardwood trees is necessary for their efficient conversion into finished products. This information is of particular importance to the pulp and paper industry (Wollmage, 1965). Since the within-tree variation in wood properties constitutes a major part of the variability that can be expected for the species, the establishment of inherent within-tree variation patterns is required for successful evaluation of wood properties (Richardson, 1961).

Wood properties such as ring width, proportion of structural elements, density and shrinkage vary from the base to the top of the tree as well as from the pith to the bark. The explanation of the variations in these properties can, ultimately, be found in the influence of intrinsic and environmental factors. However, the variability in these properties within the species can be best described by first considering the vertical and horizontal patterns of variations which appear within a single tree (Panshin et al., 1964).

The objective of this study was to characterize patterns of variation of ring width, proportion of wood elements, specific gravity and shrinkage within a silver maple tree (Acer saccharinum L.) as well as to find the relationships of these wood properties to such variables as height, cambial age and year of formation.
Silver maple is one of Iowa's most important lumber, pulp and veneer species used in increasing amounts for furniture, paper and other products requiring high quality wood. It is third in the state in terms of volume of saw timber produced annually surpassed only by American elm and cottonwood (Brundemuehl et al., 1961). The importance of this species is enhanced by its rapid growth rate and the fact that it grows well on land unsuitable for agriculture due to frequent flooding.

Information on within-tree patterns of variation in ring width, wood elements, wood density and shrinkage and the influencing factors will enable wood scientists to proceed more effectively with research on variation of such properties between trees and within species. Such information should lead to more reliable sampling methods for evaluating variation in wood properties prior to industrial processing and improve the assessment of wood quality.
REVIEW OF LITERATURE

Ring Width

The annual ring forms a starting point for most investigations in wood anatomy and evaluation of physical properties. However, there have been few critical studies of its variation throughout the tree. Since the early fifties a few outstanding investigations have been conducted (Onaka, 1950) (Duff and Nolan, 1953) (Forward and Nolan, 1961) (Richardson, 1961) and (Walters and Soos, 1962). All these studies have been on a limited number of coniferous species. Hence, the general similarity assumed among species must be checked carefully before applying these principles on hardwoods. Duff and Nolan (1953) presented data on within tree variation of ring widths. They described the horizontal and vertical organization of growth in terms of three sequences. In type 1, or the oblique sequence, changes in ring width within each single ring are followed from the top of the tree downward (i.e. rings formed in the same year but from cambia of different ages). Type 2, or the horizontal sequence, is shown by plotting ring widths from the pith to the bark at intervals of height. The rings in this sequence are formed by cambia of different ages during different seasons. In type 3, or the vertical sequence, the ring widths are plotted for successive internodes down the tree but at constant ring number from the pith (i.e. rings formed by cambia of approximately the same age). Duff and Nolan
(1953) in a study of red pine, showed that in the first sequence the ring width increases rapidly to about the fifth internode from the apex and then decreased towards the base of the tree, finally losing any appearance of systematic pattern. The second sequence (horizontal) is essentially similar. However, no systematic pattern of increase or decrease was observed in the third sequence (vertical). The existence of these patterns of variation in ring width was explained on the basis of intrinsic and extrinsic factors controlling cambial growth (Walters and Soos, 1962). The first sequence or the oblique, reveals the effect of intrinsic factors. The year of formation is constant in this sequence. Duff and Nolan (1953) postulated that this pattern is the result of intrinsic factors such as nutritional gradients which are induced by the distribution of the foliage along the tree stem. However, the change in cambial age, forming the annual layer up the tree, produced another intrinsic factor which may be considered. The second sequence (horizontal) involved both the effect of cambial age and year of formation on the growth. In the third sequence (vertical) the cambial age is constant while the year of formation varies. This reveals the effect of extrinsic factors (Duff and Nolan, 1953).

To illustrate the variation in the form of the annual sheath, Farrar (1961) has reviewed the work of Onaka (1950), Duff and Nolan (1953) and others on a hypothetical tree. In this tree, during the early years of its life, ring width
increases from the apex to base, assuming that the tree is free from competition and the crown extends to the base. As this tree gets older, competition increases and the lower limbs die and maximum ring width occurs in the part of the most foliage in the crown. Later on, the position of maximum width moves up the tree. If the tree is released, substantial changes occur in the shape of annual layer (Onaka, 1950)(Farrar, 1961). In this case the lower part of the annual layer becomes much wider and ring width increases all the way from apex to the base. Forward and Nolan (1961) noted that this new shape does not persist for more than a few years then the annual layer resumes gradually its normal form with a maximum near the node bearing the most foliage.

Following the work of Duff and Nolan (1953) on red pine, other studies have been reported on other coniferous species (Richardson, 1961) (Walters and Soos, 1962). The vertical and horizontal organization of growth of these coniferous species were described in terms of Duff and Nolan's terminology. The ring width sequences were shown to parallel those recognized earlier for red pine (Richardson, 1961) (Walters and Soos, 1962).

The variations in the annual layer have been explained in several studies on conifers. Farrar (1961) in a comprehensive review, showed that in the apical internode the ring is comparatively narrow. Its width increases rapidly for a few internodes and reaches a first maximum near the whorl of the most foliage (Farrar, 1961). In the lower part of the crown
ring width decreases, then at the base of the tree the ring becomes thicker. This generalized picture of variation in ring width is subject to considerable variation (Farrar, 1961). Several factors that might influence the vertical and horizontal organization of growth, have been reported in different studies. However, no specific results concerning these factors and their influence on hardwoods are yet available. The influence of the stand density has been reported. In trees which are more crowded, the internode of maximum ring width is found near the top of the tree. The whole layer is thinner and with very little variation in thickness. In a severely crowded tree, the sheath may not extend to the base (Farrar, 1961). It is reported that missing and discontinuous rings were observed in suppressed trees (Larson, 1956). In open grown trees with crowns extending to the base, ring width may increase all along the stem (Onaka, 1950). In the upper part of the stem the shape of the annual ring is similar to that of a dominant tree in a stand because both are exposed to full sunlight (Farrar, 1961). Walters and Soos (1962) have categorized the factors controlling cambial growth into intrinsic and extrinsic factors. Intrinsic factors are such as nutritional gradients while extrinsic factors are either systematic or randomized. Systematic extrinsic factors controlling ring widths are such as site and stand density (Onaka, 1950)(Walters and Soos, 1962). Randomized extrinsic factors are such as climatic conditions (Walters and Soos, 1962). Erickson (1949) reported that crown
surface area was correlated with the annual cross-sectional increment of the tree.

Wood Elements

Variation in proportion of various wood elements (vessels, rays and fibers) have been investigated in a few studies. The influence of various wood elements on pulp properties has created an interest in these investigations. Vessel members, longitudinal parenchyma and ray parenchyma are generally thought of as having a negative influence on paper properties (Forest Biology Subcommittee, Tappi, 1960). The same reference points out that large vessel members are undesirable in printing grades of paper because they tend to be pulled out of the surface during printing. Dadswell and Wardrop (1959) reported that higher ratio of fibers to vessels and ray elements is desirable for pulp from hardwood species.

Variations in proportion of structural elements were investigated in different studies. Myer (1922) related the large variation in ray volume to inheritance. Myer (1930), in a survey study on American woods, reported a higher increase in the vessel volume from the stump to sixteen feet in height. The ray volume was found in the same study to be greater at the stump and low at a higher position then high at the top of merchantable height. Desh (1932) found that the number of vessels per unit area increases with the decrease in ring width. Vasiljevic (1951) in a study on *Acer platanus* L.
found that number of rays per square millimeter was greater in narrow ringed than in wide ringed wood. Horizontal variation in vessel element size in *Acer platanoides* L. was found to confirm Sanio's first law in that vessel element size increases from pith to periphery and also varies with height in the stem. However, vessel size also varied with the ring width (Vasiljevic, 1955). Scaramuzzi (1956) studied the proportion of wood elements in a single ten-year old stem of *Populus* sp. He used three cross sections from the whole stem; and generally concluded that little variability was found in proportion of wood elements within the growth rings and across the radius. The variation in fiber volume was reported by the same author to be less than that for vessel volume within the ring; however, it was approximately equivalent across the radius. Ray volume showed a wider range of variation across the radius in the same study. Scaramuzzi (1956) reported that the correlation between proportion of wood elements varies at different heights, while a negative correlation was found between vessel and ray volume at ground level, and between vessel and fiber volumes at the top level; an intermediate situation occurred at the ten meter level and closer to the top (Scaramuzzi, 1956).

**Wood Density**

Consideration of wood density is of prime importance in both evaluation of pulp yield and structural properties of
wood. The study of specific gravity variation in tree stem has, in recent years, received new impetus particularly in relation to the production of pulpwood (Schniewind, 1961). Krahmer (1966) indicated that information on specific gravity variations within the tree, correlated with possible causes of variation, is effective for estimating wood quality and helpful in tree improvement programs. Wangaard et al. (1966) concluded that there are significant effects of wood specific gravity upon pulp sheet properties. Due to this relative importance of specific gravity both to the pulp and paper industry and in structural use of wood, there has been considerable research in this area. Literature has included studies on both hardwoods and conifers. Since it is known that entirely different conclusions may be arrived at, depending on the species, this review is limited largely to studies dealing with diffuse-porous species. Major studies of within-tree patterns of variation in density and possible factors influencing them are included even though the species were not diffuse-porous.

The within-tree variation in wood density is distinctly different for ring-porous hardwoods than for diffuse-porous. Prestemon (1966). Paul (1956) found that large variation in specific gravity among poplar stands and within sites have a bearing on the production of solid wood substance. Larson (1962) indicated that basic patterns of variation of wood quality are undoubtedly controlled by heridity with other factors such as site and environments. Gohre (1960) found that
density within poplar stems has a complex pattern. He found that variation between and within trees was very large (Gohre, 1960). Farmer and Wilcox (1966), in a study of specific gravity variation in cottonwood, found that most variation was associated with individual trees. Richardson (1961) used the method of Duff and Nolan (1953) to examine the density patterns of variation in Corsican pine. Examination of the oblique sequence revealed a decrease in density to a minimum at the fifth internode from the apex and then increase to the twentieth internode beyond which there was no systematic variation. Thus, the density pattern in Corsican pine was almost the converse of that revealed by ring width pattern in the oblique sequence. At any level, density was high in the first ring from the pith, decreased to a minimum around the sixth ring and then increased. Density exhibited no systematic variation in the vertical sequence. Thus, there are two systematic within-tree patterns of density variation and one unsystematic in conifers (Richardson, 1961). Saucier and Taras (1966), in a study of specific gravity variation in one year-old red maple sprouts, found that the specific gravity does not vary appreciably between internodes except at the last formed internodes near apex. They concluded that sampling at fixed percentages of total height reveals patterns of variation equally well as complete internodal sampling.

Considerable literature is available on research concerning the influence of various factors on wood density; only a
few, however, deal with diffuse-porous hardwoods. Although these studies have resulted in an abundance of pertinent facts, the primary controlling factors have not as yet been discovered. The controversies in the literature about these factors may be attributed to the interrelations of the independent variables in influencing wood density (Brunden, 1964). Panshin et al. (1964) reported that in diffuse-porous hardwoods, there is little relationship between the specific gravity and ring width for mature timber. However, exceptions are found in trees with extremely slow growth increments containing very high percentage of vessel volume which result in a low specific gravity. Paul (1963) indicated that within diffuse-porous species considerable differences in the pattern of ring width and specific gravity was exhibited such as differences between sugar maple and aspen. Lenz (1954) found no definite relation between ring width and wood density in some poplars cultivated in Switzerland. Radcliff (1953) detected no significant correlation between rate of growth and strength properties of sugar maple. Paul (1963) reported that continued growth retardation in the older trees resulted in a progressive decrease in specific gravity towards the bark in aspen, red maple and basswood. Erickson (1949) found that the specific gravity of yellow poplar was inversely related to number of rings per inch with a weak correlation. Paul (1963) reported that the wood of highest specific gravity has been found in young trees of yellow poplar that maintain a fairly rapid to moderate growth
rate. In general, he did not find a very strong relationship between rate of growth (rings per inch) and specific gravity in yellow poplar (Paul, 1963). Wilde and Paul (1959) reported that some stands of *Populus sp.* that grew more slowly in diameter within a site produced heavier wood than those that grew rapidly. Kennedy and Smith (1959) observed an inverse relation between rate of growth and wood specific gravity in poplar. Chech *et al.* (1960) in a study on one-year old cottonwood arrived at similar conclusions. Paul (1963) confirms this by reporting that the low specific gravity of *Populus sp.* and hybrids is associated with rapid growth.

There is a great deal of controversy as to whether the effect of age or growth rate predominates on influencing the density gradients in the tree. Brunden (1964) reported that the effect of the age of the tree when wood was formed in specific gravity within the tree was very weak in red pine. In a study on yellow poplar, Erickson (1949) found that the age has some effect on specific gravity, especially in blocks of twenty rings per inch or less. However, he indicated that these results were not considered conclusive. Paul (1963) concluded that the yellow poplar wood of highest specific gravity has been found in young trees that maintain a fairly rapid to moderate growth. Lenz (1954) found that wall thickness increased with age in poplar. However, Paul (1956) reported that in *Populus sp.* and hybrids, age of the trees did not show a consistent relation to the specific gravity of the wood.
However, in sugar maple which is another diffuse-porous species (Paul, 1963) found that wood produced by young trees is heavy and hard whether the growth rate was rapid or slow.

The variation in density from pith to the bark, or the horizontal sequence in Richardson's study on Corsican pine (1961), have been studied by many wood technologists. Below the crown, the wood near the pith was formed on the part of the stem bearing living branches while the wood on the outer part of the bole was formed on the branchless part of the stem. This horizontal sequence of density variation is systematic and controlled by intrinsic factors such as age, nutrient gradients and extrinsic effects in the years of formation. Wood in this sequence in the successive rings is derived from cambia of different age and in different years of formation (Duff and Nolan, 1953). This effect of distance from the pith in the horizontal variation in wood density differs from conifers to hardwoods. Bryan and Pearson (1955) in a study on Sitka spruce, Richardson (1961) in a study on Corsican pine, and Nylander (1963) in a study on Norway spruce found that the density decreases for a number of rings from the pith and then increases outwardly. Spurr and Hsuing (1954), Yandle (1956), Jayne (1958) and Brunden (1964) found in different studies on conifers that specific gravity increases from the pith outwards. In forest grown ring-porous species, density was reported to decrease from pith to bark while the inverse has been reported for diffuse-porous hardwoods (Paul, 1963). Thus,
diffuse-porous species appear generally to be similar to soft woods in horizontal variation in wood density (Prestemon, 1966). Desh (1932) in a study on Acer sp., Betula sp., Fagus sp. and some other dicotyledonous species, found that at a given height in the tree, specific gravity tended to be low at the pith then increases outwards to a certain point and then decreases to the bark. Paul and Baudendistel (1945) reported an increase from the pith outwards in sugar maple. However, Lenz (1954) did not detect a consistent trend in density variation outward from the pith in a study on some poplars cultivated in Switzerland. Thorbjornsen (1961), on the other hand, reported an increase in specific gravity from core to outer wood in yellow poplar. Farmer and Wilcox (1966), in a study on Mississippi valley cottonwood, found that wood near cambium was more dense.

The variation in wood density at different heights in the tree have been considered in many studies using both conifers and hardwoods. Myer (1930) in a study on American woods mentioned that specific gravity exhibits no marked fluctuation in the merchantable part of the maple tree. However, Paul (1963) reported that wood density in diffuse-porous woods tends to decrease with increasing height. Paul and Baudendistel (1945) found that specific gravity decreases upward in sugar maple open-grown trees. However, Lenz (1954) found that wood density increased uniformly from base to the crown in poplar trees cultivated in Switzerland. On the contrary, Paul (1956) found a decrease in specific gravity with height in hybrid poplars.
In the conifers the crown class was found not to be correlated with wood density by Spurr and Hsuing (1954) and Zobel (1956). Paul (1963) noted that in early years of growth, crown size appears to be the principal factor determining the specific gravity of wood. A small crown size was reported to be related to heavier wood.

The influence of varying growth environments on density in diffuse-porous hardwoods is not clear. There are some indications that a moderate rate of growth may be best for producing wood of above average specific gravity (Prestemon, 1966). Paul (1963) found that between locality variation in specific gravity of sugar maple overlapped, and concluded that the selection on the basis of locality alone would not insure distinctly superior timber. Wilde and Paul (1951) reported that in aspen, wood of highest specific gravity was produced on well drained, fine textured soils. Paul and Baudendistel (1945) found that open-grown sugar maple has higher specific gravity at the stump than upward in the tree. Larson (1962) indicated that the effect of environment directly on growth processes and indirectly on xylem growth factors such as fertile soil, plentiful soil moisture and ample growing space for roots and crowns, influenced the rate of growth and character of formed wood.

In a review of studies about yellow poplar, no definite correlation was established between density and climate or elevation factors (Paul, 1963). In sugar maple studies, Paul (1963) reported that there was a tendency toward heavier wood in the
second growth stand. However, the average difference in the wood weight from different stands were not significant.

Heridity affects specific gravity of wood through the geographic races that evolve by differences in site and climatic conditions. Mitchell (1956) hypothesized that xylem characteristics such as fibril angle and density are subject to strong genetical control. Zobel (1956) found that trees of very high and very low specific gravity were found close together on uniform sites. Nicholls et al. (1963) found that fiber length and specific gravity have significant narrow sense heritability. Kennedy (1966) observed that specific gravity within increments in Norway spruce was strongly heritable.

The effect of cardinal directions on specific gravity within the tree has been considered in few studies. Erickson (1949) found no difference with respect to specific gravity between the north and south sides of the yellow poplar trees.

The influence of wood structure on the specific gravity in diffuse-porous species was studied by few researchers. Myer (1930) found the relative proportion of vessels and rays do not influence specific gravity. Desh (1932) did not find any relationship between specific gravity and cell size or proportion of different tissues. Lenz (1954) related the difference in density between some poplar species to differences in fiber structure.

Explanations of specific gravity variations within the
tree has been investigated from various other angles. One of these explanations was postulated by Schniewind (1961) and relates vertical and horizontal variations in specific gravity within the stem to the efficient use of available material according to mechanical principles; and that a structural basis exist for specific gravity increase from pith to bark. However, Schniewind's (1961) theory does not explain the reverse patterns of horizontal variation that exist in ring-porous species, or the decrease in specific gravity in wood formed in old trees.

Shrinkage

Stamm (1964) pointed out that natural hygroscopic gels such as wood, that are originally formed in a water-saturated state, shrink on loss of moisture. He defined shrinkage as "the decrease in the dimensions of a gel material per unit dimensions of the starting material accompanying desorption of an adsorbate held in naturally formed solid solution within the gel". Shrinkage and its accompanying effects of checking, splitting, and warping, etc., constitute woods most troublesome physical property. In order for free shrinking and swelling to occur in an adsorbent, Stamm (1964) outlined two conditions to be met. First, the absorbent must be a plastic solid. The second is that the adsorbate must have sufficient affinity for the absorbent to spontaneously form intimate solid solutions with the adsorbent accompanied by evolution of heat. It is known that wood-water systems meet both of these conditions.
In normal wood, shrinkage is a result of the microfibril structure and orientation in the cell wall. The hygroscopic nature of wood is attributed to the exposed hydroxyl groups occurring in the amorphous regions, along the cellulose chains, and on the surface of the crystalline regions (Pentoney, 1953), (Stamm, 1964). When the water evaporates on desorption, surface tension forces are set up over the areas of contact of water with cellulose chains that tend to draw the chains together. This drawing together of the cellulose chains in the imperfectly oriented amorphous regions tends to better orient these chains, and on the average to occur at right angles to the length of the crystallites (Stamm, 1964). Because the cellulose chains are oriented approximately parallel to the long axis of the cell, maximum shrinkage and swelling would be expected in the transverse direction, with small axial change in dimensions. Peck (1957) pointed out that since the crystallites are joined end to end, they can approach or move away from each other only in their lateral directions. However, Preston (1942) reported that a contraction of two percent occurs along the long direction of the cellulose chains. The axial change is attributed to the deviation of cellulose chains from a perfectly axial orientation (Stamm and Loughbrough, 1941). Little information is available about variation in hygroscopic properties of wood between and within the trees. Erickson (1949) found that in yellow poplar, wood near the pith was lower in radial shrinkage than wood farther out, however, there was little difference in
volumetric shrinkage.

Several researchers have tried to investigate the relationship between shrinkage and density of the wood. Erickson (1949) found that volumetric shrinkage increased as specific gravity increased in yellow poplar. However, he reported that the correlation of specific gravity with radial shrinkage was somewhat lower than with tangential shrinkage. Barefoot (1963) reported that both tangential and radial shrinkage are positively correlated with specific gravity. Stamm (1964) pointed out that for hard woods, if volumetric shrinkage values are plotted against swollen volume specific gravity of wood, a linear relationship is obtained. This differs in species which are subject to collapse. Thus, the shrinkage of wood increases with increase in specific gravity (Stamm, 1964).

The radial and tangential directions of wood differs in the magnitude of their shrinkage values. The tangential shrinkage generally is greater than the radial. Pentoney (1953) in a study on Douglas fir explained the differential shrinkage of gross wood on the basis of many separate factors. However, Stamm (1964) reported that the difference between tangential and radial shrinkage is currently believed to be a result of a combination of factors. The presence of springwood and summerwood, larger number of pits on the radial walls, difference of cell wall thickness in the radial and tangential directions, and the ray cells possible restrain in the radial direction are all possible factors influencing the differential shrinkage of
wood. It appears that at least these four different explanations are effective in a varying degree in different woods (Stamm, 1964). Kelsey (1963) reported that the ratio of tangential to radial shrinkage decreases with increasing density.

The anatomical basis of dimensional changes of wood was discussed in several studies. Hale (1957) suggested that the submicroscopic structure of secondary wall, annual ring structure, and wood rays are the main factors that affect dimensional changes in wood. Erickson (1949) obtained an inverse relationship between number of rings per inch and tangential, radial and volumetric shrinkage. However, Sacre (1963) did not find correlation between volumetric shrinkage and ring width in poplar wood. Chalk (1955) suggested that the proportion of ray tissue may determine the extent to which rays affect differential shrinkage. Schniewind (1959) reported that gross anatomical structure, particularly the alignment of the rays, was found to be the primary cause of transverse anisotropy of shrinkage. However, Kelsey (1963) found that shrinkage of wood free of large rays was considerably less radially than tangentially, which indicates that the rays may not be the wholly responsible factor for the difference. Evidence of quantitative correlation between the shrinkage and proportion of rays is somewhat conflicting (Kelsey, 1963) (Stamm, 1964).

One other factor that influence the shrinkage of wood is the presence of abnormal tissue. In addition to the increase in longitudinal shrinkage, tangential shrinkage of tension wood
was found to be greater than that for normal wood, with no difference between radial and tangential directions (Dadswell and Wardrop, 1949). However, Barefoot (1963) reported that tangential and radial shrinkage decreased while longitudinal shrinkage increased in wood containing gelatinous fibers. Arganbright (1964) arrived to similar results in a study of soft maple.
METHODS OF INVESTIGATION

General Considerations

Although a considerable amount of research has been done on within-tree variation in conifers, very little information is available on hardwoods. Studies that have treated some of the within-tree variation of wood properties have not given the whole picture by omitting such properties as shrinkage or proportion of wood elements.

As was discussed in the literature review, Duff and Nolan's pioneer work on red pine ring width, led to the description of two within-tree systematic patterns and one unsystematic. This was confirmed by other studies on conifers using additional wood properties such as density and tracheid length. Some of these studies pointed out the probable presence of systematic variation within the tree in properties other than wood density, ring width and tracheid length (Richardson, 1961). Thus, studies on individual trees are needed to describe patterns of variations for other important wood properties in hardwoods as well as conifers. Further investigations are also needed to explain the relationship between these wood properties and factors such as height, cambial age and year of wood formation. The contribution of these intrinsic and extrinsic factors to patterns of variation in some wood properties have met little attention. However these factors have been generally stated in certain studies.
The contribution of factors such as age and height to the existence of variation patterns of wood properties can be studied in different ways. In this study, the author chose to investigate the relationship of ring width, proportion of wood elements, specific gravity and shrinkage to cambial age, year of wood formation and height in the tree.

Objectives

The broad objective of this study was to investigate within-tree variation in ring width, proportion of wood elements, specific gravity and shrinkage. Additional investigations involving the computation of prediction equations for ring width, proportion of wood elements, specific gravity and shrinkage were part of the objectives.

The objectives are more specifically stated as follows:

1. To find the relationship of ring width, proportion of wood elements (fibers, rays and vessels), specific gravity and shrinkage to such variables as cambial age, year of wood formation and height.

2. To observe any patterns of variation within the tree in ring width, proportion of wood elements, specific gravity and shrinkage.

3. To exploit the data for any other informative relationship which may be present with regard to ring width, proportion of wood elements, specific gravity and shrinkage.
Procedure

The material for investigation was obtained during the winter of 1965-1966 from a natural stand of silver maple (Acer saccharinum L.) growing on a plain along the Des Moines river near Fraizer, Iowa. The tree selected was dominant with a d.b.h. of 14.2 inches, a total height of 48 feet and with 24 feet to the first branch. The lean of the tree was less than two degrees to the south as measured at breast height. The tree was cut as near as possible to the ground line. From the stem, two four inch sample discs were cut as nearly as possible at two foot intervals (Figure 1). If the sample was near a branch, the discs were shifted downward to avoid tension wood (Arganbright, 1964). A total of forty discs were sampled. All sampled discs were marked to identify the height above the ground line and the cardinal direction. Discs were wrapped in plastic bags and transferred to the laboratory.

Laboratory procedure

From each disc a dimetrical segment was cut 2 x 4 inch from north to south (Figure 1). Each segment was marked with a wax pencil and kept in plastic bags at a temperature below freezing. Thus, at every two foot interval of the tree stem, two segments were available for the study. The lower one of each pair of segments was used for ring width, wood elements and specific gravity studies while the matching upper segment was used for shrinkage determinations. Each lower segment
Figure 1. Location of sampled discs and dimetrical segments cut from north to south with respect to the stem.
FOR SHRINKAGE

2'

2'

4"

32 RINGS

S.

N.
sampled at each height, was divided into two longitudinally matched proportions (Figure 2). One proportion (1 x 1.5 inch) was used for ring width measurements and proportion of wood elements microtome sections. The other portion was 1 x 1.5 inch and was used for specific gravity determinations. The rest of the diametrical segments were stored under refrigeration in plastic bags for later use if required.

**Ring width determinations**

Each of the 1 x 1.5 inch segments cut for the ring width study were machined to get smooth transverse surface. The ring width determinations were made by using a Swedish device designed for such measurements. This device has a Zeiss binocular measuring microscope combined with an electric adding machine, the ADDO-X. Measurements on the green wood were made to the nearest tenth of a millimeter. The coupling of the measuring microscope to the adding machine facilitated the accumulation of ring width measurements on a recording sheet. From this record the average ring width and the average cambial age when the wood was formed were determined.

**Proportion of wood elements**

The diametrical segments used in this study were those used previously in the ring width measurements. These diametrical segments were then marked at every three year radii from the bark inward, soaked in distilled water to facilitate cutting, and cut into three year blocks at the boundary between
Figure 2. Sampled segments:

a. shrinkage samples
b. specific gravity samples.

The solid lines represent the lines of cutting and the broken lines represent projected radii. The symbols show the coding system.
the rings. A large curved blade was used to get a sharp cut. This was easily accomplished once the splitting was at the boundary. If any three ring block at the pith was less than a fourth of an inch, a six ring block was obtained. Only odd numbered blocks were picked for the study, so every other block from the bark to the pith was sampled. This was done due to the time required to take the measurements on each block. The labeled three annual increment blocks were then grouped in bottles; each bottle contained the blocks from one side of the diametrical segment (north or south). These three year blocks were softened using Franklin's method (Franklin, 1946). Polyethylene glycol (P.E.G.) was then used as embedding material for the three ring blocks. P.E.G. molecular weight 1000 was used first then replaced by P.E.G. of 1450 molecular weight which is slightly higher in melting point and less sensitive to humid conditions. An A.O. sliding microtome was used to get twenty microne transverse sections from the three years blocks. Sections were then stained with safranin and mounted as permanent slides. The staining was used to enhance the contrast in the photomicrographs taken later.

Sampling for proportion of wood elements

Each section of three annual rings was sampled in order to determine the proportion of wood elements. Photomicrographs were taken at random points within each section. Picking these points at random was facilitated by using the mechanical stage
of an A.O. microscope and a random numbers table. The negative films of these photomicrographs were then used for measurements of proportion of wood elements. A developed technique using a microfilm viewer was used. By using this viewer, each negative film was projected on a special designed dot-grid with 400 dots (Figure 3). At a magnification of 850, the area occupied by a wood fiber projected through the viewer on the grid, was a little less than the area sampled by one dot (Figure 4). For each three ring section, the number of photomicrographs required to give an estimate of the mean of the wood elements that would fall within a specified confidence interval was calculated. The calculations were based on data from a sample taken in a preliminary study in order to estimate the variance. The required number of observations (photomicrographs per section) necessary to give an estimate of the mean of wood element that would fall within a range of 0.1 of the mean with 95% confidence level, were done by using Stein's two stage sample procedure (Stein, 1945). The equation used for the calculations was: 

\[ N = \frac{t^2 s^2}{d^2} \]

Where: 

- \( N \) = photomicrographs per section
- \( s \) = estimated standard deviation of the sampled wood element
- \( t \) = the tabulated "t" value for the desired confidence level (0.95 level used here) and the degrees of freedom of the preliminary sample
Figure 3. The grid system used in the structural elements analysis
Figure 4. The method of counting proportion of structural elements. The image of the film negative is projected vertically by the microfilm-viewer on the sampling dot grid.
\[ d = \text{half-width of the desired confidence interval} \]
\[ (0.1 \text{ of the mean } \bar{x} \text{ was used here}) \]

The number of photomicrographs needed per section were then calculated for fiber, vessel and ray elements. The range of photomicrographs needed was 14-18 (Appendix). It was decided on this basis to use a sample size of 20 photomicrographs per section. A check was made by partition of variance which indicated that using this number of photomicrographs was adequate (Cochran and Cox, 1964).

In sampling, the proportion of points falling on each wood element (fibers, vessels and rays) gave the percentage of each element in the section (Ladell, 1959) (Lewis, 1964). If a dot falls on the compound middle lamella between two different types of cells, the first time it is counted for the one type of cell and the next time for the other type. Each one of the microscopic transverse sections was thus evaluated for each wood element present in it. This was done for sections from ten different discs sampled at different heights along the tree.

Specific gravity determinations
The 1 x 1.5 inch diametrical segments used for this part of the research were marked at every three year radii from the bark to the pith, soaked in distilled water to facilitate cutting at the boundary between rings, and then cut. In order to have equal portions of the tree circumference included in
each successive segment from the pith out, wedges of three year increments were cut such that they represent equal arcs of their own circles. (Millar and Malac, 1955). Each wedge was identified by a code number. The basic specific gravity was then measured for these wedges (based on green volume and oven dry weight). This was done by saturating the three ring wedges in water then measuring the green volume of each wedge by the water displacement method using a Mettler balance measuring to the nearest hundredth of a gram. The three ring wedges were air-dried then oven-dried at 105° C to a constant weight. The oven-dry weight was measured to the nearest hundredth of a gram by the same Mettler balance. The specific gravity of each three ring wedge was then calculated by using the equation:

\[
\text{specific gravity} = \frac{\text{O.D. wt.}}{\text{wt. D.V.}}
\]

where

- O.D. wt. = oven-dry weight
- wt. D.V. = weight of displaced volume of water.

This was done for all twenty diametrical segments cut from twenty discs along the tree at two foot intervals.

**Shrinkage measurements**

From each diametrical segment cut for shrinkage measurements (Figure 1), a 1/2 x 1/2 inch segment was prepared and divided into three ring radial blocks. The cut was facilitated by using a curved blade to split the blocks at the boundary between rings. The three ring blocks were stored under refrigeration until measurements were taken. The radial and tangen-
tial green dimensions were taken at certain points which were marked on the blocks. After taking the green dimensions the blocks were allowed to air-dry to about 12 percent moisture content to avoid collapse and then oven-dried at 105° C. In view of the amount of thermal expansion of wood, the blocks were allowed to cool to room temperature before measuring in the oven-dry state. This cooling took place in a desiccator. Tangential and radial measurements were recorded, from which the tangential and radial shrinkages were calculated by using the equation:

\[ V = T + R - \frac{TR}{100} \]

(Kelsey and Kingston, 1953)

where:

- \( V \) = Volumetric shrinkage
- \( T \) = Tangential shrinkage
- \( R \) = Radial shrinkage.

By this technique volumetric shrinkage was calculated from linear shrinkage values assuming that the longitudinal shrinkage value was zero in all cases. This assumption is not quite true; however, the error is very small and can be neglected in studies on normal wood. Kelsey and Kingston (1953) pointed out that the major part of this small error is due to thermal expansion since direct volumetric observations are done on cool specimens while calculated volumetric values are based on linear measurements made on warm specimens taken after being oven-dried. Amending the standard test to specify cooling the
oven-dry specimens before taking linear measurements will very much reduce the difference between calculated and observed shrinkage values (Kelsey and Kingston, 1953). With the small longitudinal dimension of the three ring blocks used in this study (1/2 inch), the neglect of longitudinal measurements was felt to be justified. This procedure considerably reduces the time involved in taking measurements.

In all the four phases of this research for ring width, proportion of wood elements, density and shrinkage determinations the investigator was able to keep track of the same annual rings at all heights in the tree. A coding system was used to distinguish between the different years of wood formation as well as the cambial age. This allowed complete stem analysis with respect to the properties studied within the tree.
RESULTS

Because of the preliminary nature of this study and the manner in which it was physically conducted, the data were examined using a regression analysis. Using Jesperson's regression program, analyses were run with two objectives. The first was to test the predictive adequacy of constructed theorized models on the basis of hypothesized trends as well as trends found in the literature. The second objective was to investigate the relationship between the dependent variables.

Investigation of vertical and horizontal trends of variation of certain properties within the tree was graphically done by plotting the data. When it was possible the prediction models were used to obtain these graphs by mathematical manipulations and by using the simplotter.

Data from both sides of the tree were combined for the regression analyses and the investigation of patterns of variation within the tree.

Model Construction

The models for studying the relationships of ring width, proportions of wood elements, specific gravity and shrinkage, to cardinal direction, height, coded year of formation and coded cambial age were constructed on the basis of hypothetical or reported trends. These variables were chosen as the most desirable for the formation of prediction equations. The following prediction polynomial model used in the analyses:
\[ Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_{11} X_{1i}^2 + \beta_{33} X_{3i}^2 \]
\[ + \beta_{44} X_{4i}^2 + \beta_{13} X_{1i} X_{3i} + \beta_{14} X_{1i} X_{4i} + \beta_{34} X_{3i} X_{4i} + \epsilon_i \]

where:

- \( \beta \)'s = partial regression coefficients
- \( X_{1i} \) = height in feet from the ground line for the \( i^{th} \) observation
- \( X_{2i} \) = cardinal direction (north and south) for the \( i^{th} \) observation
- \( X_{3i} \) = coded year of wood formation for the \( i^{th} \) observation
- \( X_{4i} \) = coded cambial age for the \( i^{th} \) observation
- \( Y_i \) = ring width, fibers percentage, vessel percentage, ray percentage, tangential shrinkage, radial shrinkage, volumetric shrinkage and specific gravity for the \( i^{th} \) observation.

The terms of these polynomial models were then fitted by the method of least squares.

Analyses of Annual Ring Width Model

In Table 1, the average ring width regression was significant at the .01 probability level, as tested by the F statistic. The combined effect of the variables expressed by the multiple "R" was 0.7971, indicating that 63.54 percent of the total variability in ring width was accountable. In Table 2, the test of each coefficient after the effects of all other variables have been fitted, is not significant. Thus, the ring width model was reduced by elimination of the least effective terms.
### Table 1. Analysis of average ring width regression variance (full model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>10</td>
<td>72596.12</td>
<td>7259.61</td>
<td>51.77**</td>
</tr>
<tr>
<td>Residual</td>
<td>297</td>
<td>41651.77</td>
<td>140.24</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>114247.89</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.6354.
Square root of multiple R = 0.7971.

** Denotes significance at .01 probability level.

### Table 2. Test of the significance of the average ring width partial regression coefficients (full model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>0.3263</td>
<td>9.5086</td>
<td>0.0343</td>
</tr>
<tr>
<td>$X_2$</td>
<td>-0.2266</td>
<td>1.3496</td>
<td>-0.1679</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-62.9917</td>
<td>98.0885</td>
<td>-0.6422</td>
</tr>
<tr>
<td>$X_4$</td>
<td>-58.6148</td>
<td>98.0885</td>
<td>-0.5975</td>
</tr>
<tr>
<td>$(X_1)^2$</td>
<td>-0.0423</td>
<td>0.0418</td>
<td>-1.0104</td>
</tr>
<tr>
<td>$(X_2)^2$</td>
<td>3.2279</td>
<td>4.5077</td>
<td>0.7161</td>
</tr>
<tr>
<td>$(X_3)^2$</td>
<td>2.8937</td>
<td>4.5077</td>
<td>0.6419</td>
</tr>
<tr>
<td>$(X_1X_2)$</td>
<td>0.0179</td>
<td>0.8859</td>
<td>0.0202</td>
</tr>
<tr>
<td>$(X_1X_3)$</td>
<td>-0.0161</td>
<td>0.8859</td>
<td>-0.0182</td>
</tr>
<tr>
<td>$(X_1X_4)$</td>
<td>7.4373</td>
<td>8.9858</td>
<td>0.8277</td>
</tr>
</tbody>
</table>

*Note: The table provides a detailed analysis of the regression coefficients, including their coefficients, standard errors, and t-values, which are used to assess the significance of each term in the model.*
in the model. The deletion of such terms was based on testing the partial regression coefficients ("t" test) and considering the known importance of each of these terms. Interrelations between these variables and the independent variables were also taken into consideration (Table 3). A type of backward elimination procedure considering the biological known facts was followed in order to select the best regression equation.

In Table 4 the final reduced model of average ring width regression is presented. The ring width regression in the model is significant at .01 probability level. The multiple "R" of this reduced regression model is 0.7969, indicating that 63.51 percent of the total variability in ring width is accountable. Table 5 shows that except for height all the coefficients of the terms included in this model are significant at the .01 level. From observing the intercorrelations between the independent variables in Table 3, it can be implied that the reason for the non-significance of the height term in the ring width regression model was due to its high correlation with (height)$^2$ and other independent terms. In spite of the non-significance of this variable in the reduced regression model it was retained on the basis of its known importance and the fact that its addition cannot detract from the accuracy of the prediction equation. In addition, there was a highly significant simple correlation between ring width and the height variable (0.6966). This reduced model, thus, has the advantage over the full model presented in Table 2, since the reduced
Table 3. Simple correlations of the height term to all independent terms in the average ring width model

<table>
<thead>
<tr>
<th>Term</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>1.0000**</td>
</tr>
<tr>
<td>$X_2$</td>
<td>-0.0000</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-0.2594**</td>
</tr>
<tr>
<td>$X_4$</td>
<td>-0.2594**</td>
</tr>
<tr>
<td>($X_1)^2$</td>
<td>0.9650**</td>
</tr>
<tr>
<td>($X_2)^2$</td>
<td>-0.2896**</td>
</tr>
<tr>
<td>($X_3)^2$</td>
<td>-0.2897**</td>
</tr>
<tr>
<td>($X_4)^2$</td>
<td></td>
</tr>
<tr>
<td>($X_1X_3$)</td>
<td>0.6920**</td>
</tr>
<tr>
<td>($X_1X_4$)</td>
<td>0.6920**</td>
</tr>
<tr>
<td>($X_2X_4$)</td>
<td>0.5941**</td>
</tr>
</tbody>
</table>

$X_1 =$ height in feet.
$X_2 =$ cardinal direction (north and south).
$X_3 =$ coded year of formation.
$X_4 =$ coded cambial age.

**Denotes significance at .01 probability level.

The model contains fewer terms while still accounting for almost the same percent of variability in ring width as the full model. A classification model based on the fact that all values of the independent variables were represented by two observations, one from each side of the tree was used. Treating the two sides of the tree as replicates enabled us to obtain a measure of error independent of functional relationships of the dependent variables and thus to obtain a lack of fit. The lack of fit was significant, however, the proportion of variability accounted for by the classification model almost matched that
Table 4. Analysis of average ring width regression variance (reduced model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>7</td>
<td>72556.36</td>
<td>10365.19</td>
<td>74.58**</td>
</tr>
<tr>
<td>Residual</td>
<td>300</td>
<td>41691.53</td>
<td>138.97</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>114247.89</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.6351.
Square root of multiple R = 0.7969.
**Denotes significance at .01 probability level.

Table 5. Test of the significance of the average ring width partial regression coefficients (reduced model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>0.3357</td>
<td>0.2769</td>
<td>1.2125</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-61.0379</td>
<td>14.4123</td>
<td>4.2351**</td>
</tr>
<tr>
<td>$X_4$</td>
<td>-60.3764</td>
<td>14.4123</td>
<td>-4.1892**</td>
</tr>
<tr>
<td>$(X_1)^2$</td>
<td>-0.0423</td>
<td>0.0100</td>
<td>-4.2136**</td>
</tr>
<tr>
<td>$(X_3)^2$</td>
<td>3.0518</td>
<td>0.7730</td>
<td>3.9479**</td>
</tr>
<tr>
<td>$(X_4)^2$</td>
<td>3.0610</td>
<td>0.7730</td>
<td>3.9598**</td>
</tr>
<tr>
<td>$(X_3X_4)$</td>
<td>7.4285</td>
<td>1.5232</td>
<td>4.8768**</td>
</tr>
</tbody>
</table>

**Denotes significance at .01 probability level.
accounted for by the reduced regression prediction equation. Thus, I was reluctant to add terms of higher order to the model. The resulting prediction equation for average ring width \( Y_1 \) based on the data is:

\[
Y_1 = 344.3953 + 0.3357X_1 - 61.0380X_3 - 60.3764X_4
- 0.0423X_1^2 + 3.0518X_3^2 + 3.0610X_4^2 + 7.4285X_3X_4.
\]

After the formulation of the average ring width reduced model, the data from the north and south sides of the tree were combined to make two dimensional plots. The data were then presented in three ways. In type 1 (oblique) the average ring width of rings formed in the same years, but from cambia of different ages, were plotted against the height variable. In type 2 (horizontal), the average ring width of successive rings were plotted from the pith outward at each given height. In this sequence it should be realized that the data represent annual rings formed in different years from cambia of different ages. In type 3 (vertical), the average ring width of rings formed from cambia of the same age, but in different years of formation, were plotted against the height variable. It is realized that these three ways of presenting the data match that of Duff and Nolan in their studies of red pine (Duff and Nolan, 1953). It can be seen that in type one the year of formation is considered as a constant, while in type three the cambial age is the constant. Both cambial age and year of formation are not kept constants in type 2.
The resulting prediction equation for average ring width regression was then used to plot only type 1 sequence while all three types were plotted from the original data. In order to plot the average ring width as a function of height in type 1, the year of formation must be kept constant. And since the cambial age changes up the tree, a check with the original data was necessary to find the matching cambial age within each range of height. Based on that, it was decided to use five values of the coded cambial age as constant levels covering the height range and matching the coded year of formation. Two levels of the year of formation (coded 1 and 3) were plotted from the model. Each one of these two levels was matched by the following five levels of coded cambial age: 9, 8, 7, 6, 5 and 7, 6, 5, 4, 3 respectively. This manipulation facilitated the calculation of five quadratic equations of ring width as a function of height. These five equations were selected to cover the range of the height variable in the tree. Thus, predicted annual ring width was plotted as a function of height in Figure 6. It is clear that Figure 6 agrees with the graphs plotted for type 1 from the original data in Figure 5. Figures 7, 8 show both type 2 and 3 sequences as plotted from the original data. In type 1 Figure 5, there is a clear trend expressed in the years of formation. In this oblique sequence, the ring width tends to decrease from the apex down to a certain point at a level of about 30 feet (63% of total height), then it increases rapidly to a maximum about the level of 22
Figure 5. A family of curves of ring widths each one representing an average of three years of wood formation.
Figure 6. Two curves of ring widths each one representing an average of three years of wood formation as plotted from the reduced prediction equation.
TYPE I (OBLIQUE)

BLOCKS FROM BARK
NO. 1
NO. 2
PLOTTED FROM THE MODEL

CROWN AREA

AVERAGE RING WIDTH mm.

HEIGHT IN FEET
Figure 7. A family of curves of ring widths across the radius of the stem. Each curve representing a certain height level in the tree.
TYPE 2 (HORIZONTAL)

AVERAGE RING WIDTH mm

HEIGHT RANGE
0.8'-21.8'

HEIGHT RANGE
27.8'-45'

PITH

NO. OF BLOCKS FROM PITH
Figure 8. A family of curves of ring widths each one representing an average of three years of cambial age.
feet (46% of total height) from ground and then levels off towards the base of the tree. It will be noted that the shape change occurs near the base of the crown. Type 2 (horizontal) in Figure 7 presents graphs representing each of the sampled twenty levels in the tree. A clear systematic trend is noticed in these graphs. Up to a height of 21.8 feet, the annual ring width increases from the bark to a maximum around block No. 5 (each block represents 3 annual rings, except for rings at the pith), then it declines to a minimum at the pith. At higher levels in the crown area of the tree this trend is not shown. It appears that the effect of nutritional gradients is not pronounced in the crown and in addition the age variation between the rings is small. Figure 8 shows the type 3 sequence (vertical) and indicates a trend in the crown area (beyond about 24 feet). This sequence (vertical) is the only way of presenting the effect of environmental conditions since the cambial age is kept constant. The unexpected trend within the crown area may be explained on the basis of the crown physiological effects that masked the fluctuations due to the different years of formation (environmental factors). Hence, this trend in the type 3 sequence does not refer to a constant type of relationship, but it does reveal the influence of the crown on the wood within the crown area. Beyond the crown area it is clear that there is much fluctuation in this sequence. This is due to the fact that each graph represents wood formed from cambia of a given age. Thus, below 24 feet in Figure 8
some of the graphs refer to wood formed in previous years when the crown area was at a lower height and other graphs represent wood which was formed far from the crown area. Hence, the influence of the year of formation is somewhat more clear and not masked as in the height beyond 24 feet. The area below 24 feet reflects the inconsistent influence of year of formation as well as proximity to the crown and represents no systematic pattern.

The presence of some systematic within-tree variation is supported by relatively high within-tree coefficient of variation for ring width of 35.12%.

Analyses of Wood Elements Models

**Fiber proportion model**

Table 6 shows that the fiber proportion regression is significant at the .01 probability level (F statistic). Table 7 shows the non-significance of the test of each coefficient after the effects of all other variables have been fitted. When the least effective terms were eliminated from the fiber proportion model a reduced model resulted (Table 8, 9). The deletion of the terms from the full model was based on testing the partial regression coefficients ("t" test) and considering the known importance of each term. This was done by a type of backward elimination procedure considering the biological facts in order to select the "best" regression equation.

In Table 9 the final reduced model of the regression for
Table 6. Analysis of fiber proportion regression variance (full model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>10</td>
<td>513.0759</td>
<td>51.3076</td>
<td>7.4438**</td>
</tr>
<tr>
<td>Residual</td>
<td>74</td>
<td>510.0546</td>
<td>6.8926</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>84</td>
<td>1023.1305</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.5015.
Square root of multiple R = 0.7082.

**Denotes significance at .01 probability level.

Table 7. Test of the significance of the fiber proportion partial regression coefficients (full model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>-5.8789</td>
<td>5.6817</td>
<td>-1.0347</td>
</tr>
<tr>
<td>X2</td>
<td>-0.3006</td>
<td>5.6988</td>
<td>-0.5276</td>
</tr>
<tr>
<td>X3</td>
<td>-46.1671</td>
<td>57.9206</td>
<td>-0.7971</td>
</tr>
<tr>
<td>X4</td>
<td>-49.9994</td>
<td>57.7876</td>
<td>-0.8652</td>
</tr>
<tr>
<td>(X1)^2</td>
<td>0.0314</td>
<td>0.0248</td>
<td>1.2656</td>
</tr>
<tr>
<td>(X2)^2</td>
<td>1.9838</td>
<td>2.6548</td>
<td>0.7473</td>
</tr>
<tr>
<td>(X3)^2</td>
<td>2.2550</td>
<td>2.6417</td>
<td>0.8536</td>
</tr>
<tr>
<td>(X1X2)</td>
<td>0.4919</td>
<td>0.5282</td>
<td>0.9314</td>
</tr>
<tr>
<td>(X1X3)</td>
<td>0.5315</td>
<td>0.5277</td>
<td>1.0072</td>
</tr>
<tr>
<td>(X1X4)</td>
<td>4.2307</td>
<td>5.2873</td>
<td>0.8002</td>
</tr>
</tbody>
</table>
Table 8. Analysis of fiber proportion regression variance (reduced model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>7</td>
<td>503.6209</td>
<td>71.9458</td>
<td>10.6635**</td>
</tr>
<tr>
<td>Residual</td>
<td>77</td>
<td>519.5096</td>
<td>6.7469</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>84</td>
<td>1023.1305</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.4922.
Square root of multiple R = 0.7016.
**Denotes significance at .01 probability level.

Table 9. Test of the significance of the fiber proportion partial regression coefficients (reduced model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X_1</td>
<td>-0.5943</td>
<td>0.2014</td>
<td>-2.9505**</td>
</tr>
<tr>
<td>X_3</td>
<td>5.5285</td>
<td>3.6530</td>
<td>1.5134</td>
</tr>
<tr>
<td>X_4</td>
<td>0.5376</td>
<td>1.4274</td>
<td>0.3766</td>
</tr>
<tr>
<td>(X_1)^2</td>
<td>0.0076</td>
<td>0.0036</td>
<td>2.0967*</td>
</tr>
<tr>
<td>(X_3)^2</td>
<td>-0.3817</td>
<td>0.2575</td>
<td>-1.4825</td>
</tr>
<tr>
<td>(X_1X_4)</td>
<td>0.0486</td>
<td>0.0230</td>
<td>2.1094*</td>
</tr>
<tr>
<td>(X_3X_4)</td>
<td>-0.3914</td>
<td>0.2629</td>
<td>-1.4885</td>
</tr>
</tbody>
</table>

*Denotes significance at .05 probability level.
**Denotes significance at .01 probability level.
the proportion of fibers is presented. The fiber proportion regression in the model is significant at .01 probability level. The multiple $R^2$ of this reduced model regression is .7016, indicating that 49.22 percent of the total variability in fiber proportion is accountable. Table 9 shows that the coefficients of the height, $(height)^2$ and $(height) \times (age)$ interaction are significant at the .05 level. The coefficients of year of formation, cambial age, $(year of formation)^2$, and $(year of formation) \times (cambial age)$ interaction are not significant at the .05 level. Table 10 presents the intercorrelations between the independent variables. Thus, it can be speculated that the non-significances of the year of formation and $(year of formation)^2$ terms are due to their correlation with the remaining variables. It is plausible that the non-significance of average cambial age and $(year of formation) \times (cambial age)$ interactions is due to the same reason. However, the known importance of these terms was the reason for retaining them in the reduced model since their addition cannot detract from the accuracy of the prediction equation. The reduced model has an advantage over the full model since it contains fewer terms and accounts for almost the same percent of variability in proportion of fiber element as the full model. As in the analyses of the ring width regression model, a comparison with the classification model was used in order to provide a measure of the lack of fit. In spite of the significance of the lack of fit, the proportion of variability
Table 10. Simple correlations of the non-significant independent terms to all other independent terms in the fiber proportion model

<table>
<thead>
<tr>
<th></th>
<th>$X_3$</th>
<th>$X_4$</th>
<th>$(X_3)^2$</th>
<th>$X_3X_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>-0.3195**</td>
<td>-0.2444*</td>
<td>-0.3561**</td>
<td>0.5618**</td>
</tr>
<tr>
<td>$X_2$</td>
<td>0.0191</td>
<td>0.0018</td>
<td>0.0071</td>
<td>0.0209</td>
</tr>
<tr>
<td>$X_3$</td>
<td>1.0000**</td>
<td>-0.8296**</td>
<td>0.9691**</td>
<td>0.2019</td>
</tr>
<tr>
<td>$X_4$</td>
<td>-0.8296**</td>
<td>1.0000**</td>
<td>-0.7768**</td>
<td>0.1313</td>
</tr>
<tr>
<td>$(X_1)^2$</td>
<td>-0.3335**</td>
<td>-0.2417*</td>
<td>1.0000**</td>
<td>-0.5581**</td>
</tr>
<tr>
<td>$(X_2)^2$</td>
<td>0.9691**</td>
<td>-0.7768**</td>
<td>0.3666**</td>
<td>0.0462</td>
</tr>
<tr>
<td>$(X_4)^2$</td>
<td>-0.7642**</td>
<td>0.9695**</td>
<td>-0.3035**</td>
<td>-0.0018</td>
</tr>
<tr>
<td>$(X_1X_3)$</td>
<td>0.3186**</td>
<td>-0.6775**</td>
<td>0.5882**</td>
<td>-0.3320**</td>
</tr>
<tr>
<td>$(X_1X_4)$</td>
<td>-0.6945**</td>
<td>0.3099**</td>
<td>0.6888**</td>
<td>-0.4283**</td>
</tr>
<tr>
<td>$(X_3X_4)$</td>
<td>0.2019</td>
<td>0.1313</td>
<td>-0.5881**</td>
<td>1.0000**</td>
</tr>
</tbody>
</table>

$X_1 =$ height in feet.

$X_2 =$ cardinal direction.

$X_3 =$ coded year of formation.

$X_4 =$ coded cambial age.

* Denotes significance at .05 probability level.

** Denotes significance at .01 probability level.

accounted for by the classification model almost matched that accounted for by the reduced regression model. Thus, presenting the model without addition of higher order terms was
was justified. The resulting prediction equation for fiber proportion \( Y_2 \) is

\[
Y_2 = 62.2193 - 0.5943 x_1 + 5.5285 x_3 + 0.5376 x_4 + 0.0076 (x_1^2)
- 0.3817 (x_3^2) + 0.0486 (x_1 x_4) - 0.3914 (x_3 x_4).
\]

The data was combined for both sides of the tree in order to plot two dimensional graphs. The way of presenting the graphs is similar to that for presenting the data on average ring width. The fiber proportion variation within the tree was studied in the oblique, horizontal and vertical sequences referred to by types 1, 2, and 3 respectively. Only type 1 was plotted from both the prediction model and the original data by a procedure similar to that developed in the analyses of the average ring width model. Figure 9 shows type 1 (oblique) sequence where the fiber proportion in rings formed in the same years but from cambia of different ages were plotted against the height variable. The influence of different cambial ages and height are expressed in this sequence. When comparing Figure 9 and Figure 10, which represents the plots obtained from the fiber proportion prediction equation, it appears that the graph plotted from the prediction equation shows a slight trend of decreasing fiber proportion from apex downward. However, in Figure 9 the original data plots do not reveal such a trend. It must be noted that the graph (Figure 10) plotted from the prediction equation is using only two levels (1 and 3) of the
Figure 9. A family of curves of percentages of wood elements each one representing an average of three years of wood formation.
Figure 10. A family of curves of percentages of wood elements each one representing an average of three years of wood formation as plotted from the reduced prediction equation.
TYPE I (OBLIQUE)
BLOCKS FROM THE BACK
BLOCK NO I
NO 3

HEIGHT IN FEET

FIBERS
VESSELS
RAYS

PROPORTION OF WOOD ELEMENTS

HEIGHT IN FEET

%
year of formation while the original data represents five levels. It appears that the value of such a trend, however, is very minor since the variation in proportion of fibers within the tree is very low. With a coefficient of variation of 4.99% for fiber proportion in the tree it can be seen that not much variation is expected to be expressed in a specific trend. Figures 11 and 12 present both type 2 (horizontal) and 3 (vertical) sequences in the same way that the average ring width data were presented in the previous section. In both horizontal and vertical sequences no trend can be detected in the data. This is due to the lower within-tree variation in the proportion of fiber elements.

Vessel proportion model

The vessel proportion regression presented in Table 11 shows that the regression is significant at the .01 level as tested with F statistic. The combined effect of the variables expressed by the multiple $R$ is 0.7903, indicating that 62.45 percent of the total variability in vessel proportion is accountable. Table 12 shows that the test of each of the coefficients, after the effects of all other variables have been fitted, is not significant. This model provided a start for selecting the "best" regression equation for using a type of backward elimination procedure considering biologically known facts.

The final vessel element proportion model is presented in
Figure 11. A family of curves of percentages of wood elements across the radius of the stem. Each curve representing a certain height level in the tree.
TYPE I (HORIZONTAL)
HEIGHT RANGE
1.8 - 33.1 FEET

PROPORTION OF WOOD ELEMENTS

% 80 -
70 -
60 -
50 -
40 -
30 -
20 -
10 -
0 -

NO. OF BLOCKS FROM PITH 1 3 5 7 9

FIBERS
VESSELS
RAYS
Figure 12. A family of curves of percentages of wood elements each one representing an average of three years of cambial age
TYPE 3 (VERTICAL)

CROWN AREA

FIBERS

VESSELS

RAYS

%  PROPORTIONS OF WOOD ELEMENTS

80

70

60

50

40

30

20

10

HEIGHT IN FEET

4  8  12  16  20  24  28  32  36  40  44  48

44  48
Table 11. Analysis of vessel proportion regression variance (full model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>10</td>
<td>592.2652</td>
<td>59.2265</td>
<td>12.3087**</td>
</tr>
<tr>
<td>Residual</td>
<td>74</td>
<td>356.0698</td>
<td>4.8118</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>84</td>
<td>948.3350</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.6245.

Square root of multiple R = 0.7903.

** Denotes significance beyond .01 probability level.

Table 12. Test of the significance of the vessel proportion partial regression coefficients (full model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X_1</td>
<td>5.6927</td>
<td>0.7472</td>
<td>1.1992</td>
</tr>
<tr>
<td>X_2</td>
<td>0.1287</td>
<td>0.4762</td>
<td>0.2702</td>
</tr>
<tr>
<td>X_3</td>
<td>36.8616</td>
<td>48.3941</td>
<td>0.7617</td>
</tr>
<tr>
<td>X_4</td>
<td>38.6989</td>
<td>48.2829</td>
<td>0.8015</td>
</tr>
<tr>
<td>(X_1^2)</td>
<td>-0.0340</td>
<td>0.0207</td>
<td>-1.6373</td>
</tr>
<tr>
<td>(X_3^2)</td>
<td>-1.5088</td>
<td>2.2181</td>
<td>-0.6802</td>
</tr>
<tr>
<td>(X_4^2)</td>
<td>-1.6098</td>
<td>2.2072</td>
<td>-0.7293</td>
</tr>
<tr>
<td>(X_1X_3)</td>
<td>-0.4644</td>
<td>0.4413</td>
<td>-1.0522</td>
</tr>
<tr>
<td>(X_1X_4)</td>
<td>-0.4840</td>
<td>0.4409</td>
<td>-1.0975</td>
</tr>
<tr>
<td>(X_3X_4)</td>
<td>-3.1227</td>
<td>4.4177</td>
<td>-0.7069</td>
</tr>
</tbody>
</table>
Table 13. The vessel proportion regression in the model is significant at the .01 level. The multiple "R" of this reduced model regression is 0.7841, indicating that 61.47 percent of the total variability is accounted for by the model. With fewer highly significant terms, this reduced model has the advantage over the full model presented in Table 12. Table 14 presents the test of each of the coefficients after the effects of all other variables have been fitted. In spite of the significance of the lack of fit as obtained with computation of the classification model, this model was presented without addition of higher order terms. This was done since the proportion of variability accounted for by the classification model almost matched that accounted for by the reduced prediction equation.* The resulting prediction equation for vessel element proportion is:

\[ Y_3 = 75.1554 + 0.5891 \, (X_1) - 13.7984 \, (X_3) - 14.1014 \, (X_4) \]
\[ \quad - 0.0195 \, (X_1^2) + 0.7511 \, (X_3^2) + 0.8508 \, (X_4^2) + 1.5979 \, (X_3X_4). \]

The combined data from both sides of the tree were then plotted in three ways similar to that followed in the ring width analyses. Type 1 (oblique) in Figure 9 shows that there is a slight trend in the original data. Figure 10 presents the plots obtained from the prediction equation to represent

*Computation of the classification model was done by the same procedure explained in the analysis of ring width model.
Table 13. Analysis of vessel proportion regression variance (reduced model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>7</td>
<td>582.9765</td>
<td>83.2824</td>
<td>17.5519**</td>
</tr>
<tr>
<td>Residual</td>
<td>77</td>
<td>365.3585</td>
<td>4.7449</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>84</td>
<td>948.3350</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.6147.
Square root of multiple R = 0.7841.
** Denotes significance at .01 probability level.

Table 14. Test of the significance of the vessel proportion partial regression coefficients (reduced model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>0.5891</td>
<td>0.1096</td>
<td>5.3744**</td>
</tr>
<tr>
<td>$X_2$</td>
<td>-13.7984</td>
<td>4.7148</td>
<td>-2.9266**</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-14.1014</td>
<td>4.6940</td>
<td>-3.0042**</td>
</tr>
<tr>
<td>$(X_1^2)$</td>
<td>-0.0120</td>
<td>0.0035</td>
<td>-3.4338**</td>
</tr>
<tr>
<td>$(X_2^2)$</td>
<td>0.7511</td>
<td>0.2609</td>
<td>2.8787**</td>
</tr>
<tr>
<td>$(X_3^2)$</td>
<td>0.8508</td>
<td>0.1596</td>
<td>3.2770**</td>
</tr>
<tr>
<td>$(X_1X_2)$</td>
<td>1.5979</td>
<td>0.5130</td>
<td>3.1148**</td>
</tr>
</tbody>
</table>

** Denotes significance beyond the .01 probability level.
type 1 and was computed similarly to that for the ring width analyses. A decrease in vessel proportion is noted from the apex downward. This trend is revealed only by plotting the vessel proportion in rings formed in the last six years of wood formation (two levels are plotted from the equations for 1 and 3 blocks, each block representing three years). The value of this trend in the whole tree can be judged by the extent of within-tree variation in vessel proportion. The original data reveals that the coefficient of variation for vessel proportion within the tree is 6.55%. With this amount of variation it was doubtful if a trend for the whole tree can be justified. Figures 9, 10 show no pronounced trend with respect to vessel proportion within the tree. However, in type 2 it will be noted that there is a slight increase in vessel proportion from the pith to age 21 years (block 7) and then a leveling off. From this analysis the low value of within-tree variation of proportion of vessels is understandable.

Ray proportion model

Table 15 shows that the ray proportion regression is significant at the .01 level (F statistic). The test of each of the coefficients, after the effects of all other variables have been fitted, is not significant (Table 16).

When the least effective terms were removed from the ray proportion model a reduced model resulted. The deletion of the
## Table 15. Analysis of ray proportion regression variance (full model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>10</td>
<td>36,6536</td>
<td>3.6654</td>
<td>3.6761**</td>
</tr>
<tr>
<td>Residual</td>
<td>74</td>
<td>73.7848</td>
<td>0.9971</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>84</td>
<td>110.4384</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.3319.

Square root of multiple R = 0.5761.

**Denotes significance at .01 probability level.

## Table 16. Test of the significance of the ray proportion regression coefficients (full model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>1.3363</td>
<td>2.1609</td>
<td>0.6184</td>
</tr>
<tr>
<td>$X_2$</td>
<td>0.1735</td>
<td>0.2168</td>
<td>0.8004</td>
</tr>
<tr>
<td>$X_3$</td>
<td>20.2660</td>
<td>22.0297</td>
<td>0.9199</td>
</tr>
<tr>
<td>$X_4$</td>
<td>21.6439</td>
<td>21.9791</td>
<td>0.9848</td>
</tr>
<tr>
<td>($X_1^2$)</td>
<td>-0.0029</td>
<td>0.0094</td>
<td>-0.3107</td>
</tr>
<tr>
<td>($X_2^2$)</td>
<td>-0.9787</td>
<td>1.0097</td>
<td>-0.9693</td>
</tr>
<tr>
<td>($X_3^2$)</td>
<td>-1.0936</td>
<td>1.0048</td>
<td>-1.0884</td>
</tr>
<tr>
<td>($X_1X_2$)</td>
<td>-0.1344</td>
<td>0.2009</td>
<td>-0.6692</td>
</tr>
<tr>
<td>($X_1X_3$)</td>
<td>-0.1483</td>
<td>0.2007</td>
<td>-0.7389</td>
</tr>
<tr>
<td>($X_2X_4$)</td>
<td>2.0619</td>
<td>2.0109</td>
<td>-1.0254</td>
</tr>
</tbody>
</table>
terms from the full model was based on testing the partial regression coefficients ("t" test) and considering the known importance of each term. In Table 17 the final reduced model of the regression for the proportion of rays is presented. The multiple "R" of this reduced model regression is 0.5703, indicating that 32.52 percent of the total variability in ray proportion is accountable. The coefficients of all the terms included in this model as tested by "t" statistic are significant at the .01 level (Table 18). By using a classification model, a measure of error independent of functional relationships of the dependent variables was obtained and thus a lack of fit test was carried out. The lack of fit test was not significant. The reduced prediction equation for ray proportion is:

\[ Y_4 = 59.7618 + 0.6747 (X_1) + 13.6671 (X_2) + 15.0654 (X_4) \]
\[ - 0.6773 (X_2^2) - 0.7942 (X_4^2) - 0.0731 (X_1X_3) - 0.0871 (X_1X_4) \]
\[ - 1.4613 X_3X_4. \]

The data from both sides of the tree were combined and presented in three ways similar to that for presenting the data on average ring width. The ray proportion variation within the tree was studied in the oblique, horizontal and vertical sequences referred to by types 1, 2 and 3 respectively. Only type 1 was plotted from both the original data and the prediction equation of ray proportion. From Figures 9, 11 and 12...
### Table 17. Analysis of ray proportion regression variance (reduced model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>8</td>
<td>35.9137</td>
<td>4.4892</td>
<td>4.5781**</td>
</tr>
<tr>
<td>Residual</td>
<td>76</td>
<td>74.5246</td>
<td>0.9806</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>84</td>
<td>110.4383</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.3252.

Square root of multiple R = 0.5703.

**Denotes significance at .01 probability level.

### Table 18. Test of the significance of the ray proportion partial regression coefficients (reduced model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X_1)</td>
<td>0.6747</td>
<td>0.3256</td>
<td>2.0722*</td>
</tr>
<tr>
<td>(X_3)</td>
<td>13.6671</td>
<td>5.6239</td>
<td>2.4302*</td>
</tr>
<tr>
<td>(X_4)</td>
<td>15.0654</td>
<td>5.5934</td>
<td>2.6934**</td>
</tr>
<tr>
<td>(X_3^2)</td>
<td>-0.6773</td>
<td>0.2742</td>
<td>-2.4699*</td>
</tr>
<tr>
<td>(X_4^2)</td>
<td>-0.7314</td>
<td>0.2716</td>
<td>-2.9245**</td>
</tr>
<tr>
<td>(X_1X_3)</td>
<td>-0.0731</td>
<td>0.0341</td>
<td>-2.1433*</td>
</tr>
<tr>
<td>(X_1X_4)</td>
<td>-0.0871</td>
<td>0.0340</td>
<td>-2.5603*</td>
</tr>
<tr>
<td>(X_2X_4)</td>
<td>-1.4613</td>
<td>0.5321</td>
<td>-2.7461**</td>
</tr>
</tbody>
</table>

*Denotes significance at .05 probability level.

**Denotes significance at .01 probability level.
presenting type 1 (oblique), type 2 (horizontal) and type 3 (vertical) respectively, it is clear that very little variation exists in ray proportion within the tree. However, the graphs in Figure 10 plotted from the reduced prediction equation, shows that the ray proportion decreases slightly from the top of the tree to a minimum at a height of 14 feet (29 percent of total height), then it increases toward the base. Two main points must be noticed here. First, that these graphs plotted from the prediction equations represent only the last six years of wood formation in the oblique sequence in the tree (two blocks from the bark, each one representing 3 years). The second point to be considered is the lower within-tree coefficient of variability of 8.16% for ray proportion.

Analyses of Specific Gravity Model

The specific gravity regression in Table 19 is significant at the .01 level, as tested by the F statistic. The combined effect of the variables expressed by the multiple "R" is 0.6133, indicating that 37.62 percent of the total variability in specific gravity is accountable. Except for cardinal direction, Table 20 shows that the test of each of the coefficients, after the effects of all other variables have been fitted, is significant except for the cardinal direction term. Thus, the specific gravity model was reduced by elimination of the least effective terms in the model. Table 21 presents the reduced model regression which is highly significant. Table 22 of the
Table 19. Analysis of specific gravity regression variance (full model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>10</td>
<td>0.1226</td>
<td>0.0123</td>
<td>17.9086**</td>
</tr>
<tr>
<td>Residual</td>
<td>297</td>
<td>0.2034</td>
<td>0.0007</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>0.3260</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.3762,
Square root of multiple R = 0.6133.

**Denotes the significance at .01 probability level.

Table 20. Test of the significance of the specific gravity partial regression coefficients (full model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>-0.0895</td>
<td>0.0210</td>
<td>-4.2605**</td>
</tr>
<tr>
<td>$X_2$</td>
<td>0.0008</td>
<td>0.0029</td>
<td>0.2761</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-0.8004</td>
<td>0.2167</td>
<td>-3.6928**</td>
</tr>
<tr>
<td>$X_4$</td>
<td>-0.7937</td>
<td>0.2167</td>
<td>-3.6618**</td>
</tr>
<tr>
<td>$(X_1)^2$</td>
<td>0.0004</td>
<td>0.0001</td>
<td>4.5332**</td>
</tr>
<tr>
<td>$(X_2)^2$</td>
<td>0.0347</td>
<td>0.0099</td>
<td>3.4857**</td>
</tr>
<tr>
<td>$(X_3)^2$</td>
<td>0.0337</td>
<td>0.0099</td>
<td>3.3863**</td>
</tr>
<tr>
<td>$(X_1X_3)$</td>
<td>0.0081</td>
<td>0.0020</td>
<td>4.1322**</td>
</tr>
<tr>
<td>$(X_1X_4)$</td>
<td>0.0082</td>
<td>0.0020</td>
<td>4.1683**</td>
</tr>
<tr>
<td>$(X_2X_4)$</td>
<td>0.0718</td>
<td>0.0199</td>
<td>3.6177**</td>
</tr>
</tbody>
</table>

**Denotes the significance at .01 probability level.
Table 21. Analysis of specific gravity regression variance
(reduced model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>9</td>
<td>0.1226</td>
<td>0.0136</td>
<td>19.9518**</td>
</tr>
<tr>
<td>Residual</td>
<td>298</td>
<td>0.2034</td>
<td>0.0007</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>0.3250</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.3760.
Square root of multiple R = 0.6132.

**Denotes the significance at .01 probability level.

Table 22. Test of the significance of the specific gravity
partial regression coefficients (reduced model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>-0.0895</td>
<td>0.0209</td>
<td>-4.2671**</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-0.8004</td>
<td>0.2164</td>
<td>-3.6986**</td>
</tr>
<tr>
<td>$X_4$</td>
<td>-0.7937</td>
<td>0.2164</td>
<td>-3.6675**</td>
</tr>
<tr>
<td>$(X_1^2)$</td>
<td>0.0004</td>
<td>0.0001</td>
<td>4.5402**</td>
</tr>
<tr>
<td>$(X_3^2)$</td>
<td>0.0347</td>
<td>0.0099</td>
<td>3.4911**</td>
</tr>
<tr>
<td>$(X_4^2)$</td>
<td>0.0337</td>
<td>0.0099</td>
<td>3.3916**</td>
</tr>
<tr>
<td>$(X_1X_3)$</td>
<td>0.0080</td>
<td>0.0020</td>
<td>4.1387**</td>
</tr>
<tr>
<td>$(X_1X_4)$</td>
<td>0.0082</td>
<td>0.0020</td>
<td>4.1748**</td>
</tr>
<tr>
<td>$(X_3X_4)$</td>
<td>0.0718</td>
<td>0.0198</td>
<td>3.6234**</td>
</tr>
</tbody>
</table>

**Denotes the significance at .01 probability level.
reduced model shows that the test of each of the coefficients after the effects of all other variables have been fitted, in the reduced model, to be significant. The combined effect of the variables expressed by the multiple $R$ in the reduced model is 0.6132, indicating that 37.60 percent of the total variability in specific gravity is accountable in the reduced model. A lack of fit test was done by using a classification model which provided a measure of error independent of functional relationships of the dependent variables. The classification model was based on the fact that all values of independent variables were represented by two observations, one from each side of the tree. The lack of fit test was not significant. Thus, it was justified to proceed with the reduced model. The resulting prediction equation for specific gravity based on the data is:

$$Y_5 = 4.9847 - 0.0895 (X_1) - 0.8004 (X_3) - 0.7937 (X_4)$$

$$+ 0.0004 (X_1^2) + 0.0347 (X_3)^2 + 0.0337 (X_4)^2 + 0.0081 (X_1X_3)$$

$$+ 0.0082 (X_1X_4) + 0.0718 (X_3X_4).$$

After the formulation of the specific gravity reduced model, the data from both sides of the tree were combined to make two dimensional plots. The data were presented in three ways similar to that followed in plotting the average ring width data. The three types (sequences) 1, 2 and 3 were plotted from the original data while type 1 (oblique) was plotted from
the original data of specific gravity. In type 1 Figure 13, the data plots for the whole tree represent no clear trend, however, there is indicated a comparatively low specific gravity at 3 to 12 feet from the ground level. In Figure 14 the type 2 sequence (horizontal) is plotted from the original data for the whole tree. It is noted that specific gravity in this sequence increases from the pith outward to about age 12 years and then decreases toward the bark. This trend reveals a combined effect of cambial age and year of wood formation. The low coefficient of variation (6.87%) of the specific gravity within the tree, however, cannot be ignored. Such a percentage indicates that the existing trend of variation represent only a limited variability in specific gravity within the tree. The vertical sequence, type 3 Figure 15 reveals little or no trend of variation from the top to the tree base. This sequence projects the influence of year of wood formation on the specific gravity at constant cambial ages. Large fluctuations in this unsystematic sequence are expected since the year of formation variable combines many environmental factors which change from one year to another. Hence, the existence of any systematic pattern in type 3 would indicate a masking influence of systematic intrinsic factors.
Figure 13. A family of curves of specific gravity measurements each curve representing an average of three years of wood formation.
Figure 14. A family of curves of specific gravity measurements across the radius of the stem. Each curve representing a certain height level in the tree.
TYPE 2 (HORIZONTAL)
HEIGHT RANGE .8 - 45 FEET
Figure 15. A family of curves of specific gravity measurements each curve representing an average of three years of cambial age
TYPE 3 (VERTICAL)  
BLOCKS FROM PITH

SPECIFIC GRAVITY

HEIGHT IN FEET
Analysis of Shrinkage Models

The wood anisotropy and the dependence of both radial and tangential shrinkage on several factors were the reasons for investigating both radial and tangential shrinkage values in this study. A full regression model including the same terms was fitted to the data for radial, tangential and volumetric shrinkage values within the tree.

Analyses of tangential shrinkage model

In Table 23 the tangential shrinkage regression was significant at the .01 level, as tested by F statistic. However, the combined effect of the variables expressed by the multiple "R" was 0.5408, indicating that only 29.25 percent of the total variability was accountable. In Table 24 the test of each of the coefficients, after all other variables, is presented. The tangential shrinkage model was reduced both on the basis of the significance of the partial regression coefficients of each term ("t" test) and considering the known importance of each. The interrelations between these variables and the independent variables were considered in the deletion of each term in order to select the "best" regression equation (Table 27).

Table 25 shows that the reduced model for the tangential shrinkage regression is significant at the .01 probability level. The multiple "R" of this reduced model regression is 0.5299, indicating that only 28.09 percent of the total variability in tangential shrinkage is accountable. Table 26 shows
Table 23. Analysis of tangential shrinkage regression variance (full model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>10</td>
<td>289,3529</td>
<td>28.9353</td>
<td>12.2776**</td>
</tr>
<tr>
<td>Residual</td>
<td>297</td>
<td>699.9558</td>
<td>2.3568</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>989.3087</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.2925.

Square root of multiple R = 0.5408

** Denotes the significance at .01 probability level.

Table 24. Test of the significance of the tangential shrinkage partial regression coefficients (full model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₁</td>
<td>-0.4758</td>
<td>1.2326</td>
<td>-0.3860</td>
</tr>
<tr>
<td>X₂</td>
<td>-0.3470</td>
<td>0.1749</td>
<td>-1.9835</td>
</tr>
<tr>
<td>X₃</td>
<td>-6.8413</td>
<td>12.7156</td>
<td>-0.5380</td>
</tr>
<tr>
<td>X₄</td>
<td>-3.2261</td>
<td>12.7156</td>
<td>-0.2537</td>
</tr>
<tr>
<td>(X₁²)</td>
<td>0.0018</td>
<td>0.0054</td>
<td>0.3269</td>
</tr>
<tr>
<td>(X₂²)</td>
<td>0.4468</td>
<td>0.5844</td>
<td>0.7647</td>
</tr>
<tr>
<td>(X₃²)</td>
<td>0.0681</td>
<td>0.5844</td>
<td>0.1166</td>
</tr>
<tr>
<td>(X₁X₃)</td>
<td>0.0675</td>
<td>0.1148</td>
<td>0.5881</td>
</tr>
<tr>
<td>(X₁X₄)</td>
<td>0.0399</td>
<td>0.1148</td>
<td>0.3471</td>
</tr>
<tr>
<td>(X₃X₄)</td>
<td>0.5387</td>
<td>1.1649</td>
<td>0.4625</td>
</tr>
</tbody>
</table>
### Table 25. Analysis of tangential shrinkage regression variance (reduced model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>6</td>
<td>277.8592</td>
<td>46.3099</td>
<td>19.5928**</td>
</tr>
<tr>
<td>Residual</td>
<td>301</td>
<td>711.4496</td>
<td>2.3636</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>989.3088</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.2809.

Square root of multiple R = 0.5299.

**Denotes the significance at .01 probability level.

### Table 26. Test of the significance of the tangential shrinkage partial regression coefficients (reduced model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₁</td>
<td>-0.0398</td>
<td>0.0465</td>
<td>-0.8547</td>
</tr>
<tr>
<td>X₃</td>
<td>-1.1261</td>
<td>0.6719</td>
<td>-1.6758</td>
</tr>
<tr>
<td>X₄</td>
<td>2.1353</td>
<td>0.3788</td>
<td>5.6368**</td>
</tr>
<tr>
<td>(X₃²)</td>
<td>0.1618</td>
<td>0.4438</td>
<td>3.6450**</td>
</tr>
<tr>
<td>(X₄²)</td>
<td>-0.1842</td>
<td>0.0438</td>
<td>-4.2102**</td>
</tr>
<tr>
<td>(X₁X₃)</td>
<td>0.0244</td>
<td>0.0078</td>
<td>3.1512**</td>
</tr>
</tbody>
</table>

**Denotes the significance at .01 probability level.
Table 27-28. Simple correlations of the non-significant independent terms to all other independent terms in the tangential shrinkage model

<table>
<thead>
<tr>
<th></th>
<th>$X_1$</th>
<th>$X_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_2$</td>
<td>-0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-0.2594**</td>
<td>1.0000**</td>
</tr>
<tr>
<td>$X_4$</td>
<td>-0.2594**</td>
<td>-0.8516**</td>
</tr>
<tr>
<td>$X_1^2$</td>
<td>0.9650**</td>
<td>-0.2673**</td>
</tr>
<tr>
<td>$X_3^2$</td>
<td>-0.2897**</td>
<td>0.9715**</td>
</tr>
<tr>
<td>$X_4^2$</td>
<td>-0.2897**</td>
<td>-0.8069**</td>
</tr>
<tr>
<td>$X_1X_3$</td>
<td>0.6920**</td>
<td>0.3661**</td>
</tr>
<tr>
<td>$X_1X_4$</td>
<td>0.6920**</td>
<td>0.7002**</td>
</tr>
<tr>
<td>$X_3X_4$</td>
<td>0.5941**</td>
<td>0.1689**</td>
</tr>
</tbody>
</table>

$X_1$ = height.

$X_2$ = cardinal direction.

$X_3$ = coded year of formation.

$X_4$ = coded cambial age.

**Denotes the significance at the .01 probability level.

that all the coefficients of the terms included in this model are significant at the .01 level except the height and the year of formation. It can be speculated that the reason for the non-significance of the year of formation term in the tangential shrinkage reduced model is due to its high correlation to
the (year of formation)^2 and other independent terms. The high correlation between the height variable and other independent terms in the reduced model can be a reason for the non-significance of this term. In spite of the non-significance of these two variables, they were retained in the reduced model on the basis of their known importance and the fact that their addition cannot detract from the accuracy of the prediction equation. A lack of fit test was done in a similar way to that in the analysis of the ring width model. In spite of the fact that this model explains only 28.09 percent of the variability in tangential shrinkage, the lack of fit test was not significant, indicating that adding higher order terms is not justified. Thus, the resulting regression equation for tangential shrinkage as based on the data is:

\[ Y_6 = 6.8609 - 0.0397 (X_1) - 1.1261 (X_2) + 2.1353 (X_4) + 0.1618 (X_3)^2 - 0.1842 (X_4)^2 + 0.0244 (X_1 X_3). \]

The data from both sides of the tree were then combined to make two dimensional plots presented in three ways similar to that in the ring width analyses. Type 1, (oblique sequence), is presented in Figure 16. Starting at the stump of the tree a close inspection of the graphs in this figure suggests a slight increase in tangential shrinkage to the base of the crown (24 feet) and then a decrease toward the apex. This sequence when plotted from the prediction equation for the last three years of wood formation (Figure 17) also shows the
Figure 16. A family of curves of tangential shrinkage values each curve representing an average of three years of wood formation.
Figure 17. A curve of tangential shrinkage values each representing an average of three years of wood formation as plotted from the prediction equation.
TYPE I (OBLIQUE)
BLOCK NO I (3 YEARS)

TANGENTIAL SHRINKAGE %

HEIGHT IN FEET

4 8 12 16 20 24 28 32 36 40 44
increase in shrinkage near the base of the crown. The horizontal sequence (type 2) in Figure 18, 19 shows a decrease in tangential shrinkage in heights below the crown at ages below 18 years (block 6 from pith). At older ages below the crown area as well as all ages in the crown area (heights 28.8 to 45.4 feet) a considerable variation present with no trends shown. Type 3, Figure 20 does not reveal a clear pattern with respect to tangential shrinkage. It must be considered that the variability in tangential shrinkage values is not high within the tree. The coefficient of variation for tangential shrinkage was computed to be 9.20 percent.

Radial shrinkage model

Table 29 shows that the radial shrinkage regression is significant at the .01 level. The multiple \( R \) is 0.5961, indicating that 35.53 percent of the variability in radial shrinkage is accountable. A type of backward elimination procedure based on the test of partial regression coefficients of each term was done. Considerable importance was given to the interrelations between the independent variables before the deletion of any term. Table 30 presents the full model of radial shrinkage regression. The test of each of the coefficients, after the effects of all other variables have been fitted, is not significant. Table 31 shows that the reduced model regression is significant at the .01 level. The multiple \( R \) is 0.5902, indicating that 34.83 percent of the total variability in radial shrinkage is accountable. In Table 32
Figure 18. A family of curves of tangential shrinkage values across the radius of the stem. Each curve representing a certain height level in the tree.
TYPE 2 (HORIZONTAL)
HEIGHT = 1.2' - 22.00'

TANGENTIAL SHRINKAGE %

PITH 1 2 3 4 5 6 7 8 9

BLOCKS NO. FROM PITH
Figure 19. A family of curves of tangential shrinkage values across the radius of the stem. Each curve representing a certain height level in the tree.
TYPE 2 (HORIZONTAL)
HEIGHT: 26.8' - 45.4'

TANGENTIAL SHRINKAGE %

PITH 1 2 3 4 5 6 7 8 9

BLOCKS NO. FROM PITH
Figure 20. A family of curves of tangential shrinkage values each one representing an average of three years of cambial age
TYPE 3 (VERTICAL)
NO. OF BLOCKS FROM PITH

TANGENTIAL SHRINKAGE %

HEIGHT IN FEET

4  8  12  16  20  24  28  32  36  40  44
Table 29. Analysis of Radial shrinkage regression variance (full model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>10</td>
<td>163.8079</td>
<td>16.3808</td>
<td>16.3704**</td>
</tr>
<tr>
<td>Residual</td>
<td>297</td>
<td>297.1892</td>
<td>1.0006</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>460.9971</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.3553.
Square root of multiple R = 0.5961.

**Denotes the significance at the .01 probability level.

Table 30. Test of the significance of the radial shrinkage partial regression coefficients (full model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₁</td>
<td>-0.2735</td>
<td>0.8032</td>
<td>-0.3405</td>
</tr>
<tr>
<td>X₂</td>
<td>0.0264</td>
<td>0.1140</td>
<td>0.2318</td>
</tr>
<tr>
<td>X₃</td>
<td>-4.6717</td>
<td>8.2855</td>
<td>-0.5638</td>
</tr>
<tr>
<td>X₄</td>
<td>-1.3778</td>
<td>8.2855</td>
<td>-0.1663</td>
</tr>
<tr>
<td>(X₁²)</td>
<td>0.0014</td>
<td>0.0035</td>
<td>0.4013</td>
</tr>
<tr>
<td>(X₂²)</td>
<td>0.3341</td>
<td>0.3808</td>
<td>0.8773</td>
</tr>
<tr>
<td>(X₄²)</td>
<td>0.0046</td>
<td>0.3808</td>
<td>-0.0121</td>
</tr>
<tr>
<td>(X₁X₂)</td>
<td>0.0419</td>
<td>0.0749</td>
<td>0.5601</td>
</tr>
<tr>
<td>(X₁X₄)</td>
<td>0.0180</td>
<td>0.0749</td>
<td>0.2409</td>
</tr>
<tr>
<td>(X₃X₄)</td>
<td>0.2763</td>
<td>0.7590</td>
<td>0.3640</td>
</tr>
</tbody>
</table>
Table 31. Analysis of radial shrinkage regression variance (reduced model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>6</td>
<td>160.5833</td>
<td>26.7639</td>
<td>26.8161**</td>
</tr>
<tr>
<td>Residual</td>
<td>301</td>
<td>300.4139</td>
<td>0.9981</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>460.9972</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.3483.
Square root of multiple R = 0.5902.

**Denotes the significance at .01 probability level.

Table 32. Test of the significance of the radial shrinkage partial regression coefficients (reduced model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>-0.0528</td>
<td>0.0302</td>
<td>-1.7490</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-1.7912</td>
<td>0.4367</td>
<td>-4.1019**</td>
</tr>
<tr>
<td>$X_4$</td>
<td>1.0095</td>
<td>0.2462</td>
<td>4.1008**</td>
</tr>
<tr>
<td>$(X_3^2)$</td>
<td>0.1739</td>
<td>0.0288</td>
<td>6.0292**</td>
</tr>
<tr>
<td>$(X_4^2)$</td>
<td>-0.1192</td>
<td>0.0284</td>
<td>-4.1921**</td>
</tr>
<tr>
<td>$(X_1X_3)$</td>
<td>0.0194</td>
<td>0.0050</td>
<td>3.8442**</td>
</tr>
</tbody>
</table>

**Denotes the significance at .01 probability level.
the tests of significance of the partial regression coefficients are highly significant except for the height term.

Table 33 presents the simple correlations of the height term to all independent terms in the radial shrinkage model. It can be speculated that the non-significance of this term is due to its high correlations with other independent terms. Since the addition of this term does not detract from the accuracy of the prediction equation, it was retained due to its known importance. A lack of fit test was done and proved to be non-significant. Thus, no justification was present to add higher order terms to the model. The following is the resulting prediction equation for radial shrinkage:

\[
Y = 6.4137 - 0.0528 (X_1) - 1.7912 (X_2) + 1.0095 (X_4) \\
+ 0.1739 (X_3)^2 - 0.1192 (X_4)^2 + 0.0194 (X_1X_3).
\]

The data were then plotted in three ways, similar to that in the ring width analyses (type 1, 2 and 3). Type 1 (oblique) presented in Figure 22 shows that the radial shrinkage increased from base to the top of the tree. Figure 21 presents type 1 as plotted from the prediction equation for the last six years of formation (each line represents a three year average). Again a clear trend is presented. A slight decrease in radial shrinkage is noticed from the base of the tree to a height of around 16 feet, then an increase to a point close to the apex followed by a slight decrease to the apex. Type 2 (horizontal sequence) is presented in Figures 23, 24. For
Table 33. Simple correlations of the height term to all independent terms in the radial shrinkage model

<table>
<thead>
<tr>
<th>$X_1$</th>
<th>$X_2$</th>
<th>$X_3$</th>
<th>$X_4$</th>
<th>$(X_1)^2$</th>
<th>$(X_2)^2$</th>
<th>$(X_3)^2$</th>
<th>$(X_4)^2$</th>
<th>$(X_1 X_2)$</th>
<th>$(X_1 X_3)$</th>
<th>$(X_1 X_4)$</th>
<th>$(X_3 X_4)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$-0.0000$</td>
<td>$-0.2594$</td>
<td>$-0.2594$</td>
<td>$0.9650$</td>
<td>$0.2897$</td>
<td>$0.2897$</td>
<td>$0.6920$</td>
<td>$0.5941$</td>
</tr>
</tbody>
</table>

$a X_1 = \text{height.}$

$X_2 = \text{cardinal direction.}$

$X_3 = \text{coded year of formation.}$

$X_4 = \text{coded cambial age.}$

heights of 1.2 feet to 22.0 feet, which is near the base of the crown, the radial shrinkage decreases from the pith to the bark. At heights of 28.8 feet to 45.4 feet (Figure 24) there is much variation in radial shrinkage along the radius and no clear trend is evident. This sequence presents the combined influences of year of wood formation and cambial age. The significant simple correlation coefficient between radial and
Figure 21. A family of curves of radial shrinkage values each curve representing an average of three years of wood formation
TYPE 'I' (OBLIQUE) BLOCKS FROM BARK

CROWN AREA

RADIAL SHRINKAGE %

HEIGHT IN FEET

16 20 24 28

1 2 3 4 5 6 7 8 9
Figure 22. A family of curves of radial shrinkage values each one representing an average of three years of wood formation as plotted from the prediction equation.
TYPE I (OBLIQUE) BLOCKS FROM BARK

BLOCK NO. 1
NO. 2

RADIAL SHRINKAGE %

HEIGHT IN FEET
Figure 23. A family of curves of radial shrinkage values across the radius of the stem. Each curve representing a certain height level in the tree
Figure 24. A family of curves of radial shrinkage values across the radius of the stem. Each curve representing a certain height level in the tree.
TYPE 2° (HORIZONTAL)
HEIGHT RANGE: 28.8°-45.4°

RADIAL SHRINKAGE %

PITH 1 2 3 4 5 6 7 8 9
NO. OF BLOCKS FROM PITH
tangential shrinkage, found in this study, explains the similarity in trends of the horizontal sequences of both shrinkages (Figures 18, 19 and 23, 24). Type 3 (vertical sequence) does not reveal any clear trend (Figure 25). It will be noted that the trends of variation are expected to be more pronounced in radial shrinkage than in tangential shrinkage since the coefficient of variation in radial shrinkage is 25.42% as compared to 9.20% for tangential shrinkage, indicating more variation of radial shrinkage within the tree.

**Volumetric shrinkage model**

Volumetric shrinkage as computed in this study represents the result of radial and tangential shrinkages. Table 34 shows that the volumetric shrinkage regression is highly significant. Table 35 shows that the test of each of the coefficients, after the effects of all other variables have been fitted, is not significant. In order to obtain the "best" regression equation the volumetric shrinkage model was then reduced by a type of backward elimination procedure considering biologically known facts.

Table 36 shows the regression of the volumetric shrinkage reduced model to be significant at the .01 level. The multiple "R" is 0.6590, indicating that 43.43 percent of the total variability in volumetric shrinkage is accountable. In Table 37, the test of each of the coefficients, after the effects of all other variables have been fitted, is signifi-
Figure 25. A family of curves of radial shrinkage values each one representing an average of three years of cambial age
CROWN AREA

TYPE 3 (VERTICAL) BLOCKS FROM PITH

RADIAL SHRINKAGE %

HEIGHT IN FEET
Table 34. Analysis of volumetric shrinkage regression variance (full model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>10</td>
<td>645,256</td>
<td>64,5256</td>
<td>23.5876**</td>
</tr>
<tr>
<td>Residual</td>
<td>297</td>
<td>812,4667</td>
<td>2.7356</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>1,457,7228</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.4426.
Square root of multiple R = 0.6653.
** Denotes the significance at .01 probability level.

Table 35. Test of the significance of the volumetric shrinkage partial regression coefficients (full model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>-0.8829</td>
<td>1.3280</td>
<td>-0.6649</td>
</tr>
<tr>
<td>$X_2$</td>
<td>-0.2810</td>
<td>0.1885</td>
<td>-1.4910</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-12.0537</td>
<td>13.6995</td>
<td>-0.8799</td>
</tr>
<tr>
<td>$X_4$</td>
<td>-5.8475</td>
<td>13.6995</td>
<td>-0.4268</td>
</tr>
<tr>
<td>$(X_1^2)$</td>
<td>0.0038</td>
<td>0.0058</td>
<td>0.6429</td>
</tr>
<tr>
<td>$(X_2^2)$</td>
<td>0.7711</td>
<td>0.6296</td>
<td>1.2249</td>
</tr>
<tr>
<td>$(X_3^2)$</td>
<td>0.1262</td>
<td>0.6296</td>
<td>0.2005</td>
</tr>
<tr>
<td>$(X_4^2)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(X_1X_3)$</td>
<td>0.1174</td>
<td>0.1237</td>
<td>0.9489</td>
</tr>
<tr>
<td>$(X_1X_4)$</td>
<td>0.0714</td>
<td>0.1237</td>
<td>0.5772</td>
</tr>
<tr>
<td>$(X_3X_4)$</td>
<td>0.8782</td>
<td>1.2550</td>
<td>0.6999</td>
</tr>
</tbody>
</table>
Table 36. Analysis of volumetric shrinkage regression variance (reduced model)

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>6</td>
<td>633.0263</td>
<td>105.5044</td>
<td>38.5073**</td>
</tr>
<tr>
<td>Residual</td>
<td>301</td>
<td>824.6965</td>
<td>2.7399</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>307</td>
<td>1457.7228</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Multiple R square = 0.4343.
Square root of multiple R = 0.6590.
** Denotes the significance at .01 probability level.

Table 37. Test the significance of the volumetric shrinkage partial regression coefficients (reduced model)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficients</th>
<th>Standard error</th>
<th>&quot;t&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>-0.0883</td>
<td>0.0500</td>
<td>-1.7647</td>
</tr>
<tr>
<td>$X_3$</td>
<td>-2.6742</td>
<td>0.7235</td>
<td>-3.6963**</td>
</tr>
<tr>
<td>$X_4$</td>
<td>2.9085</td>
<td>0.4079</td>
<td>7.1311**</td>
</tr>
<tr>
<td>($X_3^2$)</td>
<td>0.3042</td>
<td>0.0478</td>
<td>6.3665**</td>
</tr>
<tr>
<td>($X_4^2$)</td>
<td>-0.2831</td>
<td>0.0471</td>
<td>-6.0091**</td>
</tr>
<tr>
<td>($X_1X_3$)</td>
<td>0.0403</td>
<td>0.0084</td>
<td>4.8237**</td>
</tr>
</tbody>
</table>

** Denotes the significance at .01 probability level.
cant at .01 level except for the height term. A lack of fit test was done for the model and proved to be non-significant. Thus, I was reluctant to add higher order terms to the reduced model. The retention of the height term was based on the fact that adding this term will not detract from the accuracy of the model. The high interrelation between this term and other independent variables in the model is likely the reason for its non-significant coefficient in the reduced model. The resulting prediction equation for volumetric shrinkage \( Y_6 \) based on the data is:

\[
Y_6 = 13.1228 - 0.0883 \cdot (X_1) - 1.6742 (X_3) + 2.9085 (X_4) \\
+ 0.3042 (X_3^2) - 0.2831 (X_4^2) + 0.0403 (X_1 X_3).
\]

The reduced model resulting from the elimination procedure includes the same terms as for both tangential and radial shrinkage reduced models. This is not unexpected since the calculated volumetric shrinkage is based on both shrinkages. However, the multiple "R" and the variability accounted for by this model are higher than those for either tangential and radial shrinkages. This means that both tangential and radial shrinkage are influenced by factors in addition to those in the reduced models of each.

The combined data from both sides of the tree were plotted in three ways similar to that in the ring width analyses. Figure 26 presents the type 1 (oblique) sequence and does not reveal a clear systematic variation in volumetric
Figure 26. A family of curves of volumetric shrinkage values each curve representing an average of three years of wood formation.
shrinkage. However, the graphs plotted from the prediction equation (Figure 27), representing the last six years of wood formation, follow a pattern similar to that in type 1 of radial shrinkage. Little change is noticed from the base of the tree to a height of 16 feet which is just below the crown area; then an increase occurs from this height up the tree to a point close to the top followed by a slight decrease toward the apex. Figures 28 and 29 represent the type 2 sequence, the horizontal variation in volumetric shrinkage within the tree. It is clear that the volumetric shrinkage decreases from the pith to the bark. For heights between 30.2 feet and 45.4 feet which are within the crown (Figure 29) there is considerable variation and no trend is indicated. Figure 30 presents type 3 and reveals no systematic trend of variation. This is expected in this sequence which reveals the fluctuation effect of different years of wood formation.

It should be noted that the volumetric shrinkage was computed in this study as well as both radial and tangential shrinkages in order to clarify the dependence of each on the terms used in the regression models. The variation of radial shrinkage with height influenced the volumetric shrinkage and this in turn helps to explain the volumetric shrinkage oblique sequence. Similarly both the tangential and radial shrinkages influenced volumetric shrinkage as shown in the horizontal sequence.
Figure 27. A family of curves of volumetric shrinkage values each one representing an average of three years of wood formation as plotted from the prediction equation.
Figure 28. A family of curves of volumetric shrinkage values across the radius of the stem. Each curve representing a certain height level in the tree.
TYPE 2 (HORIZONTAL)
HEIGHT RANGE: 1.2' - 28.8'

VOLUME SHRINKAGE %

NO. OF BLOCKS FROM PITH
Figure 29. A family of curves of volumetric shrinkage values across the radius of the stem. Each curve representing a certain height level in the tree.
TYPE "2" (HORIZONTAL)
HEIGHT RANGE: 30.2'-46.4'

VOLUMETRIC SHRINKAGE %

NO. OF BLOCKS FROM PITH
Figure 30. A family of curves of volumetric shrinkage values each one representing an average of three years of cambial age.
TYPE 3
NO. OF BLOCK FROM PITH

VOLUMETRIC SHRINKAGE %

HEIGHT IN FEET
The explanation of within-tree variation in anatomical and physical properties of wood can ultimately be found in the influence of physiological, genetic and environmental factors. The objectives of this study varied from determining the relationships of several factors considered simultaneously to that of investigating variation patterns of ring width, proportion of wood elements, specific gravity and shrinkage within a silver maple tree (*Acer saccharinum* L.).

The significance of the variables of height, coded cambial age, and coded year of wood formation in explaining the variation of wood properties within the tree are dependent upon the acceptance of the chosen polynomial models. All the terms in the models used accounted for different percentages of the variations in ring width, proportions of wood elements, specific gravity and shrinkage. The terms in these models accounted for a comparatively higher percentage of variation in ring width than in other properties such as specific gravity. In many cases the lack of fit test was not significant. In others, the amount of variation accounted for by a classification model almost matched that accounted for by the multiple regression model. This did not justify the addition of higher order terms to the models used. It is suggested that in future studies other factors be included with height, cambial age and year of formation.
The magnitudes of within-tree variation in ring width, proportion of wood elements, specific gravity and shrinkage were examined by computing the coefficients of variation for each variable. As reported in the Results section, the coefficients of variation were high with respect to ring width (35.12%) and radial shrinkage (25.42%). The coefficient of variation for fiber proportion was low (4.99%). It must be noted that the low cellular variation within the tree is a desirable feature for industry indicating a raw material having a high degree of uniformity. The low variability in vessel proportion (6.55%), ray proportion (8.16%) and specific gravity (6.87%) as well as volumetric shrinkage (13.54%) is also a strong advantage for silver maple wood if this is proved to be the case in all trees. Myer, in a general study (1930), commented on the homogeneity of this species with respect to the low variation in specific gravity within the stem. The results reported here confirm the general conclusion made by Myer.

Including only height, cambial age and coded year of wood formation as independent variables in the models was done to give a clear picture of the contribution of these independent variables to the within-tree variation in structure, density and shrinkage. This yielded information on how these variables contributed to variation in the properties investigated. In some cases such as ring width, these independent variables alone accounted for as much as 63.54% of the varia-
tion. However, in some cases these independent variables did not account for much of the variation. This is important for planning future research in the construction of models for similar studies. In some cases it was clear from the results, that the addition of one of the characters measured as a new term may improve the model. An example might be including the specific gravity term in the prediction equation of tangential shrinkage. This would seem desirable since the simple correlation of tangential shrinkage and specific gravity (0.1268) was significant at the .05 probability level. However, this was not done since the objective of the study was to determine within-tree variation and not to account for a maximum amount of variation in the dependent variables.

Structure, Density and Shrinkage as Related to Height

Ring width

From the results of this study it is shown that with a decrease in height from the apex of the tree (the oblique sequence) there occurs a slight decrease in ring width to a point at 63% of total height. This is followed by a rapid increase to a maximum at a level just below the living crown. From this point to the base of the tree there is no consistent change in ring width as related to height. The relationship of height to ring width agrees with that reported in the literature for newly released coniferous trees (Farrar, 1961). It is of interest to see this response in a diffuse-porous
tree also.

**Wood elements**

Fiber proportion of the last six years of tree growth increased very slightly as height increased. However, the effect of the height on variations in fiber proportions in different years of wood formation was not clear. The plots of the prediction equation indicated a slight increase in vessel proportion with increase in height but this was not evident in the plots of the original data. The original data did show a higher vessel proportion at two locations along the stem - a few feet below the crown and at the apex. These results agree quite well with the few studies conducted by Myer (1930). Ray proportion variation within the tree was very little. However, the proportion of ray tissue in the last six years of wood formation as indicated by the prediction equation plots slightly decreased with an increase in height to a point on the stem (29\% of total height), then it increases gradually to the apex. This also agrees with the general conclusions of Myer (1930). From the results of this study it can be speculated that while proportions of wood elements (fibers, vessels and rays) varied slightly within the tree, the effect of height is more pronounced in the last six years of wood formation. This effect is known to combine the nutritional gradients with the cambial age effect. Within young trees such as the one studied it is expected that the influence of height would be
more pronounced in the areas away from the crown. This is why the trends of variations in proportions of wood elements were masked when the data from the whole tree were plotted. The influence of the height variable was pronounced when the crown area moved up the tree, resulting in a differential effect of nutritional gradients and cambial age. Consequently variation in wood elements is likely to be greater in the outer growth rings.

**Specific gravity**

Several investigators have reported on the influence of height on specific gravity. The few available studies on diffuse-porous species are not in agreement. Paul (1963) found a decrease in specific gravity with increasing height in sugar maple, while Lenz (1954) reported an increase from the base up to the crown in poplar. The results of this study show that specific gravity tends to decrease with an increase in height up to about 12 feet and then increases to the base of the crown. In the crown area there is a slight decrease in specific gravity to the apex. These results from silver maple agree with those reported by Lenz (1954) in poplar. However, a check with the simple correlation coefficients of specific gravity and height shows that the simple correlation is not significant. This indicates that the height effect on specific gravity is not clear and was confounded with other factors.
**Shrinkage values**

Tangential shrinkage values as indicated by original data plots, increased slightly with increase in height to a point near the base of the crown and then decreased to the apex. However, this trend was not clearly defined. Radial shrinkage was more influenced by the height and showed an increase up to the base of the crown and is somewhat more clearly shown in the plots of the prediction equation. This similar trend of both radial and tangential shrinkages is explained by the positive simple correlation between both variables (0.2229) which is significant at the .05 probability level.

It is shown in the Results section that the coefficients of the height term in the reduced models were highly significant for fiber proportion, vessel proportion, ray proportion and specific gravity. The height term was not significant, however, for ring width and all shrinkage values but was retained in the reduced models. The simple correlation of height to fiber proportions (-0.3991) was highly significant (.01 probability level). Also the simple correlations between height and vessel proportion (0.5603), ray proportion (-0.3790) and radial shrinkage (0.3164) were highly significant. In spite of the non-significance of the height term in the ring width model, the simple correlation between the two was 0.6966, indicating that the non-significance of the height term in the ring width model was due to the interrelations between height and other variables in the model. The height variable was not
correlated with either tangential shrinkage or specific gravity. However, height was significant in the specific gravity model which may be due to close association of height with other significant variables in the multiple regression model.

Structure, Density and Shrinkage as Related to Cambial Age

Part of the controversy in the literature about the effect of age on wood properties may be due to the type of age measurement made (Brunden, 1964). Sometimes age is referred to as the tree age when wood was formed while in other studies including the one reported here it is measured as ring count from the pith.* It is noted that while the oblique sequence presents the ultimate effect of height, it includes the effect of cambial age which changes up the tree within a given ring. In the horizontal sequence both the cambial age and the year of wood formation are different. However, the horizontal sequence can be used to express the age effect, keeping in mind that the fluctuating factor of the year of formation may mask its effect.

Ring width

It is shown in the Results section that at a given height, ring width increases from the pith outward to a maximum at

*Measuring age as ring count from the pith is a more accurate indication of the age of the specific cambia forming the wood tissue. Tree age when the wood tissue was formed ignores the age of the cambia producing it.
about age 15 years and then it decreases toward the bark. This
trend is clear at levels below the crown area where there is
a difference in age and nutritional gradients across the stem
radius. The total age of the tree studied was 32 years.
Assuming that the trend of decreasing ring width beyond 15
years would continue, it can easily be seen that in older
timber the wide rings would be relatively close to the pith.
This would agree with Duff and Nolan's work on red pine (Duff
and Nolan, 1953).

Proportion of wood elements

The results show very little horizontal variation in fiber
proportion from the pith to the bark. Scaramuzzi (1956)
found similar results in *Populus sp.*

Vessel proportion varied somewhat across the tree radius.
At the pith where cambial age is very young the vessel
proportion was relatively low. An increase in vessel propor­
tion was noted from the pith outward to about age 21 years and
then it levels off. These results are similar to what
Vasiljevic (1951) found in (*Acer platanus* L.) and are reported
to confirm Sanio's first law. No clear cut trend was found
with respect to variation in ray proportion across the tree
radius.

Specific gravity

Specific gravity was found in this study to increase from
the pith outward to about age 15 years and then to decrease
toward the bark where the cambial age is older. This trend is similar to what is reported for diffuse-porous species (Paul, 1963) and also agrees with the results found in coniferous trees (Richardson, 1961).

**Shrinkage**

From the Results section it is shown that all shrinkages (tangential, radial and volumetric) decrease from the pith to the bark at a given height. However, this trend was more clearly shown in the case of radial shrinkage. These results are confirmed by the negative simple correlations between age and shrinkages in this study.

It is shown in the Results section that the coefficients of the cambial age term in the reduced models were significant at the .01 probability level in the case of ring width, vessel proportion, specific gravity, radial shrinkage and volumetric shrinkage. Also it was significant at .05 level in the case of ray proportion. The cambial age term was not significant only in the cases of fiber proportion and tangential shrinkage. In spite of the non-significance of the cambial age term in the fiber proportion and tangential shrinkage models, the simple correlations between the cambial age and each of those variables were 0.6107 and 0.3789 respectively. These correlations show that the non-significance of the age in these two models might have been due to the interrelations between age and other variables in these models.
Structure, Density, Shrinkage and Year of Formation

The Results section includes all the graphs of the vertical sequence for ring width, proportions of wood elements, specific gravity and shrinkage. This sequence is the only one through which the fluctuation of year of formation effect can be studied (Duff and Nolan, 1953). There were no significant simple correlations found between year of formation and ray proportion, ring width and specific gravity. However, the simple correlations of year of formation to tangential shrinkage (0.4306), radial shrinkage (0.3725), volumetric shrinkage (0.5065), fiber proportion (0.6107) and vessel proportion (-0.5831) were significant at .01 probability level.

Interrelations Between Structure, Density and Shrinkage Variables

Although not a direct part of this study, an investigation of the interrelations between the variables was conducted. The simple correlation coefficients between the ring width, proportion of wood elements, specific gravity and shrinkage were calculated. In such an investigation between the populations of fibers and ring width, the assumptions for correlation analyses are provided in that both populations are assumed to be normal bivariate and randomly sampled. Fiber and vessel proportions were simple correlated with ring width at .01 probability level and with ray proportion at .05 probability level (0.2883, -0.3865, 0.2405 respectively). It is noted
that while fiber and ray proportions were positively correlated with ring width, the vessel proportion and ring width were negatively correlated. Fibers and vessels were negatively correlated at the .01 probability level (-0.9370) while fibers and rays negatively correlated at the .05 level (-0.2617). The simple correlation between vessel and ray proportions was not significant.

Specific gravity did not show a significant correlation with ring width; however, the simple correlations between specific gravity and proportions of wood elements were close to significant at the .05 level. The lower variation in specific gravity is suggested to be the reason of masking its relations with other variables.

The tangential shrinkage was positively correlated with fiber proportion (0.2064) and specific gravity (0.1268) at the .05 probability level while it was not significantly correlated to vessel proportion or ray proportion. Radial shrinkage showed a different correlation than tangential shrinkage. While both were correlated at .01 probability level, radial shrinkage exhibited a negative highly significant simple correlation with ring width (-0.3207) which was not the case in the tangential shrinkage.

With respect to these results it can be speculated that within this silver maple tree the fiber proportion varied slightly; however, it was correlated positively with ring width and negatively with vessel and ray proportions. This
indicates the desirability of this tree for pulp and paper because with the increased growth rate a higher fiber proportion is associated with low vessel proportion. However, the applicability of these results must be checked by additional studies on more trees.
SUMMARY AND CONCLUSIONS

The patterns of variation in ring width, fiber proportion, vessel proportion, ray proportion, specific gravity and shrinkage were investigated within a silver maple tree. The tree was intensively sampled by cutting discs at two foot intervals up the stem and removing samples along the north and south radii. A technique for determining the proportion of wood elements was developed using a microfilm viewer and projecting photomicrograph negatives on a special dot grid.

A multiple regression analysis was used to study the relation of height, cambial age (ring count from pith), and year of wood formation to the wood properties investigated. Separate equations were developed for each variable (wood property). Regression accounted for the following percentages of variation:

- Ring width: 63.51%
- Specific gravity: 37.60%
- Fiber proportion: 49.22%
- Volumetric shrinkage: 44.26%
- Vessel proportion: 61.47%
- Tangential shrinkage: 28.09%
- Ray proportion: 32.52%
- Radial shrinkage: 34.83%

An attempt was made for the first time to plot the oblique sequences for each of the variables from the resulting reduced regression equations.

The conclusions reached are:

Ring width:

1. During a given year of wood formation (oblique sequence), the ring decreases in width slowly from the apex to a
point at approximately two thirds of the distance from the apex to the base of the crown. From this point ring width increases rapidly to slightly below the living crown and then fluctuates irregularly to the base of the tree. The coefficient of variation of ring width within the tree was 35.12%.

2. At a given height, in levels below the crown area, ring width increases from the pith outward to a maximum at about 15 years and then decreases toward the bark. Within the crown there was no consistent change in ring width along the radii.

3. The ring width and height variables were positively correlated at the .01 probability level while ring width and cambial age were positively correlated at .05 probability level.

4. As ring width increases:
   a. fiber proportion increases (at .01 level)
   b. vessel proportion decreases (at .01 level)
   c. ray proportion increases (at .05 level)
   d. radial shrinkage decreases (at .01 level)

5. The simple correlations between ring width and specific gravity, volumetric and tangential shrinkages were not significant.

Proportions of wood elements:

1. Fiber proportion changes very little within the tree (4.99% coefficient of variation). However, the simple correlation between fiber proportion and height was negative and significant (.01 level). The oblique sequence did not show a clear relationship between fiber proportion and height within any given year of formation.

2. At a given height there appears to be a slight decrease in fiber proportion from the pith to about age of 21 years and then little change. This was indicated also by the fact that the cambial age and fiber proportion were negatively correlated at .01 probability level.

3. As fiber proportion increases:
   a. vessel proportion decreases (at .01 level)
b. ray proportion decreases (at .05 level)

4. No significant correlations were detected between fiber proportion and specific gravity and tangential, radial and volumetric shrinkages.

5. Within a given growth ring (oblique sequence) vessel proportion shows a slight increase from the base to the apex of the tree. Height and vessel proportion were positively correlated at the .01 probability level. The within-tree coefficient of variation in vessel proportion was 6.55%.

6. From pith to bark at a given height (horizontal sequence), vessel proportion increases slightly to about age 21 and then there is little change to the bark. This was indicated also by the positive correlation (.01 level) between cambial age and vessel proportion.

7. No significant simple correlations were detected between vessel proportion and each of ray proportion, specific gravity and tangential, radial and volumetric shrinkages.

8. The within-tree coefficient of variation for ray proportion was 8.16%. The oblique and horizontal sequences showed no clear variation trends for ray proportion. However, there was a negative simple correlation between ray proportion and height (.01 level) and a positive correlation between ray proportion and cambial age (.01 level).

9. As ray proportion increases the volumetric shrinkage decreases.

10. No significant simple correlations were detected between ray proportion and specific gravity and tangential and radial shrinkages.

Specific gravity:

1. Specific gravity changes very little within the tree. The coefficient of variation was 6.87%.

2. The specific gravity shows a slight decrease from the stump up to about 12 feet followed by an increase to the crown base, then a slight decrease in the crown area to the apex.

3. At a given height specific gravity increases from the pith outward to about age 15 years and then decreases toward the bark; this was the general shape of the horizontal sequence. This was also indicated by the negative simple correlation between cambial age and specific gravity (.05
4. As specific gravity increases the tangential shrinkage increases (significant at .05 level).

5. No significant correlations were detected between specific gravity and radial shrinkage or specific gravity and height.

Shrinkage:

1. Tangential shrinkage changes very little with height within the same annual ring (oblique sequence). The simple correlation between tangential shrinkage and height was not significant.

2. At a given height tangential shrinkage decreases from the pith to the bark. This is also shown by the significant negative correlation between cambial age and tangential shrinkage (at .01 level).

3. Within a given year of wood formation (oblique sequence), radial shrinkage increases from the tree base to the apex and was positively correlated with height at the .01 probability level.

4. The within-tree coefficient of variation in radial shrinkage was 25.42%.

5. At a given height below the crown area, the radial shrinkage decreases from pith to bark. This was also indicated by the negative correlation between cambial age and radial shrinkage (at .01 level).

6. As radial shrinkage increases, volumetric shrinkage increases (at .01 level).

7. Volumetric shrinkage is positively correlated with height (at .05 level). However, variation in volumetric shrinkage in the oblique sequence did not clearly define a specific trend.

8. Volumetric shrinkage shows a decrease from the pith to the bark, as shown by the negative correlation between cambial age and volumetric shrinkage (at .01 level).
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APPENDIX

Calculations of Number of Photomicrographs Needed for Sampling

The number of photomicrographs per section was calculated for each structural element. The required number of observations (photomicrographs per section) necessary to give an estimate of the mean of a wood element that would fall within a range of 0.1 of the mean with 95% confidence level, were done by using Stien's two stage sample procedure. In a preliminary study the standard deviation of the vessel, ray and fiber elements were calculated. The number of photomicrographs per section for each wood element was then calculated by using the equation; $N = \frac{t^2 s^2}{d^2}$. The following statistics were obtained from the preliminary sample.

<table>
<thead>
<tr>
<th>Element</th>
<th>Mean</th>
<th>Sampling Error</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel proportion</td>
<td>18.75%</td>
<td>16.71</td>
<td>4.06</td>
</tr>
<tr>
<td>Ray proportion</td>
<td>10.95%</td>
<td>4.43</td>
<td>2.11</td>
</tr>
<tr>
<td>Fiber proportion</td>
<td>70.30%</td>
<td>20.08</td>
<td>4.40</td>
</tr>
</tbody>
</table>

This facilitated the calculations of number of observations per section for each wood element.

Vessel proportion: $N = \frac{(1.96)^2 (16.71)}{(0.1) (18.75)^2} = 18.619$

Ray proportion: $N = \frac{(1.96)^2 (4.43)}{(0.1)(10.95)^2} = 14.195$
Fiber proportion: \( N = \frac{(1.96)^2 (20.08)}{(0.1) (70.30)^2} = 15.610. \)

Since a range from 15 to 19 photomicrographs was calculated for different structural elements, it was decided to use 20 photomicrographs per section for sampling proportion of wood elements.