INFLUENCE OF SITE, CLONE, AGE, AND GROWTH RATE ON WOOD PROPERTIES OF THREE *POPULUS X EURAMERICANA* CLONES

By

Ilona Peszlen

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Wood Science and Forest Products

APPROVED:

Fred M. Lamb, Chairman

Peter P. Feret

Geza Ifju, Department Head

Joeseph R. Loferski

Robert L. Youngs

February, 1993
Blacksburg, Virginia

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Committee Chairman: F.M. Lamb
Department of Wood Science and Forest Products

(ABSTRACT)

The purpose of this study was to investigate variation in selected anatomical, physical and mechanical properties of three *Populus x euramericana* (Dode) Guinier hybrid clones grown on two dissimilar sites in Hungary. Six 15 years old trees from three clones on one site and six 10 years old trees from two clones on the other site were sampled at breast height.

Anatomical properties, including vessel lumen diameter, area and shape factor, number of vessels per unit area, fiber lumen diameter and area, fiber length, ray area, and cell wall area percent were measured by an image analyzer. Site, clone and/or their interaction significantly affected one or more of these properties except fiber length. Variations were significant among trees within clone and site for all variables except vessel lumen diameter. However, most of the variations was within tree as a result of the effect of age. Statistically significant correlations were found between anatomical properties.

For specific gravity, there was no significant differences between sites but there was a significant clone effect with a repeatability of 0.51 indicating genetic control on this property. There were no significant differences among clones for modulus of rupture, crushing strength, maximum tensile strength, and tension modulus of elasticity. Strength properties were significantly higher near the bark than close to the pith except for maximum tensile strength. Specific gravity was not the single most important factor affecting strength properties of the clones.

The effect of age and growth rate on specific gravity and anatomical properties were also investigated. Differences among clones for growth ring widths were significant in the "good" years only. Specific gravity was high near the pith, then each of the clones exhibited a different radial pattern. Based on segmented regression, a quadratic model with a plateau proved to be useful for estimating the demarcation between juvenile and mature anatomical characteristics. The ages of maturation were not the same for all properties; however, the order of maturation was the same on both sites. No consistent relationships between growth rate and specific gravity and anatomical properties were found when growth rings of the same age were compared.

ACKNOWLEDGEMENT

This dissertation was an unexpected outcome of a Fulbright Scholarship which was supposed to end in one year. However, the encouragement and help of many individuals resulted in an extension of my stay at the Virginia Tech. I wish to acknowledge all those who assisted me in many ways.

First, I would like to thank Dr. Fred M. Lamb, Chair of my Graduate Committee, for his help and guidance during the research and the preparation of the dissertation. My sincere appreciation goes to committee members Drs. G.J. Buhyoff, P.P. Feret, G. Ifju, J.R. Loferski and R.L. Youngs who helped in every aspect of my work in the degree program.

Special thanks are extended to Esther and Bob Youngs for the moral support and care they gave to me and my son József during my first year in Blacksburg. The encouragement and financial support provided by Dr. Geza Ifju is also gratefully acknowledged. His guidance both in professional subjects and personal life made the last three years bearable and eventually enjoyable.

Many thanks are expressed to staff members Charlotte Barnett, Sharon Daley, Angie Riegel, J.W. Akers, and Carlile Price for their kind assistance and efforts. It seems almost impossible to acknowledge the help of all the fellow graduate students; they are too numerous. However, I wish to express special thanks to Sandhya, Jan, my roommate Rosie, Elemer, Ira, Craig, and Vijay.

This dissertation would not have been possible without the inspiration and encouragement of Professor Csaba Mátyás. I also wish to express my appreciation for the technical support and the assistance of Professor Sándor Molnár. I acknowledge the support of Rector András Winkler for permitting me to pursue this degree program. Thanks are also due to my colleagues at the University of Forestry and Wood Science, Sopron, Hungary, who covered all my duties in teaching and research while I was away.

Many friends in the U.S. and in Hungary provided moral support for me and for my family which allowed me to undertake this degree program

Last but not least, I wish to thank my parents Margit and Sándor Peszlen, my son József, and my special friend Jack in Hungary for their love, encouragement and unfailing patience.

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"The greatest obstacle to discovery is not the ignorance -
it is the illusion of knowledge." - DANIEL J. BOORSTIN

INTRODUCTION

Human life is intimately connected with the forests as a natural resource. Wood, a product of trees, is one of the most wonderful materials created by nature. The greatest value of wood is that it is a renewable raw material. Variability in its composition, appearance and properties gives wood great versatility. Combined influence of genetic and environmental factors results in natural variation in wood properties. However, variability is also a major disadvantage from the standpoint of manufacturers considering efficient utilization of wood (Zobel and van Buijtenen 1989).

The demand for wood has been increasing while the timber resources have changed significantly from natural forests to plantation grown forests in some parts of the world. Successful planting of genetically improved trees and intensive forest management practices requires cooperation among foresters, forest geneticists, and wood technologists because mistakes in selection and management can not be corrected easily or quickly (Zobel and Talbert 1984; Matyas 1986). The main issue is not only growing forests in the most economical way; but also growing trees with tolerance to pests and adverse environments and with the desired wood quality. Although the evaluation of wood quality depends on the users needs, more uniformity, both within and among trees, is demanded by manufacturers of wood products. Reduction in variability is of importance because of the impact on product quality and production efficiency (Burdon and Thulin 1965; Zobel et al. 1983; Zobel and van Buijtenen 1989).

Wood uniformity within a species can be increased either genetically by using vegetative propagation or by silvicultural manipulations, such as fertilization, cultivation, spacing, and thinning. Wood properties are determined by the genetic makeup of the tree as well as by the interaction of the genetic makeup with the environment.

Therefore, it is impossible to predict the interaction accurately (Zobel and van Buijtenen 1989). Research on wood properties is of major importance because it provides essential information to the foresters who manage the tree improvement programs and to the wood-using industries which apply new technologies to achieve the best utilization of the harvested trees.

New combinations within a genus can be produced by hybridization (Piatnitsky 1960). The hybrid is a cross between two species or different geographic races within species that would not otherwise have cross-bred. Since characteristics of a species depend on genetic inheritance, it is possible to develop trees that are different from those created by nature. Hybrids that are carrying desired characteristics can be quite useful if vegetative propagation can transfer the desirable traits to the production arena. Planting of selected clones results in more uniformity reducing the variability in wood and better meeting the demands of wood users (Zobel and Talbert 1984; Zobel and van Buijtenen 1989).

Vegetative propagation, where all individuals are expected to be perfect replicates of their parent tree, is an effective method to reduce the variability of properties. *Populus* species and their hybrids are abundant in the north temperate regions and they represent a fast growing, genetically improved and vegetatively propagated broadleaved species of the secondary forests and plantations. The most important hybrid group is *Populus x euramericana*, a number of clones produced as a result of cross between European black poplar (*Populus nigra*) and eastern cottonwood (*Populus deltoides*) (Wright 1976).

Wood from poplar plantations is generally considered for use as energy, chemicals, and as a raw material for industrial manufacturing. Investigation on the wood properties of different clones give scientists the opportunity to study the influence of environmental effects, silvicultural practices, and their interactions on wood properties. These studies provide essential information for managing tree improvement programs and to improve the utilization of these clonal material.

PROBLEM STATEMENT

Like many European countries, Hungary has a serious shortage of timber resource. Only about 18% of the land area is forested (Molnar and Feher 1991). The increasing demands for wood products have induced foresters to start a tree improvement program in the 1950's which focused on poplars an especially fast growing, genetically improved, and vegetatively propagated genus for reforestation. Many species and hybrids of *Populus spp.* can be planted extensively as exotics in Hungary because they are well adapted to the soil and climate of the country.

Due to this reforestation program, about 9% of the forested area has been planted in poplars and their hybrids (Molnar et al. 1990). The annual harvest from this stands is more than 20% of the overall timber production in the country. Research on wood properties of hybrid poplars will enhance the efficiency of the tree improvement programs and the subsequent utilization of this material. Selection of the best hybrids for the various sites in terms of growth and wood properties can effectively fine tune overall forest planning and management.

In this study the following *hypotheses* were tested:

- There are site and clonal differences for anatomical properties.
- There are site and clonal differences for specific gravity and clonal differences for mechanical properties.
- There are within-tree differences for anatomical properties and specific gravity, and there are significant relationships between growth rate and these wood properties of clonal material.

OBJECTIVES

The goal of this study was to determine the wood properties and explore the causes of their variations for three hybrid poplar clones (*Populus spp.*) planted in two different sites of Hungary. In order to accomplish this goal the following specific objectives were formulated:

1. To investigate site and clonal effects on selected anatomical characteristics of three *Populus x euramericana* clones collected in Hungary.

2. To analyze site and clonal variations of specific gravity in relation to mechanical properties of the clones.

3. To characterize the within-tree variations in selected anatomical properties and specific gravity in the radial direction as a result of age and growth rate effects.

PREFACE

This dissertation is organized into five parts: a general methodology description, three sections of research papers, and an overall discussion and conclusion. In the first part, a detailed description of material, methods, and the experimental design are presented. The three sections are formatted for publications, and so intended to be inclusive. The first section is an analysis of site and clonal effects on selected anatomical properties of the clones. The second section provides a comparison on variations in specific gravity and mechanical properties of clonal material. In the third section, the influence of age and growth rate on anatomical properties and on specific gravity are described.

Since the three sections are intended to be all-encompassing, some repetition inevitably exists in the methodology parts.

MATERIAL AND METHODS

DESCRIPTION OF SITES

For this study, three hybrid *Populus* clones with rapid growth rate were chosen from two different sites in Hungary (Site 1: Daka, Site 2: Zalavar). Both sites are located in the central part of Transdanubia, the western region of Hungary. The overall climate can be described as temperate continental, the area is in the xeric mixed hardwood forest region. The relatively low and very uneven rainfall is not favorable for forest development. Due to frequent summer drought, hydrological conditions and ground water availability greatly determine site quality. It is these marginal circumstances that make the apparently slight climatic and edaphic conditions important.

Hybrid poplar clones require continuous water supply and relatively warm climate for satisfactory development. Site parameters described in *Table 1* indicate that Site 2 is more favorable for poplar plantations. Its climate is slightly modified by mediterranean impacts which manifest themselves in more evenly distributed rainfall and reduced extremes in temperatures. Site indicator herbs and grasses confirm the superiority of Site 2: *Impatiens noli-tangere, Carex remota, Deschampsia caespitosa* and *Baldingera arundinacea* indicate continuously wet conditions while in Site 1 *Poa angustifolia, Calamagrostis epigeios* and *Solidago spp.* are common weeds on xeric, drought sensitive sites. Poplar stands in Site 1 are more likely to become water-stressed, retarded in growth and attacked by pathogens.

DESCRIPTION OF CLONES

The plantation in Site 1 was fifteen years of age and in Site 2 ten years of age. Measurements were taken on the following clones:

- *Populus x euramericana* (Dode) Gunier cv. Kopecky,
- *Populus x euramericana* (Dode) Gunier cv. I-214,
- *Populus x euramericana* (Dode) Gunier cv. Koltay.

General description of clones are detailed in *Table 2.* The well-known Italian I-214 clone was imported in 1951 and since then it has been planted extensively throughout the country. Currently, this single clone represents more than 30% of the poplar plantations in Hungary. The I-214 clone requires intensive silvicultural treatment. Its stems tend to develop large branches; furthermore, its wood is considered to be of lower density among poplars.

The Kopecky and Koltay are Hungarian bred clones, named after their breeders. The Hungarian forest geneticists Kopecky and Koltay were among those who started the forest tree improvement program in Hungary in the early 1950's. Koltay was awarded the Kossuth Prize[1] for his activity in breeding of poplars.

The Kopecky clone may be planted on a variety of sites ranging from relatively wet to semi-dry sites and does well under both extensive and intensive management regimes. Its thick, rough bark develops early; therefore, it is recommended for locations with a high potential for wildlife damage.

The Koltay clone may be used as a direct substitute for *Populus robusta*, which is considered to be the best quality poplar clone with the highest wood density. Furthermore, it is recommended for short-rotation plantations for biomass silage production (Matyas 1983; 1986). Plantations in Daka are shown in *Figure 1.*

---

[1] The highest Hungarian state award. It is equivalent with the international Nobel Prize.

DESIGN OF THE EXPERIMENT

The experimental design *(Figure 2)* involved two sites, three clones and six trees (ramets) from each clone. However, the Koltay clone was not available from Site 2. Six trees were randomly selected from each clone on each site. Samples were taken from each growth ring in each tree for the anatomical and specific gravity measurements. For the mechanical property tests, samples were taken from three positions (each 1/3 of the radius of the tree), but only from the sample trees on Site 1. Based on this sampling technique, the variations among growth rings and radial positions represented the effect of the age of the cambium when the increments were produced.

MATERIAL COLLECTION

The trees were chosen for straightness of bole and absence of visual defects. Each tree was felled and a 100mm thick **disk** was cut from each tree at breast height and a 500mm long **short log** was also taken immediately above the disk from sample trees in Site 2. Disks were used to measure the width of each growth ring and to obtain samples for anatomical property, specific gravity and micro tensile strength determination. Specimens for bending and compression strength tests were cut from the short logs.

Disks and short logs from Site 1 were cut into 50mm wide middle sections along one radius in east-west direction to minimize the presence of tension wood caused by the effect of prevailing wind. The segments of short logs were divided into three blocks representing wood near the pith, in the middle part of the radius, and close to the bark. Bending and compression strength specimens were cut from the blocks. Bending strength tests were performed in Hungary.

The segments of disks and the compression strength specimens from Site 1 and the disks from Site 2 were wrapped in plastic bags with 5% solution of sodium-pentachlorophenate to prevent fungal deterioration and mailed to the Department of Wood Science and Forest Products, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. There the middle sections of disks from Site 2 were also cut along one radius in the east west direction to prepare samples for anatomical measurements and specific gravity.

METHODS

<u>**Slide preparation**</u> (Sass 1958):

Transverse microtome sections of each growth ring were prepared for anatomical measurements. The sections approximately 20μm thick were stained with 1% aqueous safranin for 2 minutes and washed once with water and twice with 70% ethanol. Then the sections were covered with 2% fast green in 70% ethanol for one minute, drained, washed with 100% ethanol until dehydrated, and cover with xylene. Finally they were mounted on glass slides with permount. Safranin and fast green were used together to differentiate the possible tension wood fibers from normal fibers. A minimum of five slides was prepared and labelled from each growth ring.

<u>**Fiber maceration**</u> (Franklin 1945):

Three pieces about 15mm long and 2mm in cross section from the middle part of each growth ring were placed in a 1:1 mixture of 30% hydrogen peroxide and glacial acetic acid for 72 hours at 60°C. At the and of the maceration process, the fibers were washed with water twice and placed into 70% ethanol. After draining, the samples were stained with 2% fast green, then washed with 70% ethanol, swirled and drained twice.

Finally they were washed with 100% ethanol, drained, and stored in xylene pending further preparations of temporary slides for measurements.

Anatomical measurements by IMAGE1 image analyzer:

From the slides, the anatomical characteristics were measured on an image analyzer. The system, as showed in *Figure 3.*, includes:

- Zeiss Axiophot research microscope,
- CCD-72 Series camera (black and white),
- Sony Trinitron color video monitor,
- WIN 386-33 personal computer,
- Super Sync 2A color monitor,
- **IMAGE1** / AT image processing and analysis system (Universal Imaging Corporation 1990).

Using the image analyzer system the following anatomical parameters were measured or calculated for each growth ring:

- Vessel lumen diameter [μm]
- Number of vessels per unit area [No/mm^2]
- Vessel lumen area [%]
- Shape factor of vessels
- Ray cell area [%]
- Fiber lumen diameter [μm]
- Fiber lumen area [%]
- Cell wall area [%]
- Fiber length [mm]

Measurements were taken at 100x magnification using configured filters to separate vessel lumens from the fiber lumens and from the cell wall and ray area (*Figure 4*). In each growth ring, five images as random replicates were analyzed: one from earlywood, one from latewood and three from the middle part of the growth increment.

Vessel lumen diameter was calculated as an average of the system "diameter" and "longest cord" values recorded automatically. However, the "diameter" is defined by **Image1** as a measure of the thinnest portion of an object; meanwhile, the "longest cord" is defined as a measure of the greatest linear distance between any two points on the object being measured. If vessels appear one by one, "diameter" can represent the tangential diameter of vessel elements, and "longest cord" can be considered as the radial diameter. Since there were many vessel chains in the structure of these poplars, the direction of the elongation of vessels showed the opposite direction from that mentioned above (*Figure 4*). Thus the average of the two measured distances was used for calculation of the mean values of vessel lumen diameters.

Number of vessels was recorded from the same images as vessel lumen diameters and the size of region being measured (usually the whole monitor screen). These data were used to calculate the number of vessels per unit area.

Vessel lumen area as a percentage of the monitored region was counted automatically from each image analyzed.

Shape factor of vessels could be recorded on each image because **Image1** allows classification of objects based on the extent of their roundness. Values are between $\underline{0}$ and $\underline{1}$, where $\underline{0}$ represents an extremely thin object and $\underline{1}$ a perfect circle. Calculation of shape factor is described below:

$\underline{SHV = (4\pi a)/p^2}$ where SHV = shape factor
$a = \pi r^2$ a = area of a circle
$\underline{p = 2\pi r \Rightarrow r = p/2\pi}$ p = perimeter of a circle
$a = \pi(p/2\pi)^2 = p^2/4\pi$

Since the area and the perimeter are known:

$1 = p^2/(4\pi a)$ is the same equation for shape factor given above except inverted.

Ray area percent was determined after counting rays as parallel lines and multiplying that number by the average ray thickness. This method was chosen because the gray level of cell walls and that of the whole rays were similar, so that they could not be distinguished from each other automatically. After preliminary measurements where the rays were made to appear long white objects, an average ray cell thickness could be calculated because the uniseriate rays had consistent thickness values.

Fiber lumen diameter was determined at 200x magnification because at the lower magnifications used for vessel parameters, the cell wall and ray areas could not been distinguished. Furthermore, the contrast was not enough to separate the fibers. The regions of measurements were chosen between two rays and that contained only fibers (*Figure 5*). One randomly selected image was analyzed from about the middle part of each growth increment. Fiber lumen diameter values were calculated in the same way as those for vessel lumens. Each region tested had a different size but included at least 30 fibers.

Fiber lumen area percent was obtained automatically for each region monitored for measurements of fiber lumen diameters. Since only fibers were captured on these images, the fiber lumen to fiber wall ratio represented percent fiber lumen area.

Cell wall area percentage values were derived from measured parameters subtracting vessel lumen area, ray area and fiber lumen area percentages from unit area based on the following equation:

$$WA = 100-\{VLA+RA+[((100-VLA-RA)FLA/100]\}$$

where:
WA = cell wall area [%]
VLA = vessel lumen area [%]
RA = ray cell area [%]
FLA = fiber lumen area [%]

Fiber length data were obtained from macerated material using the same sections as for the slides. From each growth increment thirty-five unbroken fibers were measured. The **Image1** system cannot separate objects which are crossing one another. Therefore, instead of using the automatic measurement mode, manual measurement mode with caliper was applied (*Figure 6*).

Specific gravity (Smith 1954):

The maximum moisture method was used to determine the specific gravity of these small specimens. Specific gravity based on green volume can be calculated from the weight of the completely water saturated specimen and the weight of the specimen ovendried. Using this technique, an error may exist in obtaining the absolute maximum saturation with water and in assuming a constant value for the density of the cell wall substance. Therefore, for purposes of comparison, specific gravity of segments with the same thickness was measured by the water displacement method. Results of this control test did not differ significantly from those obtained by averaging the specific gravity values of each growth ring as determined by the maximum moisture method. The maximum moisture method was assumed to be more suitable for this investigation.

The equation and the derivation of the formula is as follows:

$$M_{max}=\frac{m_m-m_o}{m_o}=\frac{m_w}{m_o}=\frac{V_f-V_{so}}{m_o}=\frac{V_f}{m_o}-\frac{V_{so}}{m_o}$$

where M_{max} = maximum water content in grams of water per gram of ovendry wood;
m_o = ovendry weight [gr];
m_m = mass of water-saturated wood [gr];
m_w = mass of water in wood [gr];
V_f = green volume [cm^3];
V_o = ovendry volume [cm^3];
V_{so} = volume of the ovendry cell walls [cm^3];

$$G_f = \frac{m_o}{V_f} \qquad G_o = \frac{m_o}{V_o}$$

$$M_{\max} = \frac{1}{G_f} - \frac{1}{G_{so}}$$

where G_o = specific gravity of wood based on ovendry volume;
G_f = specific gravity of wood based on green volume;
G_{so} = specific gravity of wood substance = 1.53;

Specific gravity (G_f) can be calculated from the following formula if the ovendry and green (completely saturated) weight of the sample are measured :

$$G_f = \frac{1}{M_{\max} + \frac{1}{G_{so}}}$$

STATISTICAL ANALYSES

In order to compare the variations in the anatomical properties between sites and among clones, analysis of variance (ANOVA) models, or in case of unbalanced data general linear models (GLM) models were calculated using the Statistical Analysis System (SAS Institute Inc. 1985). Following an overall **F** test, Duncan's multiple comparison procedure as a posteriori test was used to evaluate all possible comparisons between means of the measured variable at a certain level (Kirk 1968). The experimental design is shown in *Figure 2.*

Nested design, as a simple hierarchical analysis of variance, was used to estimate the clonal (genetic) variation and the tree-to-tree (environmental) variation within clones for the properties on Site 1. Relating the estimated clonal variance component to the total (phenotypic) variation, repeatability (**R**) or broad sense heritability ($\mathbf{H^2}$) of a property can be calculated. The repeatability gives an estimate of the upper limit of the narrow sense heritability ($\mathbf{h^2}$) from a clonal test (Becker 1984). The total phenotypic variance ($\mathbf{V_P}$) can be calculated as follows:

$$\mathbf{V_P = V_G + V_E}, \quad \text{where } V_G = \text{genotypic variance,} \quad V_E = \text{environmental variation.}$$

The genetic variance contains two components: the additive genetic variance and the dominance variance, from clonal test only the total genetic variance ($\mathbf{V_C}$) can be determined, and thus

$$\mathbf{R = V_G / (V_G + V_E) = V_C / V_P \geq h^2}$$

Pearson correlation coefficients were calculated between all measured pairs of variables to test the intercorrelation between properties measured (Kleinbaum et al. 1988). Values of **r**'s are considered as a general indexes of linear associations between two random variables. However, if non-significant correlation is obtained it indicates that there exists a non-linear association or no association at all. To find out whether or not there were other than linear relationships between properties, the two variables were plotted against each other.

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TABLES

Table 1. - General description of sites.

Site parameters	**Site 1**	**Site 2**
Geographical data:		
City:	Daka	Zalavar
Latitude:	N 47°17'	N 46°42' +
Longitude:	E 17°25'	E 17°10'
Altitude:	100-150 m	100-150 m
Climatic data:		
Annual temperature:	9.5 °C	10.0 °C +
January temperature:	-2.0 °C	-1.5 °C +
July temperature:	19.5 °C	20.0 °C +
Date of last air frost:	April 20.	April 10. +
Annual precipitation:	650 mm	700 mm +
Annual total sunshine:	2050 hours +	2000 hours
Soil data:		
Soil type:	"meado forest soil" vertisol	"bog soil" + histosol
Hydrology:	water-loosing	wet

"+" Indicates qualities more favorable for hybrid poplar

Table 2. - General description of clones (Matyas 1986).

Clone	Male / Female	Growth and yield	Site quality demand	Disease resistance	Recommended stand density
I-214	female	good	high	medium	330-625/ha
Kopecky	male	excellent	medium	high	330-625/ha
Koltay	male	excellent	medium	high	330-625/ha

FIGURES

Figure 1. - Fifteen-year old poplar clone plantations on Daka (Site 1), Hungary. Left: clone Kopecky. Middle: clone I-214. Right: clone Koltay.

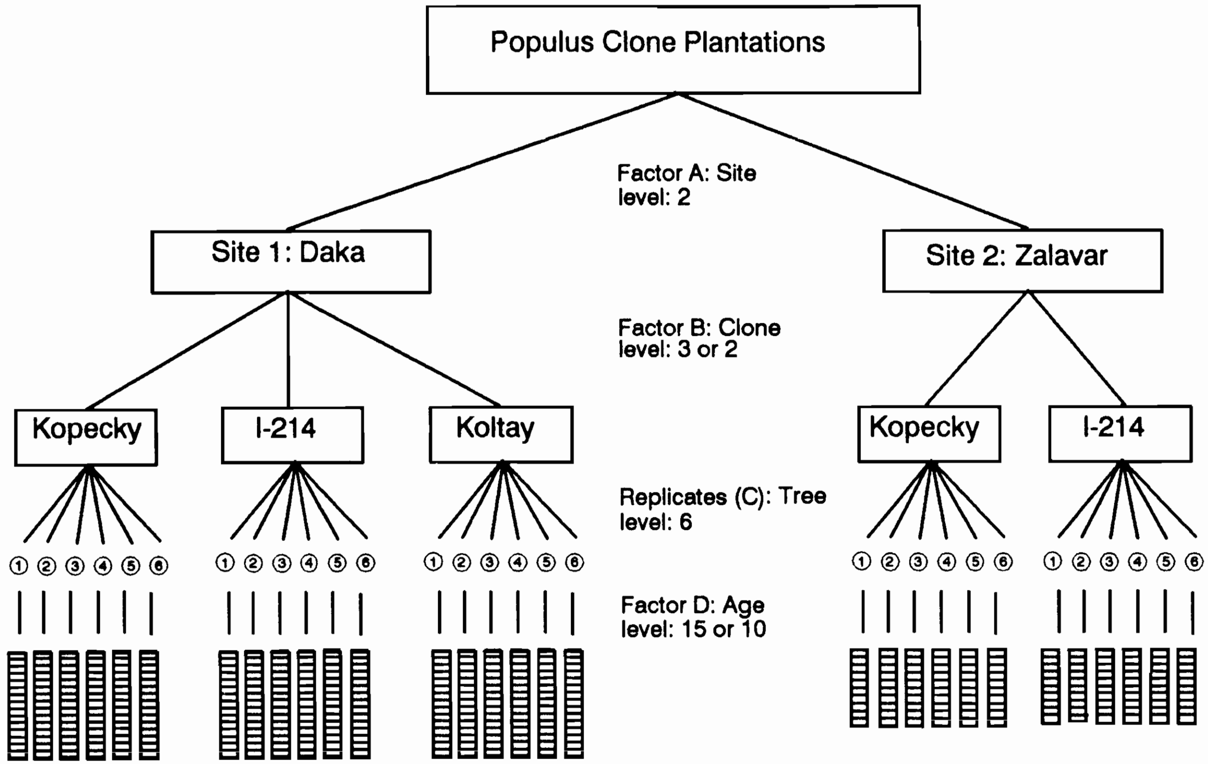

Figure 2. - Experimental design for investigation of anatomical, physical, and mechanical properties of three poplar clones planted in two different sites in Hungary.

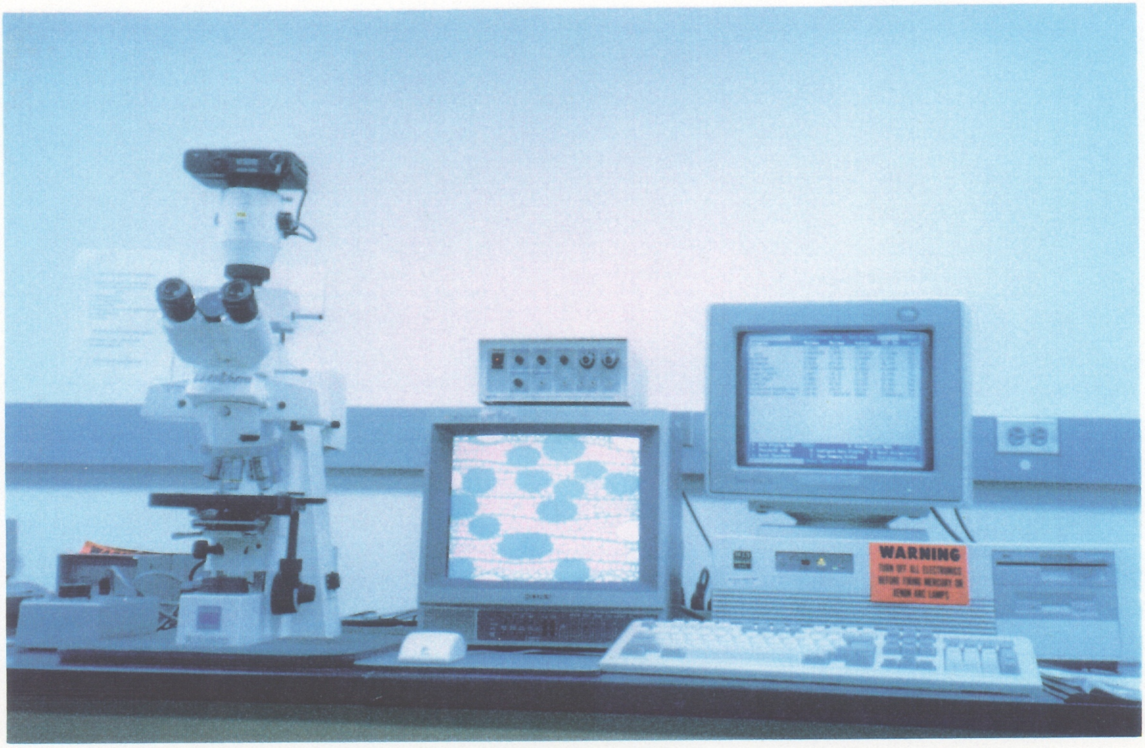

Figure 3. - Image analyzer system. Left: research microscope with photograph and video cameras. Middle: color video monitor. Right: personal computer.

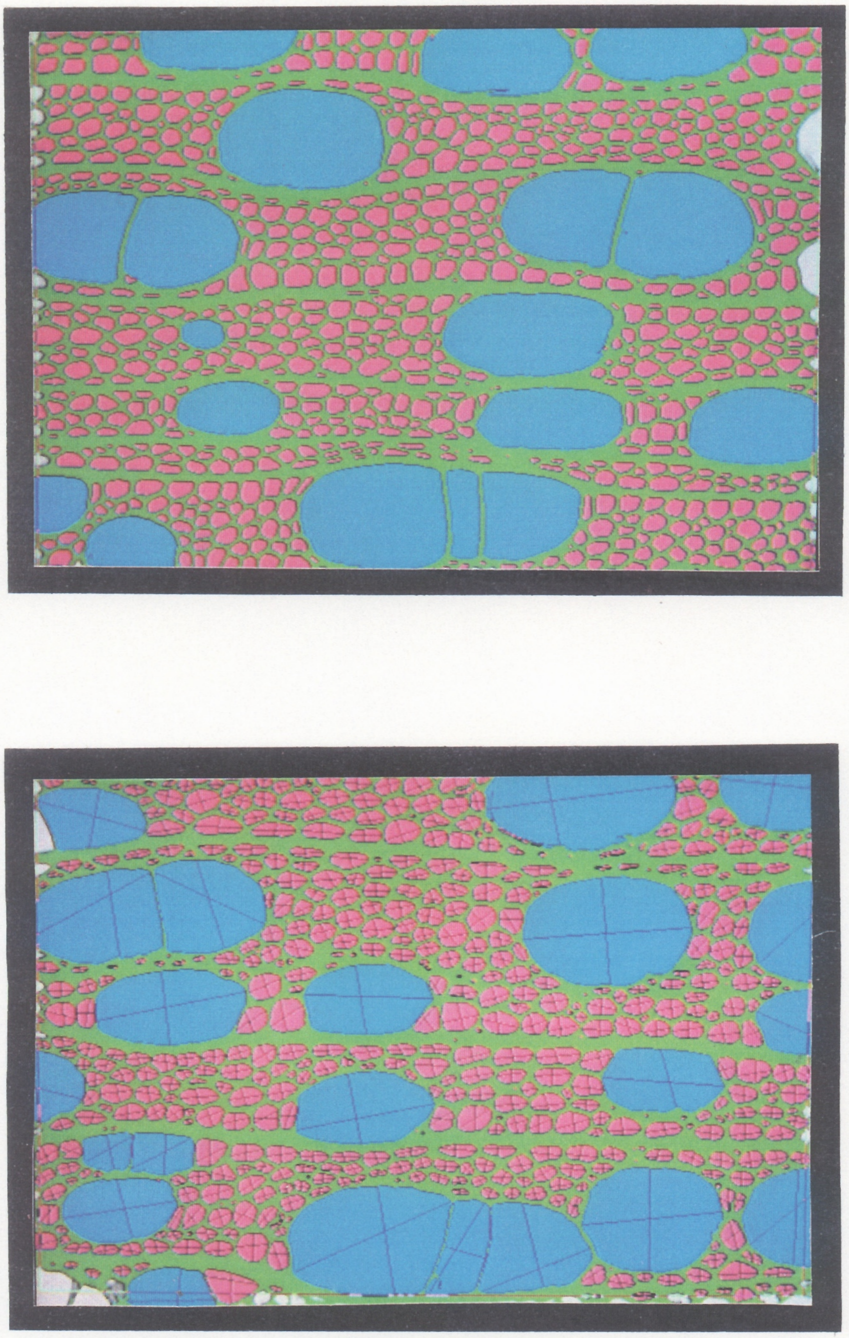

Figure 4. - Photographs of transverse sections (100x) of the Kopecky clone as shown on the monitor of the image analyzer (IMAGE1). Top: separation of cell wall (green), vessel lumens (blue) and fibers lumens (pink). Bottom: vessel and fiber lumens with their "longest cord" (longer diagonal) and "diameter" (shorter diagonal).

Figure 5. - Photographs of transverse sections (200x) of the Koltay clone as shown on the monitor of the image analyzer. Top: selected area of fibers only. Bottom: fiber lumens with "longest cord" (longer diagonal) and "diameter" (shorter diagonal).

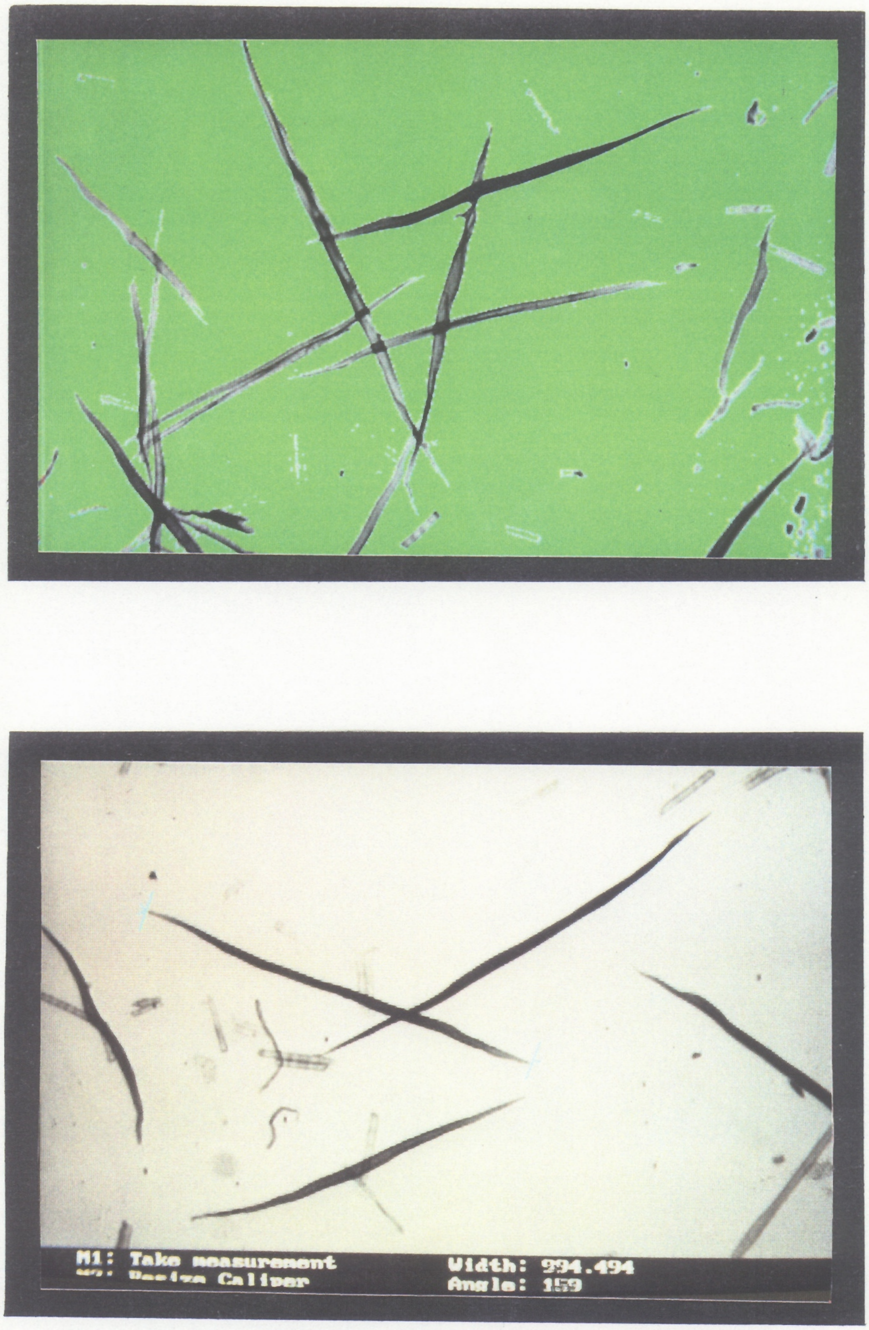

Figure 6. - Photographs of macerated fibers (25x) of the clone I-214. Top: separation of fibers by the image analyzer. Bottom: measurement of fiber length with caliper manually.

SECTION 1.

Effect of Site and Clone on Variation of Anatomical Properties of *Populus x euramericana* Clones.

ABSTRACT

Six trees were sampled from each of three clones of the hybrid *Populus x euramericana* (Dode) Guinier at two dissimilar sites in Hungary. The purpose was to determine the variation in anatomical properties between sites and among clones. Trees on one site were fifteen years old and on the other site ten years old. Sample disks were taken from each tree at breast height and transverse microtome sections of each growth increment from the eastern radius were prepared for measurements on an image analyzer. Statistical analyses were conducted on the first ten growth rings.

There were significant site differences for vessel lumen diameter, vessel lumen area, and fiber lumen area. Significant clonal effects were found for fiber lumen diameter, fiber lumen area, and cell wall area. Site had an effect on clones for vessel lumen diameter, number of vessels per mm^2, and ray percentage. However, only a small percent of the total variation was explained by site, clone, and their interaction. Fiber length was not affected either by site or by clone. Significant tree-to-tree variation was detected for all variables but vessel lumen diameter.

Correlations between anatomical properties were found significant and not clonal specific. Clones with longer fibers had larger fiber lumens with thinner cell walls and had larger vessel diameters and lumen fraction as well.

Differences detected among clones, sites, and distributions of anatomical properties were statistically significant but small, and may be negligible from a utilization standpoint. Cell wall material production of the clones was very low, less then thirty percent of the cross sectional area.

INTRODUCTION

Increasing demand for wood requires intensive management of the available timber lands. Tree improvement programs have been developed in order to produce forest with rapid growth rate, tolerance to pests and adverse environment, ease of establishment, and with desirable wood quality (Zobel and van Buijtenen 1989).

Vegetative propagation and clonal tests allow the evaluation of the genotypes and the selected superior genotype can be replicated indefinitely for commercial planting stock. Members of a clone growing as sprouts from the roots of a single tree are genetically identical. Variation among trees of the same clone is caused by the environment; whereas, variation among clones can be attributed to heredity and environment. The effect of site on the relative performance of the genotype is considered as the interaction of the genotype and its environment. An estimate of broad sense heritability of clones can be made by relating the within-clone (phenotypic) variation to the between-clone (genotypic) variation of a certain property (Becker 1984; Zobel and van Buijtenen 1989).

Species within the *Populus* genus are widely distributed in the north temperate zone. They are fast growing and especially suitable for such vegetative propagation due to the relative ease by which its cuttings can be rooted (Wright 1976). In Hungary, nine percent of the forested area are planted by poplars. They represent more than twenty percent of the annual timber production of the country (Molnar et al. 1990).

The quality of various wood-fiber products and also the physical and mechanical behavior of wood are directly related to the anatomical characteristics (Barefoot et al. 1965; Artuz-Siegel et al. 1968; Pearson and Gilmore 1980; Zobel and Talbert 1984; Zobel and van Buijtenen 1989). Research on wood anatomy of poplar clones is of great importance because it provides information for clonal selection leading to better wood utilization.

The objective of this study was to investigate the site and clonal differences in selected anatomical parameters of three *Populus x euramericana* (Dode) Guinier clones grown in two dissimilar sites in Hungary.

LITERATURE REVIEW

Research concerning the causes and control of the variation in wood properties has dealt mainly with specific gravity (Zobel and van Buijtenen 1989). However, there are many factors which can cause variation in specific gravity including changes in the anatomical structure of wood and both genetic and environmental factors.

The magnitude of variation within a species may often be greater than the differences between species (McKimmy 1959; Harris 1961; Zobel and van Buijtenen 1989). Due to the large individual tree-to-tree variations, it is very difficult to evaluate precisely the effects of site, environmental or silvicultural factors on wood properties. However, much of the tree-to-tree variation is genetically controlled and therefore it is of key importance for breeders (Zobel and van Buijtenen 1989).

Effect of clone

Natural variation and heritability for four triploid aspens were studied by Einspahr et al. (1963). Their work showed that fiber length appeared to be under moderate genetic control. Smith (1967) published a literature review regarding the heritability of fiber characteristics. Clonal studies on *Populus tremuloides* (Michx.) (trembling aspen) and *Populus deltoides* (Bart.) (eastern cottonwood) revealed that fiber length was more highly heritable than diameter and gross heritability (broad sense heritability) for fiber length was estimated 0.35 and 0.30 respectively (van Buijtenen et al. 1959; Boyce and Kaeiser 1961).

Clonal variation in wood anatomy of three different hybrid poplars with two clones from each were investigated by Marton et al. (1968). Significant clonal differences were observed for the number of vessels and for the cross sectional area of vessels, but variation among trees (ramets) within clones was not significant. Fiber length showed non-significant variation between hybrids and within each hybrid, between clones. However, Murphey et al. (1979) reported significant clonal differences in fiber length among three young *Populus* hybrids.

In a study of six *Populus* clones with rapid growth rate, Cheng and Bensend (1979) investigated many anatomical elements. The differences among six *Populus* hybrid clones in fiber length and also in percent of area occupied by fibers were statistically non-significant. Number of vessels and vessel area percentages did not show significant differences among clones either. But significant clonal differences were observed for area percentage of ray cells.

For nine short-rotation intensively cultivated *Populus* clones, Phelps et al. (1982) observed a significant clonal effect on fiber length. Percentages of vessels were not significantly different among clones. This is probably due to the inverse relationship between number of vessels per unit area and vessel diameter as demonstrated by Carlquist (1975) for 28 mesic species. Yanchuk et al. (1984) also reported significant differences in fiber length among fifteen *Populus tremuloides* (Michx.) clones. The effect of clone accounted for 43 percent of the phenotypic variation.

Microscopic sections of two poplar species were studied using an image analyzer by Zeng et al. (1985). Significant differences were detected between the two species for the ratio of vessel lumen area to cell wall, while difference in proportions of rays was not significant.

According to Kellog and Swann (1985) fibers of *Populus trichocarpa* Torr. & Gray (black cottonwood) are significantly longer than those of *Populus balsamifera* L. (balsam poplar). This observation may be explained by the higher growth rate found for black cottonwood and the positive relationship between growth rate and fiber length (Kennedy 1957). In another study, Ferrari (1987) detected heritability level of 0.85 for fiber length testing nineteen 12-year-old *Populus x euramericana* clones from experimental plots in Northern Italy. However, the genotypic variation coefficient was low for fiber length.

Effect of site

The influence of site on wood properties is complex and difficult to establish because site quality is determined by many factors and their interactions. Soil properties and climate are the major components of a site and they may differ from area to area. Therefore, variation in wood properties needs to be investigated in relation to specific site parameters. Site appears to have little influence on wood variation of low specific gravity diffuse-porous hardwoods unlike that of the high specific gravity ring-porous hardwoods and conifers. However, there are exceptions to this theory (Zobel and van Buijtenen 1989).

Ferrari and Scaramuzzi (1980) reported a significant site effect on fiber length for *Populus x euramericana*. Ferrari and Scaramuzzi (1987) investigated also the influence of site on wood properties of twelve-year-old *Populus x euramericana* clones and found significant differences between clones grown in different sites. Locations influenced fiber length significantly for *Populus tremula* grown in five locations across Turkey as reported by Tank and Akkayan (1987).

Kellog and Swann (1985) observed no significant site effect within species; however, individual trees within a site were highly variable. Sample trees of both black cottonwood and balsam poplar were obtained from three different sites, and from each site ten trees were randomly selected for the study. Kroll et al. (1992) investigated ten balsam poplar trees harvested from five different sites and found that vessel and fiber area percentage was not related to sites.

There is extensive literature on the effects of genetics, environment and their interactions on the wood anatomy of *Populus spp.* Species and hybrids of poplars could play a larger role as raw material in the future; hence, further investigations pertaining to clonal and site induced variations in anatomical properties are needed for a better understanding of the basic principles of heritability and environmental influences. Such understanding will eventually lead to more efficient selection of clones suitable for planting on specific sites.

MATERIAL AND METHODS

Material

Three hybrid *Populus* clones were chosen from two different sites in Hungary. Site 2 (Zalavar) is considered more favorable for poplars then Site 1 (Daka) because Site 2 has more evenly distributed rainfall and reduced extremes in temperatures.

Plantation in Site 1 was fifteen years old and in Site 2 ten years old. Measurements were taken on one Italian clone (*Populus x euramericana* (Dode) Guinier cv. I-214) which is the most abundant poplar clone in Hungary, and on two Hungarian clones (*Populus x euramericana* (Dode) Guiner cv. Kopecky and *Populus x euramericana* (Dode) Guinier cv. Koltay).

The experimental design involved two sites, three clones and six randomly selected trees (ramets) from each clone on each site. However, clone Koltay was not available in Site 2. Sample trees were chosen for straightness of bole and absence of discernible defects. Measurements were taken within each tree from each growth ring for each property studied.

Methods

Disks were taken at breast height from each tree to obtain samples. The width of each ring was recorded together with any visible defects.

Transverse microtome sections of each growth ring were prepared for anatomical measurements (Sass 1958). The 20μm thick sections were stained with safranin and fast green to differentiate the possible tension wood fibers from normal fibers. A minimum of five slides was prepared and labelled from each growth ring. From the mounted slides the following anatomical characteristics were measured on an image analyzer (IMAGE1, Universal Imaging Corporation 1990) for each growth ring: vessel lumen diameter, number of vessels, vessel lumen area percentage, shape factor of vessels, ray are percentage, fiber lumen diameter, and fiber lumen area percentage. Cell wall area percentage was calculated by subtracting vessel lumen, ray and fiber lumen area percentages from a unit area.

Measurements were taken at 100x magnification. In each growth ring, five images (0.75mm x 0.55mm) as random replicates were analyzed: one from earlywood, one from latewood and three from the middle part of the growth increment.

Macerated samples were prepared to determine fiber length. Using the same sections that were used for making slides, thin wood sticks from the middle part of each growth ring were placed in 30% hydrogen peroxide and glacial acetic acid mixture with ratio of 1:1 for 72 hours at 60° (Franklin 1945). The fibers were washed, stained by fast green, stored, and temporary slides were prepared before measurements.

Unfortunately the image analyzer system used cannot separate objects which are crossing one another. Therefore, instead of using the automatic measurement mode, manual measurement mode with caliper was applied. From each growth increment thirty-five unbroken fibers were measured.

STATISTICAL ANALYSES

Analysis of variance was conducted on the data with significance given at the 95% probability level ($\alpha = 0.05$) in order to evaluate the site and the clonal effects and their possible interactions on selected wood properties (SAS Institute Inc. 1985). The statistical model is of the form:

$$Y_{ijkn} = \mu + \alpha_i + \beta_j + (\alpha \text{ x } \beta)_{ij} + \gamma(\alpha \text{ x } \beta)_{ijk} + \epsilon_{ijkn}$$

Where Y_{ijkn} = property of interest,
μ = population mean,
α_i = effect of site,
β_j = effect of clone,
$(\alpha \text{ x } \beta)_{ij}$ = site x clone interaction effect,
$\gamma(\alpha \text{ x } \beta)_{ijk}$ = effect of tree within site and clone,
ϵ_{ijkn} = random error, unexplained variation.

Testing the significance of site, clone and interaction terms, and for the Duncan's procedure, type III mean square for between tree variations were specified as the error term (Hinkelmann 1992, personal correspondence).

Nested design, as a simple hierarchical analysis of variance model, was applied to estimate the clonal (genetic) variation and the tree-to-tree (environmental) variation within clones on Site 1. The following statistical model, where tree (ramet) was nested within clone, was used for testing variation of anatomical traits:

$$Y_{jkn} = \mu + \beta_j + \gamma_{k(j)} + \epsilon_{jkn}$$

Where Y_{jkn} = property of interest,
μ = population mean,
β_j = effect of clone,
$\gamma_{k(j)}$ = effect of tree within clones,
ϵ_{jkn} = random error, unexplained variation.

Relating the estimated clonal variance component to the total (phenotypic) variation, the repeatability (**R**) of a property was calculated. That gave an estimate of the upper limit of the narrow sense heritability ($\mathbf{h}^2$) of the property which is smaller or equal to the repeatability (Becker 1984).

Pearson correlation coefficients were calculated between all measured pairs of variables to test the intercorrelation between anatomical parameters (Kleinbaum et al. 1988). To find out whether or not there were other than linear relationships between properties, the two variables were plotted against each other.

For statistical analyses, the basic data set included property averages by growth increments; furthermore, regarding sample trees from Site 1, only the first 10 growth rings (from pith outward) were involved to eliminate the effect of the age difference of the two plantations. The confounding effect of the different calendar years, when the growth rings were produced, could not be removed from the models, however.

RESULTS

Average values of anatomical parameters together with their coefficients of variation are presented in *Table 1.1-1.3* for the three clones by site. Sample trees from Site 1 were harvested in the middle of the growing season; therefore, anatomical parameters for the 15th growth ring were not included. In addition, means of the first 10 yearly increments are also given.

Vessel lumen diameter

Comparing averages calculated for the first 10 increments on two sites, vessel lumen diameter ranged from 75.5 μm to 84.8 μm (*Table 1.1*). Means of 14 growth rings were higher than those for 10 growth increments on Site 1.

Analysis of variance indicated that site exhibited significant effect on vessel lumen diameter (*Table 1.2*). Clones on Site 1 had larger vessels with mean diameter of 81.6 μm than on Site 2, where the average was 76.4 μm. In addition, a significant difference was detected between Koltay and I-214, which had mean vessel lumen diameters of 82.2 μm and 77.5 μm, respectively. Kopecky did not differ significantly from the two other clones (*Table 1.3*) .

Site x clone interaction term was found significant as shown in ***Figure 1.2***. Although I-214 had similar vessels on both sites, site affected Kopecky resulting in a larger mean (84.8 μm) on Site 1 than on Site 2 (75.5 μm). Only 13% of the total variation of this variable was explained by the effects specified in the model.

Nested analysis of variance for Site 1 resulted in non-significant variation among trees within clones and a significant clonal effect which accounted for only 5.4% of the total variation (*Table 1.4*). Most of the variations (95%) were found within trees, (between growth rings).

Vessel lumen area

Table 1.1 shows that the clonal averages for vessel lumen area percentages calculated for the first 10 increments ranged from 28.0% to 33.7%. On Site 1, means of 14 growth rings were higher than those for 10 growth rings .

Analyzing the site and clonal factors, highly significant site but non-significant clonal effect were detected (*Table 1.2*). Furthermore, the null hypothesis for site x clone interaction was not rejected. Statistically significant variation was calculated between trees within sites and clones. Based on this model, approximately 32% of the total variation of vessel lumen area percentage could be explained.

Concerning the site averages, clones on Site 1 produced larger vessel lumen areas (32.7%) than those on Site 2 (28.3%) based on multiple comparison (*Table 1.3*). The Koltay clone had the largest value for this variable (32.9%), while, I-214 had the lowest mean of 29.8%. Kopecky exhibited vessel lumen area of 31.2% with non-significant deviation from the other two clones .

Based on the nested model on Site 1, small but significant variation was found among trees within clones with variance component of 8% of the total variation (*Table 1.4*). Significant clonal variation was not detected. A high level of variation (89%) occurred within trees.

Number of vessels per unit area

For the number of vessel elements, means ranged from $62.9/mm^2$ to $73.9/mm^2$ among the 10 years observations on two sites. Averages based on 14 growth rings were lower than those based on 10 growth rings for Site 1 (*Table 1.1*).

An analysis of variance resulted in significant site x clone interaction effect and significant variation between trees within site and clones (*Table 1.2*). However, in case of site and clone effects, the null hypotheses were not rejected. Only 18% of the total variation was justified by this statistical model.

Comparing site and clonal averages of vessel numbers, no significant differences were indicated by Duncan's test (*Table 1.3*). Means of the Kopecky clone were not different on the two sites with approximately 66 vessels per mm^2. However, I-214 produced more vessels ($74/mm^2$) on Site 1 and fewer ($62/mm^2$) on the other site. Consequently, site had an effect on clone I-214 but not on clone Kopecky. The site x clone interaction effect is shown in *Figure 1.2*. The trend of that interaction for number of vessels was the opposite of that found for vessel lumen diameter. In that case, site effected Kopecky but not I-214.

Results of the nested statistical analysis are detailed in *Table 1.4*. Non-significant variation was found among clones within Site 1; however, low but significant tree-to-tree variation was observed accounting only for about 9% of the total variation.

Shape factor of vessels

The means of shape factors ranged from 0.765 to 0.798 among clones on two sites counting only data based on the first 10 growth increments. However, averages for 14 growth rings were not different from means of 10 growth rings for clones from Site 1 (*Table 1.1*).

An analysis of variance showed that there were non-significant site, clone and interaction effects. Nevertheless, strong significance was found for trees within sites and clones (*Table 1.2*). The model accounted for only about 8% of the total variation suggesting that important effect or effects were hidden in the error term.

No significant difference existed between the site and among the clonal averages (*Table 1.3*). Clones showed shape factor of 0.787 and 0.774 on Site 1 and on Site 2, respectively. I-214, the Koltay and Kopecky clones all had similar means of 0.773, 0.787 and 0.788, respectively.

Analysis of the nested design resulted in non-significant genotypic variations. Between tree variation was found significant (15%) indicating the influence of environment on variation of vessel shape factor (*Table 1.4*) besides the high within tree variation.

Fiber lumen diameter

Average values for fiber lumen diameters of clones on two sites ranged from 15.2 μm to 16.6 μm considering only the values based on 10 growth rings (*Table 1.5*). Means of 14 growth rings were higher than those based on 10 growth rings.

The analysis of variance resulted in significant differences among clones. However, no significant site and site x clone interaction effects were detected (*Table 1.2*). Statistically significant tree effect was observed within sites and clones but the model explained only 19% of the variations between measurements on fiber lumen diameter.

Duncan's multiple range test showed a significant difference between site averages. Clones on Site 1 had larger fiber lumens (16.2 μm) than on Site 2 (15.5 μm) (*Table 1.3*). Clones differed significantly for fiber lumen values. The Koltay clone had larger fiber lumens (16.6 μm) than did the other two clones.

Based on analysis of the nested statistical model, no significant genetic variation was estimated (*Table 1.4*). The environmental variation was significant but low, accounting for only 8% of the phenotypic variation. The biggest part of the variation (89%) was detected within trees.

Fiber lumen area

Clonal averages on two sites for fiber lumen area percent are given in *Table 1.5*. Fiber lumen area percent represented the ratio of fiber lumens to fiber walls. The mean values based on 10 growth rings ranged from 51.2% to 57.0%. Averaging fiber lumen area values for 14 growth increments on Site 1, no significant difference was found between means of 14 rings and 10 rings.

Conducting an analysis of variance, the hypotheses that there are no significant differences between sites, among clones, and among trees within sites and clones pertaining to fiber lumen area percentage were rejected (*Table 1.2*). Although no significant site x clone interaction was found, the factors specified in the model accounted for more than 50% of the total variation.

Table 1.3 shows that clones harvested from Site 2 had a larger mean ratio (56.6%) between fiber lumen and fiber wall than those on Site 1 (53.7%). There were no significant clonal differences. The Kopecky, I-214 and Koltay clones had means of 53.7%, 55.4% and 56.2%, respectively.

Significant variations were detected between clones on Site 1 and among trees within clones (*Table 4*). Based on the estimated variance components the genotypic variation was calculated to be 34% of the total (phenotypic) variation. The tree-to-tree variation was 16%. Therefore, the remaining 50% variation was attributed to the within tree variance.

Fiber length

Table 1.5 contains mean fiber length values for clones on two sites, ranging from 1.03 mm to 1.11 mm based on 10 growth rings. On Site 1, after 14 years, the fiber length averages exhibited larger values than those after 10 years.

Analysis of variance resulted in non-significance for the effects involved in the model. The hypotheses that there were no differences between sites, clones, and trees within sites and clones were not rejected (*Table 1.2*). Most of the variations (87%) were found within trees, among observations.

Site averages for fiber length exhibited similarities with means of 1.07 mm and 1.05 mm as displayed in *Table 1.3*. Comparing clonal means, Koltay produced significantly longer fibers (1.11 mm) than Kopecky (1.04 mm) though I-214 did not differ significantly from the other two clones.

The hierarchical model for fiber length on Site 1 denoted non-significant genetic variation and significant environmental variation of 9%. This indicates that the highest percentage of the phenotypic variation (89%) occurred within trees, among growth increments (*Table 1.4*).

Ray area

Average ray area percentage values of clones on the two sites ranged from 7.8% to 9.0% if only 10 growth rings were considered (*Table 1.6*). Means based on 14 growth increments were lower than means based on 10 growth ring values on Site 1.

Evaluating the site, clone, site x clone interaction and tree effects on ray cell, only the interaction term and the variation among trees within sites and clone were significant (*Table 1.2*). The interaction effect is illustrated in ***Figure 1.3***. Site had an effect on clones because it seemed that I-214 produced more rays (9.0%) on Site 1 than on Site 2 (8.3%). Meanwhile, performance of the Kopecky clone was just the opposite with means of 7.8% on Site 1 and 8.7% on the other site. That is why clone and site averages for ray cell area did not show significant grouping based on Duncan's test (*Table 1.3*). The model with these specified effects explained only about 14% of the variation among observations.

The result of the nested procedure (*Table 1.4*) exhibited significant variation between clones on Site 1 with genotypic variation of 15% and significant but low environmental variation of 8%. This indicates that beside between clone and tree-to-tree variation, the highest variation occurred within trees, among measurements.

Cell wall area

Percentage of cell wall area of clones on two sites are compiled in *Table 1.6.* Means ranged from 25.8% to 28.6% counting measurements on 10 growth rings. Averages for 14 growth increments were slightly lower than those based on 10 growth rings.

An analysis of variance resulted in non-significant site and site x clone interaction effects (*Table 1.2*). Statistically significant clonal effect was detected; furthermore, differences among trees within sites and clones were also significant. The model with the tested effects accounted for approximately 32% of the total variation.

There was no significant difference between site averages for cell wall substance but means of clones differed significantly (*Table 1.3*). The Koltay clone showed a lower mean value (29.4%) than the Kopecky clone (31.8%); however, the I-214 clone with a mean value of 31.3% did not differ significantly from the others.

Testing the simple hierarchical model on cell wall area percentage in Site 1, significant genetic variation of 20% was observed based on the estimated variance components (*Figure 1.4*). Between-tree variation within clones, referred to as environmental variation, accounted for about 8% of the total (phenotypic) variation. Nevertheless, the highest variation of 72% was measured within trees, among growth increments.

Relationship between anatomical properties

Correlation tests were applied to vessel parameters and their results are presented in *Table 1.7*. The highest correlation of -0.81 was between vessel lumen diameter and number of vessels per unit area. Not always strong but highly significant correlations were found between all pairs of properties compared.

Relating the fiber parameters, the highest correlation of -0.73 was found between fiber length and fiber lumen diameter; nevertheless, the other two comparisons also resulted in significant relationship (*Table 1.8*).

Table 1.9 contains Pearson correlation coefficients between selected anatomical parameters. Since high negative correlation was found between vessel lumen area and number of vessels per unit area, only one of them, the vessel lumen area was involved in this comparison. Shape factor was also dropped because it should be considered as inconsistent for estimating vessels shape, since one cannot determine whether a lower value means elongated vessels or more vessel chains.

Significant correlation between variables ranged from a minimum of 0.172 to a maximum of 0.810 on the whole data set. Only two pairs of parameters did not show significant relationships. They were fiber lumen area to vessel lumen diameter, and fiber lumen area to vessel lumen area. Fiber length, the most often measured wood characteristic, indicated strong positive correlation to vessel lumen diameter (0.764), to fiber lumen diameter (0.727) and to vessel lumen area (0.592). Positive but moderate relationship was found between fiber length and fiber lumen area; meanwhile, fiber length resulted in strong negative correlation (-0.670) to ray area and moderate negative correlation (-0.503) to cell wall area percentage.

Similar trends of associations were detected between anatomical parameters of each poplar clone, suggesting that the associations between anatomical characters are not clonal specific (*Table 1.7-1.9*).

DISCUSSION

The design of the experiment involved two sites, three clones and six ramets from each clone. Measurements were taken within trees from each growth ring for each property studied. Thus, their variations represented the effect of the age of the cambium when the increments were produced. However; the effect of age of the cambium on anatomical properties was not considered in this paper, only the variations among observations which were attributed to site and clonal effects.

It must be noted that the Koltay clone was not available from both sites and the plantations on the two sites were not of the same age. In order to eliminate the effect of tree age, only the same number of growth rings were counted in the analysis; nevertheless, the effect of the different calendar years when the rings were produced may cause bias. If a larger number of clones had been collected from more sites with the same age of plantations the results of these tests could have been more broadly interpreted.

Comparison of results with other findings in the literature is not easy due to the large varieties of clonal and site selections of sample trees with different ages and measurement techniques.

Anatomical properties

Vessel diameter:

Measurements on vessels in this study resulted in clonal averages between 76 μm and 85 μm for lumen diameters. Adding a few micrometers for cell wall thicknesses, vessel sizes of the three poplar clones tested were well within the wide range published. For example, Onilude (1983) studied the quantitative anatomical characteristics of 26-year old cottonwood trees, and reported an average of 74 μm vessel diameter detected in the middle part of growth increment. Kroll et al. (1992) measured average vessel diameters ranging from 60 μm to 77 μm for 10 balsam poplar trees and they also cited Brown et al. (1949) who found a range of 75 μm to 150 μm for balsam poplar and cottonwood. Furthermore, Micko (1987) stated finding balsam poplar vessel diameters between 60 μm and 167 μm.

Vessel lumen area:

Vessel lumen area percentages of clones were calculated between 28.0% and 33.7% which is similar to those values reported by Onilude (1983) with overall mean of 30.0%. Marton et al. (1968), Isebrand (1972), Cheng and Bendsen (1979), Phelps et al. (1982) and Kroll et al. (1992) reported ranges from 10% to 41%, from 24.5% to 52.4%, from 23.1% to 29.6%, 21% to 28% and from 26.2% to 36.5%, respectively. The fact is, poplars and their hybrids have highly porous wood. If they are fast growing trees, approximately one third of their cross sectional area is occupied by vessels.

Number of vessels:

Marton et al. (1968), Cheng and Bendsen (1979) and Kroll et al. (1992) also investigated the number of vessels per unit area. They mentioned ranges from $51/mm^2$ to $96/mm^2$, from $43/mm^2$ to $54/mm^2$, and from $54/mm^2$ to $79/mm^2$, respectively. Therefore, clonal means of this study with values between $63/mm^2$ and $74/mm^2$ fall into the middle range of data cited above but slightly lower than the overall mean of $72/mm^2$ reported by Onilude (1983).

Shape factor of vessels:

Regarding shape of vessels, Onilude (1983) found slightly lower overall mean of 0.75 than it was detected for the three clones in this experiment which ranged from 0.77% to 0.79%.

Ray cells:

Means of ray area percentage varied between 7.4% and 9.0% in this study. Other investigators reported a range from 1.5% to 13.7% for ray area percentages (Myer 1922, Isebrands 1972, Holt and Murphey 1978, Murphey et al 1979, Cheng and Bendsen

1979, Kroll et al 1992). Although there is a wide range, the percent of ray area in *Populus spp.* is low due to the small, uniseriate rays present in these species.

Fiber diameter:

Fiber characters other than fiber length have not been studied extensively for poplars. Fibers are considered to be large with thick walls. According to van Buijtenen et al. (1958) fiber diameter for diploid aspen trees averaged 21 μm and 23 μm for triploid aspen as cited by Holt and Murphey (1978). In addition, they reported a range from 17.4 μm to 18.4 μm for hybrid poplar juvenile wood. Based on this investigation, clonal means of 15.2 μm to 16.6 μm were detected. However, an underestimation of this variable should be considered not only because fiber lumen diameter was measured instead of fiber diameter, but also because the gelatinous layer present in many samples often occluded the fiber lumens reducing the lumen diameter that could have been measured automatically by the image analyzer.

Isebrand (1972) investigated the percentage of fiber in eastern cottonwood, and found a range from 40.4% to 72%. Clonal means of this study had values between 51.2% and 57.0%.

Fiber length:

Regarding fiber length, the Hungarian clones investigated were not different from those planted elsewhere. The clonal means ranged from 1.03 mm to 1.17 mm.

Data on fiber length of *Populus spp.* are numerous due to their importance in pulp and paper production. Fast-growing, intensively managed poplar clones tested at young ages (3-4 years) averaged from 0.55 mm to 0.87 mm (Holt and Murphey 1978; Cheng and Bendsen 1979; Phelps et al. 1982, 1987). For older poplars, longer fiber length values averaging 0.71 mm to 1.32 mm were measured by Marton et al. (1968), Yanchuk et al. (1984), Kellog and Swan (1985), and Tank and Akkyan (1987).

Area fraction of anatomical elements

Cross sectional distribution of anatomical elements for the three *Populus* clones on two sites are illustrated in *Figure 1.4*. Significant differences were detected among clonal fractions on the two sites (*Table 1.1, 1.5, 1.6*). In general, it can be stated that less than one-third of the cross sections are occupied by cell wall material *(Figure 1.5)*.

Relationship between anatomical properties

Interrelationship among wood properties and their complexity are of importance to the tree breeders because changing one characteristic will alter another one, if they are related. Correlations between properties are effected by both genetics and environment With regard to the anatomical parameters analyzed in this study, significant correlations were detected for almost all comparisons. The relationships between properties were not clonal specific. The results indicate that clonal selection for longer fibers may result larger fiber lumens with thinner cell wall as well as larger vessel diameters and lumen fractions (*Table 1.9*). Such correlations could be either favorable or unfavorable, but always should be taken into consideration.

Site and clone effects

Analysis of variance models with site and clone factors for means resulted in significance for all variables measured except for fiber length (*Table 1.2*). Nevertheless, only a small part of the variation among observations was associated with the effects of interest in the statistical model. The highest r^2 value of 52% was detected for fiber lumen area percent. Evaluating vessel lumen area percent, vessel shape factor and cell wall area percent, the specified effects accounted for more than 30% of the total variation. Meanwhile, the other anatomical parameters had very low r^2's though the contribution of within tree variation to these values were highly significant except for vessel lumen diameter, fiber length and ray area. Consequently, other than site and clone effects, factors such as age and its interaction with site and clone should be considered as cause of variation among the observations.

Site significantly affected vessel lumen diameter, vessel lumen area and fiber lumen area as tested variables. Comparing the two different sites involved in this experiment, Site 1 produced poplar trees with significantly larger and more elongated vessels, and larger fibers but smaller fiber lumen area than Site 2, which is considered more favorable for poplar plantations.

Significant **clone** effects were found for fiber lumen diameter, fiber lumen area and cell wall area percentages. It should be emphasized that there was no clonal effect on fiber length. Among clones, Koltay had vessels and fibers with larger diameters and larger vessel lumen area fraction than I-214 and Kopecky. These are usually unfavorable characteristics for solid wood products; however, the Koltay clone produced the longest fibers with the lowest percentage of cell wall which are the most desirable parameters for the pulp and paper industry to produce quality papers from poplars. Nevertheless, the Koltay clone cannot be evaluated without information on its performance on the other site.

Evaluating **site x clone interaction**, this interaction was significant for vessel lumen diameter, number of vessels per unit area and ray cell percentage. In the case of ray cell percentage the site x clone interaction was the only significant factor.

Among the independent variables only lumen area of fibers seemed to be affected by both sites and clones without their interaction. Therefore, it should be tested through clonal selection if wood quality is of concern because this ratio indicates the cell wall material present in wood.

Significant tree-to-tree variation was detected for each anatomical element except vessel lumen diameter. Approximately 10-15% of the total variation occurred between trees within clones. This variation is attributed to environmental effect because ramets have the same genetic make-up. However, the highest differences were detected within trees among measurements. Since measurements represented the growth increments, the results of the analyses of variance indicated the importance of age effect on anatomical elements of poplar clones. The emphasis in this study was on investigation of the site and clone variations of the three poplar clones; nevertheless, the influence of the age of the cambium was also evaluated on these sample trees and it is described in another publication (SECTION 3).

Multivariate cluster analysis was used on the anatomical properties to investigate the clonal effect. However, the clones were not hierarchically clustered based on the anatomical properties. In other words, there was no clonal effect, if all the anatomical properties were involved in a multivariate statistical model.

As discussed above, statistically significant differences were found between sites and/or among clones for most of the characteristics investigated. Despite the statistical significance the differences were small and probably negligible from a utilization standpoint.

Between and within clones variations

An attempt was made to estimate the genetic and environmental effects on anatomical parameters although the experiment was not designed for this purpose. Since only three clones were involved in this investigation, relating the genetic variation to the phenotypic variation may not be a reliable estimate for the heritability of the anatomical properties. However, the magnitude of the tree-to-tree variation may be useful for evaluating the environmental effect on clones, and therefore, it has practical value (Zobel and van Buijtenen 1989).

Nested analysis of variance was applied to the data from Site 1 in order to calculate the variation between clones and within clones between trees. Interclonal variation was significant for vessel lumen diameter, fiber lumen area, ray area and cell wall area percentages. The variation between clonal means accounted for approximately 5.4%, 34.5%, 14.7% and 19.9% of the total (phenotypic) variations, respectively (*Table 1.4*). These ratios are referred to as repeatability values of properties which provide estimates of heritability or genetic control. Based on this study, fiber lumen area seemed to be under moderate genetic control. However, no significant genetic effect was found for fiber length, which is often used as clonal selection criteria in practice.

Anatomical properties - wood utilization

Comprehensive analysis on variation of anatomical properties can give an estimation of wood quality. *Populus* clones have potential as a source of raw material for pulp and paper. Both yield and quality of paper products are influenced by the size and the distribution of vessels, rays and fibers.

Wood characterized by a high percentage of long fibers with thin walls and by a low percentage of vessels and rays is the most suitable for the paper industry (Dadswell and Wardrop 1959; Dadswell at al.1959). High vessel percentage in wood not only decreases the fiber yield, but also increases the costs of refining. According to Marton et al. (1965), vessels and rays are broken into flakes during refining, thus decreasing the interfiber bonding in the paper which may reduce paper strength. Large vessels may cause problems by being torn from the paper surface during printing process.

Paper strength is affected by fiber length because longer fibers have more contact areas to create more interfiber bonds during paper production. Furthermore, the smooth texture of fine-quality writing paper requires thin cell walls. Although poplars, like other hardwoods, produce shorter fibers, their thin cell walls are useful for fine texture paper products (Phelps et al. 1987).

Vessels and fibers with large diameters, with large lumen area fraction and short fiber length are usually unfavorable characteristics for solid wood products. They lead to difficulties in drying, machining and finishing of the wood. Furthermore, directly or through specific gravity they contribute to low mechanical properties in wood which is of particular importance in case of structural applications.

Increased ray volume may raise specific gravity because it has a higher specific gravity than the other woody tissues (Taylor 1969) and influences strength properties as well. According to Myer (1922), increased ray proportion positively affected the hardness and modulus of rupture; however, inversely affected compression parallel to grain. Rays were observed as being positive factors in tangential and radial modulus of elasticity and proportional limit stress (Schniewind 1959; Kellogg 1960; Beery et al. 1983). However, Kennedy (1968) reported a positive correlation of ray volume on radial proportional limit stress only. Ray volume has a primary effect on the anisotropy of wood properties and in some species enhances the appearance of the wood. Since poplars have thin or uniseriate rays, their importance is probably not as great as in other species with larger ray fractions.

Difficulties in the drying and machining properties of poplars have been attributed to the high incidence of gelatinous fibers. Investigating these clones, gelatinous fibers were detected in almost every sample as scattered cells or groups without specific pattern *(Figure 1.6)*. Based on visual estimates, gelatinous fiber content varied among trees and was higher near the pith than close to bark. It was not related to site, clone or growth rate. However, the presence of gelatinous fibers possibly affected the anatomical properties and may have caused bias in measurement as the gelatinous layers occluded the fiber lumens. They may also have affected the physical and mechanical properties.

Since anatomical properties either increase or decrease the suitability of wood for different utilizations, there would be some advantages of in planting specific clones on specific sites. Therefore, information on size, distribution and the interrelationships of anatomical elements and on how they are affected by genetics and environments is of great importance.

CONCLUSIONS

An investigation on the size and distribution of selected anatomical elements conducted on three *Populus x euramericana* clones grown on two different sites in Hungary led to the following conclusions:

1. Analysis of variance indicated that significant differences existed among clones on two sites for most of the measured anatomical characteristics. However, the differences detected are small and may be negligible from a practical standpoint. Consequently, other selection criteria than anatomical properties should be considered for poplar clones.

2. Sites, clones and/or their interactions affected significantly one or more of the anatomical parameters except fiber length. Nevertheless, only a small percent of the total variation was explained by the specified models. This indicates the importance of another factors, such as age of cambium and crown closure, in influencing the anatomical properties.

3. Based on statistical analysis, fiber lumen area percentage was found under moderate genetic control. In addition, significant tree-to-tree variation, referred to as environmental effect, was found for all variables but vessel lumen diameter. However, the highest variation was detected within trees suggesting that the age effect is much stronger than clonal and environmental effects and should be of major concern.

4. Distribution of anatomical elements for the three clones on two sites resulted in slight but statistically significant differences. In general, the cell wall material production of poplar clones was very low, less than one-third of the total cross sectional area.

5. Statistically significant and complex but not clonal specific intercorrelations were found between anatomical properties in this study. Clonal selection for longer fibers may result in larger fiber lumens with thinner cell walls and larger vessel diameters and vessel lumens as well. In general, the correlations between wood properties (not just the anatomy) have to be explored in order to achieve improvement in several traits simultaneously in clonal selection.

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TABLES

Table 1.1. - Mean vessel parameters and the coefficients of variations for the three clones on each of two sites.

SITE	Growth ring (n)	CLONE					
		KOPECKY		I-214		KOLTAY	
		mean	cv%	mean	cv%	mean	cv%
Vessel lumen diameter [μm]							
Site 1	14	86.2 A	12.6	81.2 B	15.6	85.8 A	16.6
	10	84.8 A a	14.4	77.7 B a	16.8	82.2 AB	17.9
Site 2	10	75.5 A b	13.3	77.3 A a	16.4	-	-
Vessel lumen area [%]							
Site 1	14	34.3 A	10.3	32.8 B	13.8	34.7 A	14.2
	10	33.7 A a	11.2	31.6 B a	14.0	32.9 AB	13.5
Site 2	10	28.7 A b	15.2	28.0 A b	17.8	-	-
Number of vessels per mm^2							
Site 1	14	63.4 B	24.8	70.4 A	29.5	66.9 B	28.8
	10	64.4 B a	27.5	73.9 A a	31.2	69.0 AB	30.3
Site 2	10	67.6 A a	20.9	62.9 A b	28.4	-	-
Shape factor of vessels							
Site 1	14	0.79 A	3.6	0.78 A	4.6	0.79 A	3.5
	10	0.79 A a	3.3	0.78 B a	4.7	0.79 AB	3.0
Site 2	10	0.78 A b	4.0	0.77 B b	5.3	-	-

Differences between clones within sites for each vessel parameter are denoted by upper case letters. Differences between sites within clones for each vessel parameter are denoted by lower case letter. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

Table 1.2. - Analysis of variance results for site, clone, and their interaction effects on anatomical parameters of three poplar clones on two sites.

Source of variations	**Anatomical property**								
	Vessel lumen diameter	Vessel lumen area	Number of vessels	Shape of vessels	Fiber lumen diameter	Fiber lumen area	Fiber length	Ray area	Cell wall area
Site (S)	**	**	NS	NS	NS	**	NS	NS	NS
Clone (C)	NS	NS	NS	NS	*	*	NS	NS	*
Site x Clone	**	NS	*	NS	NS	NS	NS	**	NS
Tree (SxC)	NS	*	**	**	*	**	NS	NS	**
R^2 [%]	12.6	32.0	18.6	32.2	19.0	52.3	12.5	14.3	31.8

** - Statistically significant at the 1% level.
* - Statistically significant at the 5% level.
NS - Not significant at the 5% level.

Table 1.3. - Duncan's multiple range test for anatomical properties of site and clonal means. Means with common letters are not significantly different at the 5% level.

Source of means	Anatomical property								
	Vessel lumen diameter [μm]	Vessel lumen area [%]	Number of vessels [1/mm²]	Shape of vessels	Fiber lumen diameter [μm]	Fiber lumen area [%]	Fiber length [mm]	Ray area [%]	Cell wall area [%]
Site means of the three clones									
Site 1	81.6 **A**	32.7 **A**	69.1 **A**	0.787 **A**	16.2 **A**	53.7 **B**	1.07 **A**	8.3 **A**	31.1 **A**
Site 2	76.4 **B**	28.3 **B**	65.3 **A**	0.774 **A**	15.5 **B**	56.6 **A**	1.05 **A**	8.5 **A**	31.1 **A**
Clonal means of two sites									
Kopecky	80.1 **AB**	31.2 **AB**	66.0 **A**	0.788 **A**	15.5 **B**	53.7 **A**	1.04 **B**	8.2 **A**	31.8 **A**
I-214	77.5 **B**	29.8 **B**	68.4 **A**	0.773 **A**	16.0 **B**	55.4 **A**	1.07 **AB**	8.7 **A**	31.3 **AB**
Koltay	82.2 **A**	32.9 **A**	69.0 **A**	0.787 **A**	16.6 **A**	56.2 **A**	1.11 **A**	8.2 **A**	29.4 **B**

Table 1.4. - Analysis of variance results of nested models for anatomical properties of clones on Site 1, based on the first ten years data.

Source of variations	Anatomical property								
	Vessel lumen diameter	Vessel lumen area	Number of vessels	Shape of vessels	Fiber lumen diameter	Fiber lumen area	Fiber length	Ray area	Cell wall area
Clone (among clones)	** (5.4%)$^{+}$	NS	NS	NS	NS	** (34.5)$^{+}$	NS	** (14.7%)$^{+}$	** (19.9%)$^{+}$
Tree (within clones)	NS	* (8.1%)	* (9.2%)	** (15.8%)	* (8.1%)	** (16.4%)	* (8.6%)	* (8.1%)	* (8.2%)
Error (within tree)	(94.6%)	(88.9%)	(88.8%)	(83.2%)	(89.4%)	(49.2%)	(89.0%)	(77.1%)	(71.9%)

** - Statistically significant at the 1% level.
* - Statistically significant at the 5% level.
NS - Not significant at the 5% level.
( ) - Percent of the total variation.
$^{+}$ - Variance component x 10^{-2} = R (repeatability)

Table 1.5. - Mean fiber parameters and the coefficients of variations for the three clones on two sites.

SITE	Growth ring (n)	CLONE					
		KOPECKY		I-214		KOLTAY	
		mean	cv%	mean	cv%	mean	cv%
Fiber lumen diameter [μm]							
Site 1	14	16.2 **B**	11.8	16.4 **B**	8.9	17.0 **A**	9.0
	10	15.9 **B a**	12.9	16.0 **B a**	9.3	16.6 **A**	9.3
Site 2	10	15.2 **B a**	12.3	15.9 **A a**	9.8	-	-
Fiber lumen area [%]							
Site 1	14	51.2 **C**	7.2	54.1 **B**	6.3	56.1 **A**	5.0
	10	51.2 **C b**	7.0	53.7 **B b**	6.1	56.2 **A**	4.9
Site 2	10	56.2 **A a**	10.4	57.0 **A a**	9.4	-	-
Fiber length [mm]							
Site 1	14	1.10 **B**	16.2	1.12 **AB**	13.6	1.17 **A**	15.6
	10	1.03 **B a**	15.9	1.07 **ABa**	14.2	1.11 **A**	16.4
Site 2	10	1.04 **A a**	16.6	1.06 **A a**	15.2	-	-

Differences between clones within sites for each fiber parameter are denoted by upper case letters. Differences between sites within clones for each fiber parameter are denoted by lower class letter. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

Table 1.6. - Mean cell wall and ray areas, and the coefficients of variations for the three clones on two sites.

SITE	Growth ring (n)	CLONE					
		KOPECKY		I-214		KOLTAY	
		mean	cv%	mean	cv%	mean	cv%
Cell wall area [%]							
Site 1	14	28.4 **A**	10.5	27.0 **B**	9.1	25.2 **C**	9.3
	10	28.6 **A a**	10.9	27.4 **B a**	9.0	25.8 **C**	8.9
Site 2	10	27.4 **A a**	13.4	27.4 **A a**	14.7	-	-
Ray area [%]							
Site 1	14	7.4 **B**	18.4	8.3 **A**	22.5	7.8 **B**	15.6
	10	7.8 **B b**	17.1	9.0 **A a**	17.8	8.2 **B**	14.0
Site 2	10	8.7 **A a**	23.8	8.3 **A b**	19.2	-	-

Differences between clones within sites for cell wall area and for ray area are denoted by upper case letters. Differences between sites within clones for cell wall area and ray area are denoted by lower case letter. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

Table 1.7. - Pearson correlation coefficients between vessel parameters based on the total data set (bottom left) and separately for each clone (top right).

Vessel property	Clone	Lumen diameter	Lumen area	Number of vessels	Shape factor
Lumen diameter	Kopecky I-214 Koltay	1	0.72^{**} 0.62^{**} 0.73^{**}	-0.86^{**} -0.77^{**} -0.90^{**}	0.22^{*} 0.31^{**} 0.36^{**}
Lumen area	Kopecky I-214 Koltay	0.68^{**}	1	-0.32^{**} -0.09 -0.40^{**}	0.27^{*} 0.49^{**} 0.48^{**}
Number of vessels	Kopecky I-214 Koltay	-0.81^{**}	-0.16^{**}	1	-0.09 -0.06 -0.24
Shape factor	Kopecky I-214 Koltay	0.31^{**}	0.28^{**}	-0.15^{**}	1

*) Statistically significant at the 5% level.
**) Statistically significant at the 1% level.

Table 1.8. - Person correlation coefficients between fiber parameters based on the total data set (bottom left) and separately for each clone (top right).

Fiber property	**Clone**	**Lumen diameter**	**Lumen area**	**Fiber length**
Lumen diameter	Kopecky I-214 Koltay	1	0.46^{**} 0.59^{**} 0.28^{*}	-0.73^{**} -0.65^{**} -0.82^{**}
Lumen area	Kopecky I-214 Koltay	0.50^{**}	1	-0.25^{**} -0.30^{**} -0.17
Fiber length	Kopecky I-214 Koltay	-0.73^{**}	-0.27^{**}	1

*) Statistically significant at the 5% level.
**) Statistically significant at the 1% level.

Table 1.9. - Pearson correlation coefficients between anatomical parameters based on the total data set (bottom left) and separately for each clone (top right).

Anatomical property	Clone	Vessel lumen diameter	Vessel lumen area	Fiber lumen diameter	Fiber lumen area	Fiber length	Ray area	Cell wall area
Vessel lumen diameter	Kopecky I-214 Koltay	1	0.72** 0.62** 0.73**	-0.83** -0.69** -0.88**	0.12 0.27** 0.14	0.76** 0.76** 0.84**	-0.67** -0.70** -0.70**	-0.41** -0.51** -0.57**
Vessel lumen area	Kopecky I-214 Koltay	0.68**	1	-0.52** -0.47** -0.70**	-0.18 -0.03 -0.05	0.58** 0.67** 0.53**	-0.64** -0.47** -0.48**	-0.32** -0.56** -0.71**
Fiber lumen diameter	Kopecky I-214 Koltay	0.76**	0.52**	1	0.46** 0.59** 0.28**	0.73** 0.65** 0.82**	-0.57** -0.61** -0.60**	-0.65** -0.79** -0.66**
Fiber lumen area	Kopecky I-214 Koltay	0.17	-0.09	0.50**	1	0.25** 0.30** 0.17	-0.03 -0.40** -0.14	-0.86** -0.79** -0.64**
Fiber length	Kopecky I-214 Koltay	0.76**	0.59**	0.73**	0.27**	1	-0.71** -0.73** -0.60**	-0.45** -0.57** -0.45**
Ray area	Kopecky I-214 Koltay	-0.67**	-0.55**	-0.56**	-0.17**	-0.67**	1	0.21* 0.45** 0.29*
Cell wall area	Kopecky I-214 Koltay	-0.47**	-0.48**	-0.69**	-0.81**	-0.50**	0.31**	1

*) Statistically significant at the 5% level.
**) Statistically significant at the 1% level.

FIGURES

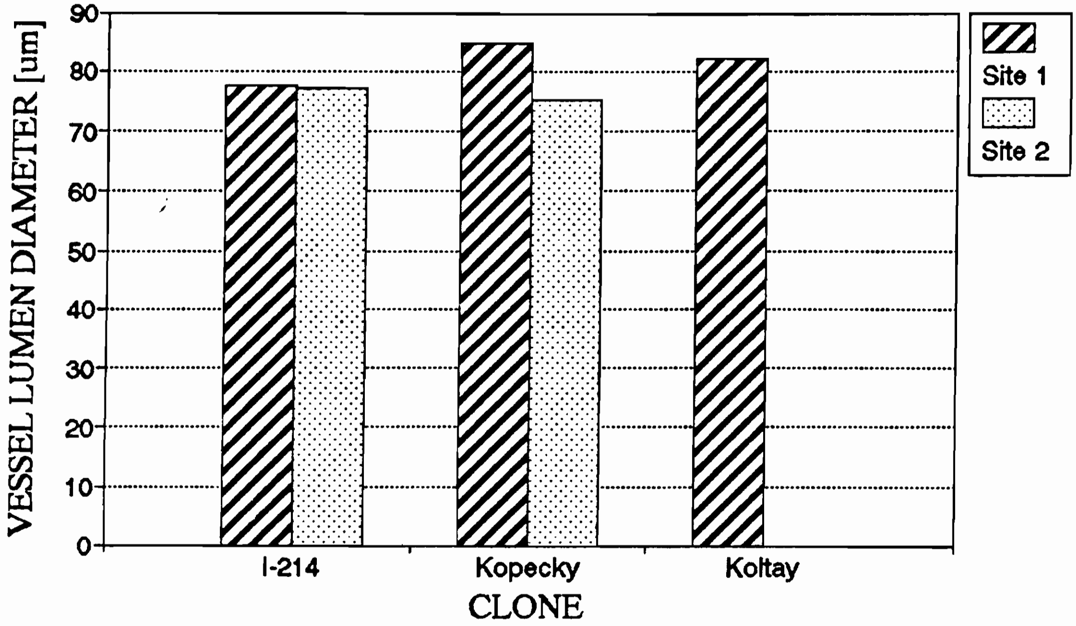

Figure 1.1. - Mean vessel lumen diameters for the three clones on two sites.

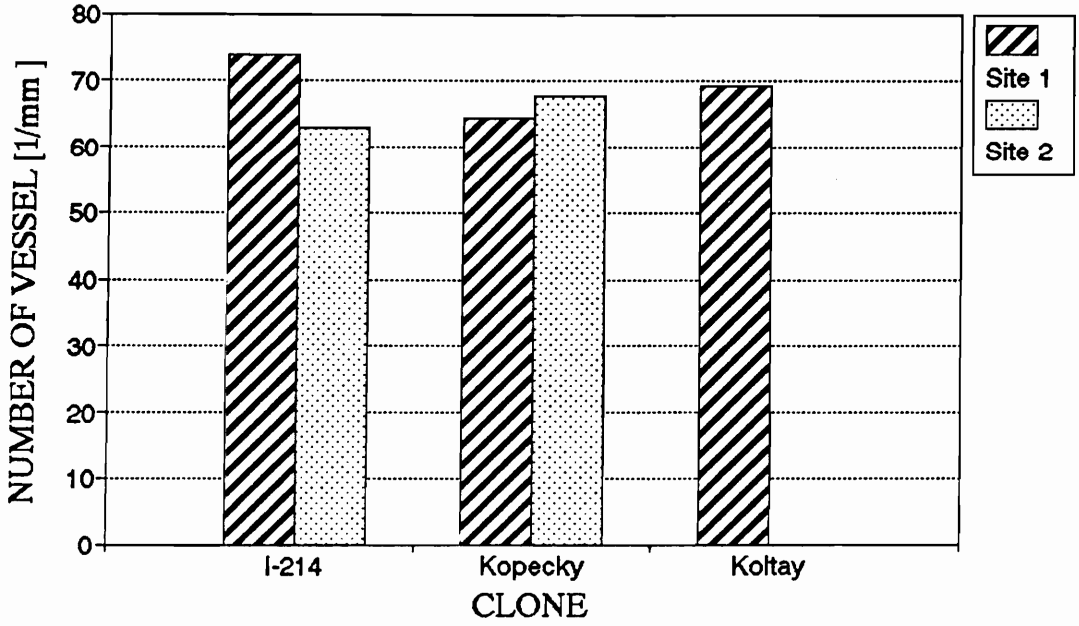

Figure 1.2. - Mean number of vessels per mm^2 for the three clones on two sites.

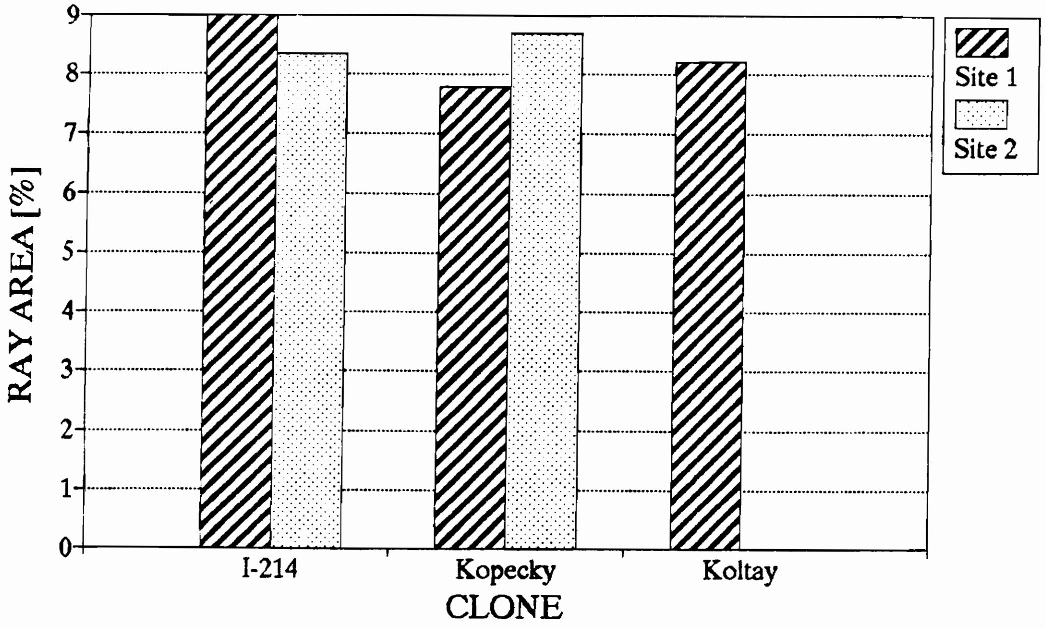

Figure 1.3. - Mean ray area percentages for the three clones on two sites.

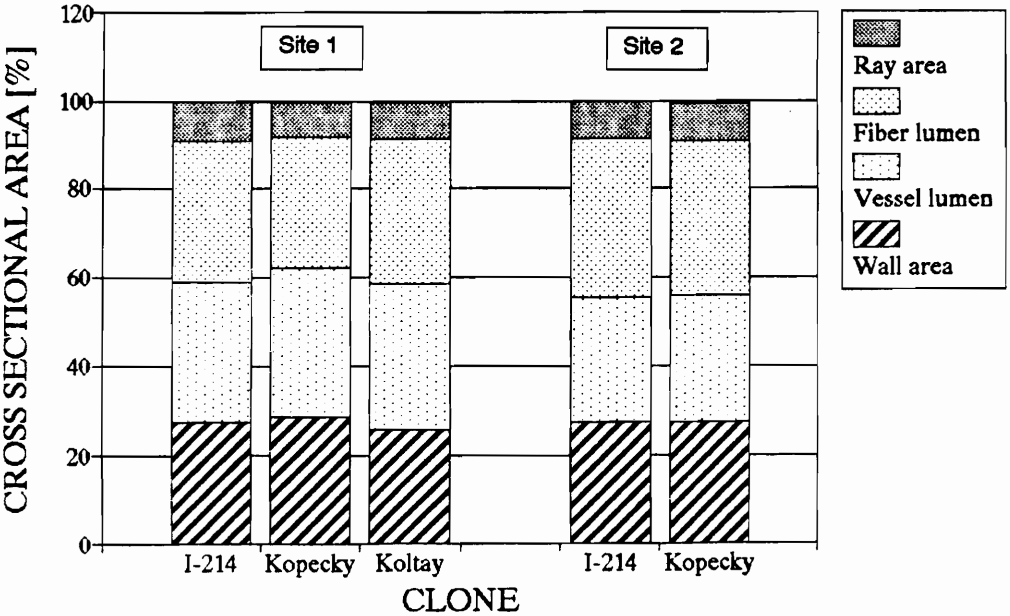

Figure 1.4. - Cross sectional distribution of anatomical element for the three clone on two sites.

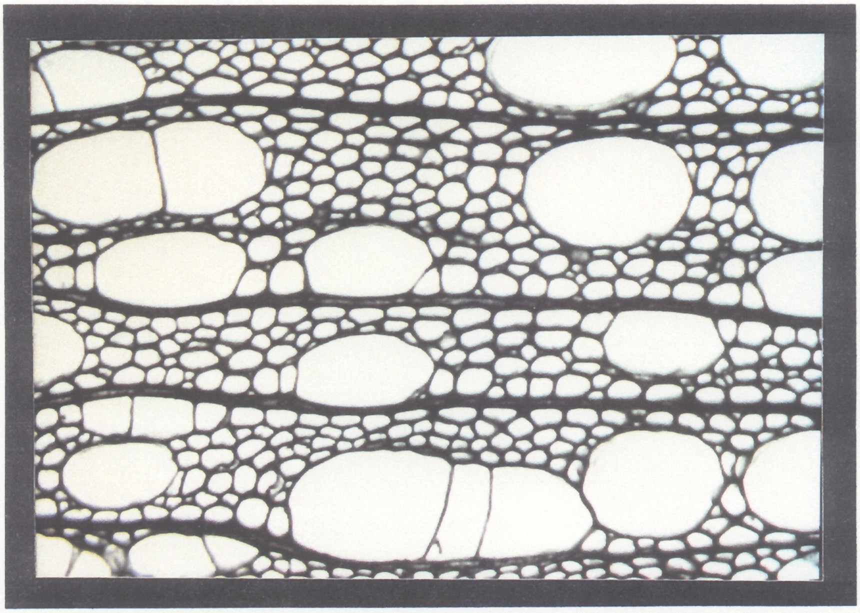

Figure 1.5. - Photograph of transverse section (100x) of the Koltay clone.

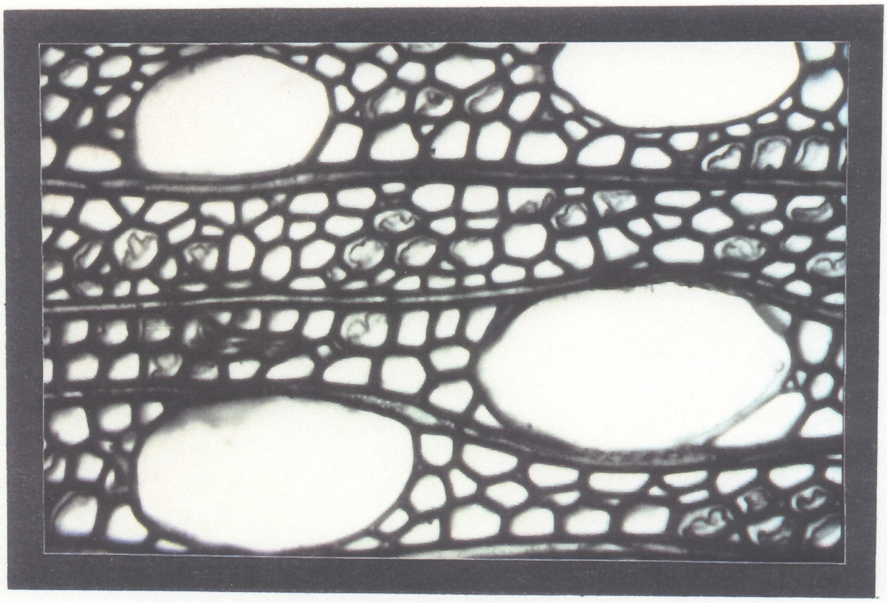

Figure 1.6. - Photograph of transverse section (200x) of the Koltay clone with gelatinous fibers.

SECTION 2.

Variation in Selected Physical and Mechanical Properties of three *Populus x euramericana* Clones.

ABSTRACT

Three clones of the hybrid *Populus x euramericana* (Dode) Guinier cv. - the Italian I-214 and the Hungarian Kopecky and Koltay - on two different sites in Hungary were investigated in this study. Plantations were fifteen years old on one site and ten years old on the other.

Six trees were sampled from each clone to examine patterns of variation for specific gravity between sites and among clones. Sample disks were obtained at breast height and the specific gravity of each growth ring were measured. Site did not affect specific gravity and the tree-to-tree variation was not significant. However, significant differences existed among clones, and the individual broad-sense heritability was 0.51.

From the fifteen years old sample trees on one site, specimens were obtained from above the disks for mechanical properties in three age groups: close to pith, middle of the radius, and near the bark. There were non-significant differences among clones and among trees for modulus of rupture, crushing strength, maximum tensile strength, and modulus of elasticity measured in tension. However, within tree mechanical properties were higher near the bark than close to the pith except maximum tensile strength.

Specific gravity was not the most important single factor affecting strength properties of the clones. There were non-significant correlation between specific gravity and bending or tensile strength. However, between specific gravity and compression strength the Koltay clone exhibited significant correlation, the other two clones did not.

INTRODUCTION

The shortage of timber resource in many parts of the world has led to the development of fast growing hybrids of certain tree species for use in plantations. Although wood is the final product of a tree improvement program, breeding for wood quality improvement has not always been the primary objective. Objectives usually included are growth, form, pest resistance, and adaptability (Paul 1953; Zobel 1971; Zobel and Talbert 1984). Genetic and silvicultural manipulations can either affect wood properties directly by causing physiological changes within the tree, or can alter the tree form which may have an influence on wood characteristics (Larson 1962).

Members of the *Populus* genus have received special attention by tree breeders because of the relative ease with which they can be hybridized and vegetatively propagated. In Europe, for example, hundreds of clones have been created by hybridizing North American and European poplars. Some of these clones, such as the Italian I-214, have been planted throughout Europe (Wright 1976).

Research on wood properties of poplars provides essential information to both foresters in managing their tree improvement programs and to the wood-using industries in applying new technologies for the best utilization of these trees.

Hungary, where only about 18% of the land area is forested, about 9% of all forests consist of hybrid poplars. Annual harvest of poplars accounts for more than 20% of the overall timber production (Molnar et al. 1990).

The objective of this study was to investigate interclonal and intraclonal variation of specific gravity in relation to mechanical properties in three *Populus x euramericana* clones grown in Hungary where poplars may be used, by necessity, for wood construction.

LITERATURE REVIEW

The quality of a material is considered to be the fitness of that material for a particular purpose (Fielding 1967). Regarding wood quality, specific gravity is the most widely measured property because it has the most significant effect on utilization (van Buijtenen 1982; Bamber and Burley 1983). Specific gravity is of importance to forest products manufacturing for two reasons. First, the yield and quality of fibrous and solid wood products are influenced by its value and variations. Secondly, it may be altered by silvicultural and genetic manipulations (Williams and Hamilton 1961; Zobel 1961; Nepveu 1984).

Specific gravity is not an independent property of wood because it is influenced by anatomical structure and chemical composition. However, it is convenient to treat it as a single property (Koch 1972). A relationship between specific gravity and strength properties has been observed to various degrees by many researchers.

Positive relationship:

Specific gravity as a single factor of greatest importance was reported by Kellogg and Ifju (1962) where the effect of specific gravity and certain other factors on the tensile properties of wood were investigated. Similarly, for Douglas-fir, Wilson and Ifju (1965) stated "specific gravity did prove to be the most important single factor influencing tensile strength".

Mitchell (1963) in a study of specific gravity variation in North American conifers pointed out that a 0.02 change in specific gravity could affect the MOR by about 1000 lbs./in^2. According to Wellwood et al. (1965) specific gravity explained up to 92% of the variability in strength properties of fibers within a growth increment five Canadian coniferous species. Bodig and Troxell (1965) examined the effect of specific gravity on shear strength and found a linear relationship between the two factors.

Specific gravity differences between materials from virgin forests and from second-growth forests resulted in 20-25 percent higher mechanical properties for virgin material (Bendtsen 1966). Specific gravity and ring orientation were found to have the greatest influence on the proportional limit stress and modulus of elasticity in a study of nine species as discussed by Kennedy (1968). Ifju (1969) investigated six southern pine trees from different species and reported a highly significant correlation between specific gravity and strength properties.

As stated by Littleford (1961) and later by Pearson and Gilmore (1980) wood density can be useful in predicting strength properties even though it is not always directly related to the variation of strength within and among trees. However, other studies have revealed different results.

No consistent relationship:

Wilson and Ifju (1965) observed the significant influence of specific gravity on tensile strength for Douglas-fir. However, they also noted that while earlywood tensile strength increased at constant rate, specific gravity was relatively unchanged. They reviewed other investigations with similar results and cited that the same tendency was observed by Kloot (1952) when large variation of load at low weight levels was observed plotting tensile breaking load against test sample weight. Hill (1949) found that specific gravity had only limited influence on tensile strength of balsa wood, while the relative amount of parenchyma cells had significant impact on the correlation. They also cited Van Vliet (1959), who found 33% of variation in Douglas-fir tensile strength due to density. Furthermore, Garland (1939) observed extremely low correlation between tensile strength and specific gravity for loblolly and shortleaf pines.

Non-significant relationships were obtained by Ifju and Kennedy (1962) and Wellwood (1962) for Douglas-fir and western hemlock between microtensile strength and specific gravity when earlywood and latewood tests were analyzed separately.

Bendtsen (1978) reviewed several publications on properties of wood from improved and intensively managed trees, among them, the investigations of Olson et al. (1947) on rapid grown plantation conifers. They concluded that specific gravity could not account for the differences in strength alone, but higher fibril angle was related to lower strength.

Onilude (1982) found that bending and compression strength values were increased as the cottonwood trees matured. However, specific gravity showed less consistent change from juvenile wood to mature wood; therefore, wood characteristics other than specific gravity might determine strength properties of plantation grown cottonwood.

For eastern cottonwood, Bendtsen and Senf (1986) reported that the large increase in mechanical properties with age was not explained by the change in the specific gravity alone, but rather reflected the composite effect of increasing specific gravity, cell length and fiber angle. Investigating the mechanical property - age relationships, Ross et al. (1990) reported that the small increase observed in specific gravity was not sufficient to account for the relatively large differences in mechanical properties. No significant correlation between specific gravity and bending, compression and tensile strengths was observed by Faust and Matlister (1989) when testing sweetgum and yellow poplar structural lumbers.

Variation in specific gravity and mechanical properties:

Ferrari and Scaramuzzi (1987) studied 12 years old *Populus x euramericana* clones from Italy and observed specific gravity values between 0.309 and 0.357. For three years old *Populus* clones, Phelps et al. (1987) published values of 0.31 to 0.39, while four years old *Populus* hybrid under intensive culture regimes had specific gravities between 0.299 and 0.465 (Blankenhorn et al. 1988). In a recent study on nine years old poplar hybrid clones, averages for individual trees ranged from 0.284 to 0.407 (Beaudoin et al. 1992).

A number of studies have dealt with interclonal and intraclonal variation of wood density in poplar species and their hybrids (Einspahr et al. 1963; Farmer and Wilcox 1968; Marton et al. 1968; Farmer 1970; Phelps et al. 1982, 1987; Yanchuk et al. 1983; Nepveau et al. 1986; Beaudoin et al. 1992). However, little information is available on the variation of strength properties in *Populus* clones. One possible reason for this is that the original intent in poplar breeding was for fiber production and not for solid wood products.

MATERIALS AND METHODS

Six trees from each of three clones of *Populus x euramericana* (Dode) Guinier were harvested for this investigation from each of two sites in Hungary. Site 2 is considered to be a better site due to the more evenly distributed rainfall and reduced extremes in temperature. The plantation on Site 1 (Daka) was 15 years of age, but on Site 2 (Zalavar) it was only 10 years old. The Italian I-214 and the Hungarian Kopecky and Koltay clones were tested. All trees were randomly selected and the height and diameter at breast height were recorded. Koltay was not available on Site 2.

A 100 mm thick disk was cut from each tree at breast height and a 500 mm long short log was also taken immediately above the disk for strength test specimens. To avoid the tension wood, 40 mm wide sections were cut in the east-west direction along one radius from each tree and short log. These sections were used to prepare samples for specific gravity and mechanical property measurements. Samples with visible defects were rejected. The width of growth increments were recorded on each section. Segments of the disks were put into plastics bags containing 5% sodium pentachlorophenate to prevent decay and sent to the Department of Wood Science and Forest Products, Virginia Polytechnic Institute and University State University, Blacksburg, Virginia.

For <u>specific gravity</u> determinations rectangular strips of the following nominal size was prepared from each disk: thickness (parallel to the grain) = 5 mm; width (tangential) = 20 mm; and length = radius of the tree. Four adjacent samples, as replicates, with width of 5 mm were cut from each growth ring of each 20 mm wide strip for determination of specific gravity of each growth ring. The maximum moisture method (Smith 1954) was used to determine specific gravity of these small specimens.

Bending strength tests were performed at the Department of Wood Science, University of Forestry & Wood Science, Sopron, Hungary, using Deutsche Industrie Norme (DIN) standards for small clear specimens. The specimens were prepared from the long blocks by cutting them from three regions along the radius: close to the pith, the middle of the radius, and next to the bark. Blocks contained totally or partly growth rings of 2-4 (age group 3), 5-7 (age group 2), and 8-13 (age group 1) years respectively. Nominal size of cross section was 20 mm x 20 mm and the length parallel to the grain was 300 mm. Before the tests, every specimen were measured using a caliper to the nearest hundredth mm. Beams were center-loaded on a 200 mm span. Only the modulus of rupture values were recorded. Three or four replicates were tested per block. The number of replicates were limited by the size of blocks, the standard size of the test specimens required and any wood defects. Tests were conducted in water-saturated (green) condition. Means for each age group from each tree of each of the three clones on Site 1 only were delivered from Hungary.

Compression strength parallel to grain was tested on rectangular samples of nominal size of 20 mm x 20 mm x 40 mm at water-saturated (green) condition. Specimens for compression were cut from the same blocks and from the same regions as those for bending. They were then mailed to the Department of Wood Science and Forest Products, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. Before testing, the size of each specimen was measured with a caliper and recorded. Compression tests were carried out on an MTS universal testing machine with crosshead speed of 0.375 mm/min. Maximum load was recorded as well as the graphic display of load-deformation curves. Modulus of elasticity could be calculated from these charts. Four replicates were tested from each of the three age groups defined above and their averages were used for further analyses.

Micro tensile strength of the clones was determined using the method described by Ifju et al. (1965). Specimens were cut from the same segments of the disks as those for the specific gravity. The size of the test specimens were 2.5 mm radially, 100 mm in longitudinal direction with 100 μm nominal tangential thickness. The specimens were cut from wood pieces from the 3rd (age group 3), the 7th (age group 2), and 11th (age group 1) growth increments to evaluate the tensile strength of clones near the pith, in the middle part of the radius, and close to the bark.

Specimens obtained from the middle part of the growth rings were sliced to proper thickness using a microtome, and then their width and length were cut by razor blade and a metal straight edge. Immediately before tests, thickness of the strips were measured in the green condition with a precision dial indicator (Mikrokator No.Y509-4 with measuring point No.S 512 having spherical surface - 100mm radius - and operated at 5 g anvil pressure) (Wilson and Ifju 1965). In addition, width of each sample was measured under a microscope and recorded.

Tensile tests were performed in the green condition using a table-model Instron testing machine. The specimens were tested over 30 mm span with crosshead speed adjusted to give an elongation rate of 0.2 mm/minute. The tests were run at room temperature using a plastic bag wrapped around the jaws holding the specimens to keep the samples in a water-saturated condition.

Maximum stress and stress to unit strain within proportional limit were obtained from recorder charts. Means obtained from five replicates of each growth ring tested were used for further examination. Instead of the conventional necked-down type specimens, simple rectangular strips were used based on the results from comparative test series. Paying careful attention to the gripping surface, pressure, and alignment, the site of failure could be controlled. Rectangular specimens are easy to prepare and the data, including strain, elasticity, and work estimates, can be obtained simply with low associated error. Approximately 20% of the specimens failed at the grips and they were discarded.

STATISTICAL ANALYSES

For specific gravity, an analysis of variance model with site and clone as factors of main interest was carried out on the data with significance given to the 95% probability level ($\alpha = 0.05$) (SAS Institute Inc. 1985). The applied statistical model is of the form:

$$Y_{ijkn} = \mu + \alpha_i + \beta_j + (\alpha \text{ x } \beta)_{ij} + \gamma(\alpha \text{ x } \beta)_{ijk} + \epsilon_{ijkn}$$

Where Y_{ijkn} = specific gravity
μ = population mean,
α_i = effect of site,
β_j = effect of clone,
$(\alpha \text{ x } \beta)_{ij}$ = site x clone interaction effect,
$\gamma(\alpha \text{ x } \beta)_{ijk}$ = effect of tree within site and clone,
ϵ_{ijkn} = random error, unexplained variation.

Type III mean squares for between tree variation were specified as the error term to test whether site, clone and interaction terms affected specific gravity significantly, and for the Duncan's range test to compare site and clonal means (Hinkelmann 1992, personal correspondence).

For strength properties the following analysis of variance model was used to evaluate the effect of clone and age:

$$Y_{jkln} = \mu + \beta_j + \gamma_{k(j)} + \delta_l + (\beta \text{ x } \delta)_{jl} + \epsilon_{jkln}$$

Where Y_{jkln} = strength property
μ = population mean,
β_j = effect of clone,
$\gamma_{k(j)}$ = effect of tree within clone,
δ_l = effect of age,
$(\beta \text{ x } \delta)_{jl}$ = clone x age interaction effect,
ϵ_{jkln} = random error, unexplained variation.

Type III mean square for between tree variation was specified as the error term to test whether clone affected strength significantly, and for the Duncan's procedure to compare clonal means (Hinkelmann 1992, personal correspondence).

Analysis of variance model with trees nested within clones on Site 1 was applied to estimate clonal (genetic) variation and between trees (environmental) variation on **specific gravity** and on **strength properties**. The following statistical model was used for testing variation:

$$Y_{jkn} = \mu + \beta_j + \gamma_{k(j)} + \epsilon_{jkn}$$

Where Y_{jkn} = property of interest,
μ = population mean,
β_j = effect of clone,
$\gamma_{k(j)}$ = effect of tree within clones,
ϵ_{jkn} = random error, unexplained variation.

Relating the estimated clonal variance component to the total (phenotypic) variation, the repeatability (**R**) of a property was calculated. The repeatability is the upper limit of the narrow sense heritability (**h^2**) (Becker 1984).

Since only three clones were involved in this investigation, the genetic variation calculated may not be a reliable estimate. However, the magnitude of the tree-to-tree variation can be useful to evaluate the environmental effect on clones, and has practical value.

Pearson correlation coefficients were calculated between specific gravity and mechanical properties to test their associations (Kleinbaum et al. 1988). Each pair of variables was plotted against each other to determine whether or not there are other than linear relationships between properties. Pearson correlation coefficients were calculated on the data set which included strength properties of specimens together with their specific gravity values based on averaging the specific gravities of the growth rings that were present totally or partly in the samples.

For statistical analyses on specific gravity, the basic data set included averages by growth increments. Regarding sample trees from Site 1, only the first 10 growth rings (from pith to bark) were used to eliminate the effect of the age difference between the two plantations. The confounding effect of the different calendar years, when the growth rings were produced, could not been removed from the models. Mechanical properties were investigated on clones from Site 1 only. Means of specimens by age groups were used for the analysis of variance.

RESULTS AND DISCUSSION

Specific gravity

The overall means for the three poplar clones tested are shown in *Table 2.1*. Only 14 growth increments were counted on Site 1 because the trees had been collected before the growing season ended; nevertheless, the means based on 10 growth rings from Site 1 are given as well in order to be compared with means of Site 2 eliminating the age difference.

The average specific gravity of clones ranged from 0.305 to 0.356; however, a minimum of 0.258 and maximum of 0.435 were observed among growth rings and range of 0.288 to 0.378 for individual trees of the data set. The average wood specific gravity of the poplar clones reported elsewhere is similar to these values even though the age of sample trees was different from those in the literature. This indicates that poplars have low specific gravity regardless of which species or hybrids and of where they are growing (Holt and Murphey 1978; Murphey, et al. 1979; Halupane Grosz 1980; Phelps et al. 1982; Bendtsen and Senft 1986; Babos 1988; Beaudoin et al. 1992).

Analysis of variance for site, clone and their interaction effects was carried out (*Table 2.2*). The null hypotheses for site and site and clone interaction effects were not rejected. No significant differences were measured between means of the two sites *(Table 2.3)* site did not have a significant effect on clones. However, significant differences existed among specific gravity values of the clones. Koltay showed the highest mean of 0.356 compared to Kopecky and I-214 that had mean specific gravities of 0.343 and 0.306, respectively *(Table 2.3)*. In addition, variation among trees within sites and clones were also significant. Only 45% of the total variation was explained by the effects involved in the model.

Further analysis of variance based on a nested procedure for Site 1 indicated that there were significant differences between clones for specific gravity *(Table 2.4)*. The effect of clones accounted for approximately 51% of the total (phenotypic) variation of this variable as suggested by the estimated variance components. This ratio of the variance components are referred to as repeatability or as broad-sense heritability. Though the experiment was not designed to estimate the heritability of specific gravity, the results based on investigation of these clones is close to those reported by Farmer and Wilcox (1968), Farmer (1970), Nepveu et al. (1978, as cited by Beaudin et al. 1992), and Beaudin et al. (1992) for euramericana hybrids and for eastern cottonwood as well. Ferrari (1987) observed even higher heritability value (0.96) while Einspahr et al. (1963) found a lower ratio of 0.39. In addition, several researcher reported significant clonal effects of specific gravity of poplar hybrids indicating strong genetic control on this property (Marton et al. 1968; Phelps et al. 1982, 1987; Yanchuk et al. 1983; Nepveu et al. 1986).

No significant variation existed among trees for specific gravity *(Table 2.4)*. Similar result was reported by Yanchuk et al. (1983) investigating wood density of three trembling aspen clones. Nevertheless, Beaudoin et al. (1992) found low but significant intraclonal variation in wood density of poplar hybrid clones. Tree-to-tree variation within a clone can be attributed to environmental effects because trees (ramets) of a clone are genetically identical. Beside the environmental differences within a plantation of a single clone, differences among ramets can be attributed to other, non-genetic effects such as not uniform planting material, failures in planting and in cultivation (Matyas 1983).

Mechanical properties

The three poplar clones from Site 1 with 14 growth increments were included in this experiment on variation of selected mechanical properties, such as modulus of rupture (MOR), crushing strength, compression modulus of elasticity (MOE_c), and maximum tensile strength and tension modulus of elasticity (MOE_t).

Analysis of variance test on the effects of clone, age and their interaction on strength properties are compiled in *Table 2.5*. Only modulus of elasticity calculated in compression showed slight but significant clonal effects. In other words, the hypotheses that there are no significant differences between clones regarding modulus of rupture, crushing strength, maximum tensile strength and modulus of elasticity in tension were not rejected. On the other hand, age had highly significant effect on each mechanical property except maximum tensile strength. Age affected clones in the cases of bending and compression as indicated by the significant clone x age interaction terms in *Figure 2.1*. Based on r^2 values, 74-92% of the variation could be explained by these models for most strength properties. However, for maximum tensile strength where none of the specified effects was found significant, the highest percent of the variation (54%) was detected between observations.

Duncan's multiple range test was conducted to determine which means were or were not significantly different from each other. The clonal mean values for modulus of rupture, crushing strength, modulus of elasticity in compression, and maximum tensile strength together with the modulus of elasticity in tension are presented in *Table 2.6*. The measurements were taken at water-saturated (green) condition resulting in the low values of strength properties.

Modulus of rupture of I-214 was significantly lower (26,062 kPa) than that of Kopecky (30,383 kPa) while Koltay was intermediate with a mean of 29,597 kPa. Similar results were published by Onilude (1982) and Bendtsen and Senft (1986) for cottonwood (about 28,000 kPa), by Ross et al. (1990) for juvenile wood (29-year old) of quaking aspen (37,500 kPa). Furthermore, Bodig and Jayne (1982) and the Wood Handbook (1987) presented a range from 27,000 kPa to 37,000 kPa for maximum bending strength of aspen and cottonwood indicating the average magnitude of this property of *Populus spp*. Higher values of 40,000 to 50,00 kPa were reported for poplars in some Hungarian literature (Kovacs 1979; Babos 1992; Kutatasi Jelentes 1989); however, those values were obtained at 12% moisture content and not in the green condition.

Crushing strength of the three clones did not differ significantly. The means ranged from 11,900 kPa to 12,337 kPa similar to other findings (Onilude 1982; Bendtsen and Senft 1986; Bodig and Jayne 1982; Wood Handbook 1987).

Maximum tensile strength measured in micro-tensile tests varied from 27,148 kPa to 33,170 kPa with a high coefficient of variation (24-43%). There were non-significant clonal differences. The values obtained were below those reported elsewhere for standard tensile tests. Micro tests, however, usually result in lower strength values. For poplars, no micro-test results are available in the literature for appropriate comparison. According to Ifju (1964), in a study on Douglas-fir, similar value of 32,270 kPa was detected for ultimate tensile strength of micro specimens from earlywood of growth increments at green condition. The wood density of poplars is close to that of Douglas-fir earlywood, indicating that these test results are in the expected range.

Stiffness of the three clones was recorded for both compression (macro) and tensile (micro) tests. Means of modulus of elasticity in compression and tension were between 1,208 MPa and 1,774 MPa with average coefficient of variation of 20%. Values found in the tensile test were slightly lower than those in compression but no significant clonal differences were detected. In general, stiffness values were low, about 25% of data cited elsewhere (Bodig and Jayne 1982; Wood Handbook 1987) for standard poplar specimens, and only about 60% of values reported for micro-tensile test of Douglas-fir earlywood samples (Ifju 1964; Wilson and Ifju 1965) and for small beams of cottonwood measured in bending (Onilude 1982). Modulus of elasticity was calculated from the recorder chart data. Perhaps the use of this method rather than strain indicators may account for the low modulus of elasticity values. Therefore, the results can be used for comparison of the clones only but not as absolute values. However, it is important to emphasize that both the macro-compression and the micro-tensile tests gave similar data, suggesting that factors other than the method or measurement errors contributed to these results, such as presence of tension wood, anatomical structure, chemical extractives and the cell walls of wood.

Radial changes of mechanical properties

Average values of mechanical properties for three different radial positions, referred to as age groups, are presented in *Table 2.7.* Each strength property reached its highest value at age group 1 (closest to the bark) and the lowest at age group 3 (nearest the pith) except maximum tensile strength, which seemed to be independent of sampling position. Comparing the differences of means between age groups, maximum bending strength increased from the pith through the middle position by 15% and from the middle position to the bark by 15%. Compression strength was not significantly different between positions near the pith and middle part, but then increased significantly from the middle position to the bark by 20%. In spite of the similar maximum tensile strengths observed radially, stiffness obtained in tensile test were increasing from pith to middle position, and from middle position to the bark, by 25% and 27% respectively.

Means for the mechanical properties of individual clones by age groups are presented in *Table 2.8.* The trend was the same as that for the overall averages described above. In particular, the strength of each clone was higher near the bark than in the middle or close to the pith, except for ultimate tensile strength of each clone, and for crushing strength of the Koltay. No significant differences were found between clones for any of the mechanical properties measured in the middle section. However, slight but significant differences occurred between clones close to the bark for bending strength, compression strength, and for stiffness in compression. The I-214 clone had a lower mean bending strength value than Kopecky and Koltay. For compression strength Kopecky had a higher mean than I-214 and Koltay. However, near the pith, the clones had slightly different values for stiffness in compression only. The Koltay clone had a higher mean stiffness value than I-214. These results suggest that clonal selections for specific gravity may be more efficient if the poplar plantations are older than about ten years.

Variation between and within trees

Analysis of variance using a nested model was conducted to check the interclonal variation and to obtain some information on heritability of mechanical characteristics. However, as mentioned earlier, the experiment was not designed for this purpose. Significant variation between clones could not be detected *(Table 2.9)*; furthermore, the tree-to-tree variations within clones were also non-significant. According to this analysis, most of the variations for strength properties occurred within individual trees; in particular, within tree variation accounted for approximately 80-100% of the total (phenotypic) variation.

Specific gravity - mechanical property relationship

In addition to determining some physical and mechanical characteristics of three poplar hybrid clones, an attempt was made to assess the relationship between these parameters as well. Specific gravity values of mechanical test specimens were calculated by averaging the specific gravities of those individual growth increment which partly or completely were included in the samples. Clonal means of specific gravities are shown in *Table 2.6* and the averages by age groups *Table 2.7.* In addition, means of clone specific gravities by age groups together with mechanical properties are presented in *Table 2.8* as well. Analysis of variance tests were also performed for specific gravity values obtained from the strength specimens *(Table 2.5, Table 2.9).*

Unlike bending, compression and tensile strength values, specific gravity exhibited significant clonal effect together with non-significant age effect suggesting that differences in specific gravity of clones did not result in differences in mechanical properties. Furthermore, specific gravity did not increase in radial direction with increasing years, but strength values increased significantly from pith to bark, except for maximum tensile strength. Comparing the outcome of the nested models, specific gravity was found to be under strong genetic control as the effect of clones accounted for more than 60% of the total variation but the strength properties exhibited the opposite trend.

Pearson correlation coefficients were calculated to determine the relationships between specific gravity and mechanical properties *(Table 2.10)*. Relating strength parameters to specific gravity, no significant correlations were found for bending and tensile strengths for both clonal and total values. Nevertheless, the Kopecky clone exhibited significant association between specific gravity and crushing strength (0.663) and compression modulus of elasticity (0.683). The Koltay clone exhibited a large correlation coefficient between specific gravity and compression modulus of elasticity. Because of this significantly large association, the r^2 value calculated on the whole data set also resulted in significant correlation (0.476). However, analyzing the three clones together, specific gravity did not correlate to crushing strength.

Modulus of elasticity had significant association with other strength properties. Therefore, estimation of strength from stiffness would be possible as indicated by relatively good r^2 values, such as 0.551 for modulus rupture, 0.788 for crushing strength and 0.628 for ultimate tensile strength. Significant correlation (0.366) was found between modulus of elasticity in compression and modulus of elasticity in tension indicating that technical or measurement error may not have caused the low values for this variable.

To summarize, specific gravity did not prove to be the most important single factor influencing strength properties of *Populus* clones. It can not be used to reliably predict mechanical behavior of these hybrids because of the absence of significant relationships and because the clones in some cases showed different associations. The three clones involved in this investigation belong to the low density diffuse porous hardwoods and their specific gravity range was very narrow (0.275 to 0.350). However, specific gravity values of the clones were significantly different. Non-significant clonal effect was detected for strength properties although the I-214 clone had lower mechanical property. However, the alleged superiority of the Koltay clone (Matyas 1986) was not seen. This may be due in part to the small sample size although the variances for mechanical properties were similar to those reported elsewhere (Wood Handbook 1989). Since the clones showed low mechanical properties, they are not recommended for solid wood structural applications but they are suitable for non-structural utilization and for composites.

The absence of association between specific gravity and strength property indicated the contribution of quality factors rather than quantity characteristics of cell wall to mechanical performance of poplar clones. For example, gelatinous fibers without pattern were found in each sample and may have affected strength properties. Slides made from the specimens were investigated under the microscope and based on visual estimates, gelatinous fiber content did not vary between clones but did vary within tree. It was higher near the pith than near the bark similar to the situation regarding the mechanical properties tested.

Based on this investigation and studies cited above, it can be concluded that in case of low specific gravity and/or narrow specific gravity range, the influence of specific gravity on strength properties seems to be less important than other factors. At high specific gravities, the differences in the amount of wood substance present and not the differences in its composition affect the strength properties. However, in the case of minimal substance at low specific gravity level, strength is not determined by the amount of cell wall material, but rather by factors reflecting the quality of cell wall, such as gelatinous fibers and fibril angle.

CONCLUSIONS

Conclusions from results of this study on interclonal and intraclonal variation of specific gravity in relation to variation of mechanical properties of three *Populus* clones planted in Hungary are as follows:

1. Analysis of variance for three poplar clones on two different sites indicated that site did not affect specific gravity; however, significant differences existed between clonal means. The highest specific gravity was found for Koltay, the lowest for I-214 while specific gravity of Kopecky was between them.

2. The effect of clones on specific gravity variation within Site 1 accounted for more than 50% of the phenotypic variation indicating strong genetic control on this property. No significant variation existed between trees within clones, but the within-tree variation was significant. This suggests that besides genetics, the age of the cambium influenced the specific gravity and not the environment.

3. Regarding modulus of rupture, crushing strength, maximum tensile strength and modulus of elasticity measured in tension, no significant clonal effect was found for the samples on Site 1. Strength values were low for each clone.

4. There were significant differences between age group means. The mechanical properties were higher near the bark than close to pith, except for ultimate tensile strength. Clonal means of strength properties were significantly different close to the bark, but they were not significantly different near the pith.

5. Based on nested analysis of variance for strength properties, no significant clonal and between tree (within clones) variations were tested. High within trees (between age groups) variation proved the importance of age of trees rather than clonal or environmental influences on mechanical properties of poplar clones.

6. No significant correlations were found between specific gravity and bending and tensile strengths of clones. However, the relationship was clonal specific in compression. Kopecky exhibited significant associations between specific gravity and both crushing strength and modulus of elasticity but the other two clones did not. Therefore, specific gravity did not prove to be the most important single factor influencing strength properties and can not be used to predict mechanical behavior of *Populus* clones.

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TABLES

Table 2.1. - Mean specific gravity values, and the coefficients of variations for the three clones on two sites.

CLONE		KOPECKY		I-214		KOLTAY	
SITE	gr (n)	mean	cv%	mean	cv%	mean	cv%
Specific gravity							
Site 1	14	0.343 **B**	7.2	0.304 **C**	7.4	0.353 **A**	6.8
	10	0.338 **B a**	7.3	0.305 **C a**	7.7	0.356 **A**	7.3
Site 2	10	0.348 **A a**	9.6	0.307 **B a**	11.2	-	-

Differences between clones within sites for cell wall area and for ray area are denoted by upper case letters. Differences between sites within clones for cell wall area and ray area are denoted by lower case letter. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

Table 2.2. - Analysis of variance results for site, clone, and their interaction effects on specific gravity of three poplar clones on two sites (N=300).

Source of variation	Df	Mean square (Type III)	F
Site	1	0.0018233	1.18
Clone	2	0.0643159	41.72**
Site x Clone	1	0.0009660	0.63
Tree (Site x Clone)	25	0.0015417	2.02**
R^2 = 45.4%			

** - Statistically significant at the 5% level.

* - Statistically significant at the 1% level.

Table 2.3. - Duncan's multiple range test for specific gravity of site (I.) and clonal (II.) means. Means with common letters are not significantly different at the 5% level.

I.

Site	**Site 1**	**Site 2**
Specific gravity	0.333 **A**	0.327 **A**

II.

Clone	**Kopecky**	**I-214**	**Koltay**
Specific gravity	0.343 **B**	0.306 **C**	0.356 **A**

** - Statistically significant at the 5% level.

* - Statistically significant at the 1% level.

Table 2.4. - Analysis of variance results of nested model for specific gravity of clones on Site 1, based on the first ten years data.

Source of variation	Df	Mean Square	F	Variance component	
Clone (among clones)	2	0.039682	40.73**	0.000645	(50.9%)
Tree (within clone)	15	0.000974	1.67	0.000039	(3.9%)
Error (within tree)	162	0.000582	-	0.000582	(46.0%)
Corrected total	179	0.001052	-	0.001266	(100.0%)

** - Statistically significant at the 1% level.

Table 2.5. - Analysis of variance results for mechanical properties and their specific gravities of three poplar clones.

Source of variation	Wood property								
	Df N=54	**Specific gravity** (bending, compression)	**Modulus of rupture**	**Crushing strength**	**Modulus of elasticity** (compression)	**Df** N=36	**Specific gravity** (tension)	**Maximum tensile strength**	**Modulus of elasticity** (tension)
Clone	2	**	NS	NS	*	2	**	NS	NS
Tree(Clone) (Error I.)	15	NS	**	*	*	9	NS	NS	NS
Age	2	NS	**	**	**	2	NS	NS	**
Clone x Age	4	**	*	**	*	4	*	NS	NS
R^2 [%]	-	85.6	92.4	78.8	74.4	-	87.0	46.4	84.1

** - Statistically significant at the 1% level.
* - Statistically significant at the 5% level.
NS - Not significant at the 5% level.

Table 2.6. - Mean mechanical properties and their specific gravities with the coefficients of variations for three poplar clones.

Property	Clone					
	KOPECKY		I-214		KOLTAY	
	mean	cv%	mean	cv%	mean	cv%
Specific gravity (bending, compression)	0.336 B	16.0	0.304 C	5.2	0.352 A	5.5
Modulus of rupture [kPa]	30,383 A	14.0	26,062 B	10.1	29,597 AB	10.3
Crushing strength [kPa]	11,709 A	14.7	11,903 A	13.6	12,337 A	11.1
Modulus of elasticity (compression) [MPa]	1,537 A	21.4	1,208 B	16.0	1,488 A	23.7
Specific gravity (tension)	0.340 A	5.0	0.293 B	8.1	0.346 A	6.0
Maximum tensile strength [kPa]	33,170 A	40.8	27,148 A	23.9	30,102 A	42.9
Modulus of elasticity (tension) [MPa]	1,774 A	20.5	1,527 A	18.0	1,746 A	23.9

Differences among clones for each property are denoted by upper case letters. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

Table 2.7. - Mean mechanical properties and their specific gravities with the coefficients of variations for radial positions of the clones.

Property	**Radial position from bark to pith**					
	Age group 1. Ring No: 8-13(bc), 11(t)		**Age group 2.** Ring No: 5-7(bc), 7(t)		**Age group 3.** Ring No: 2-4(bc), 3(t)	
	mean	cv%	mean	cv%	mean	cv%
Specific gravity (bending, compression)	0.330 **AB**	7.8	0.326 **B**	9.2	0.336 **A**	10.5
Modulus of rupture (b) [kPa]	33,437 **A**	12.5	28,432 **B**	15.8	24,174 **C**	11.2
Crushing strength (c) [kPa]	13,766 **A**	8.8	11,182 **B**	16.9	10,862 **B**	17.4
Modulus of elasticity (compression) [MPa]	1,649 **A**	23.4	1,307 **B**	22.9	1,267 **B**	25.9
Specific gravity (tension)	0.335 **A**	7.1	0.324 **A**	10.3	0.322 **A**	11.4
Maximum tensile strength (t) [kPa]	32,295 **A**	41.1	30,142 **A**	33.8	27,984 **A**	31.1
Modulus of elasticity (tension) [MPa]	2,199 **A**	21.5	1,645 **B**	20.8	1,204 **C**	23.5

Differences among age groups for each property are denoted by upper case letters. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

Table 2.8. - Mean mechanical properties and their specific gravities with the coefficients of variations for radial positions of each clone.

Property	Clone	Radial position from bark to pith					
		Age group 1. Ring No: 8-13(bc), 11(t)		Age group 2. Ring No: 5-7(bc), 7(t)		Age group 3. Ring No: 2-4(bc, 3(t)	
		mean	cv%	mean	cv%	mean	cv%
Specific gravity (bending, compression)	Kopecky	0.346 **A a**	4.5	0.333 **AB b**	3.1	0.329 **B b**	3.6
	Koltay	0.345 **B a**	3.0	0.348 **AB a**	1.9	0.363 **A a**	5.5
	I-214	0.298 **A b**	5.6	0.298 **A c**	4.2	0.317 **A b**	5.5
Modulus of rupture (b) [kPa]	Kopecky	36,727 **A a**	7.6	29,886 **B a**	18.5	24,537 **C a**	16.4
	Koltay	33,872 **A a**	9.0	30,147 **A a**	11.5	24,773 **B a**	10.2
	I-214	29,711 **A b**	11.7	25,264 **B a**	11.0	23,210 **B a**	4.2
Crushing strength (c) [kPa]	Kopecky	14,852 **A a**	8.5	10,369 **B a**	22.4	9,907 **B a**	13.9
	Koltay	13,575 **A b**	5.7	11,355 **B a**	13.6	12,029 **AB a**	14.1
	I-214	12,870 **A b**	4.4	11,821 **A a**	14.7	10,840 **A a**	20.1
Modulus of elasticity (compression)[MPa]	Kopecky	1,951 **A a**	18.2	1,415 **B a**	29.0	1,244 **Bab**	13.7
	Koltay	1,605 **Aab**	22.2	1,331 **A a**	20.7	1,534 **A a**	27.8
	I-214	1,392 **A b**	17.2	1,174 **AB a**	13.7	1,027 **B b**	14.6
Specific gravity (tension)	Kopecky	0.355 **A a**	5.2	0.340 **AB a**	1.3	0.326 **B a**	3.9
	Koltay	0.334 **Aab**	3.8	0.348 **A a**	2.5	0.357 **A a**	8.8
	I-214	0.315 **A b**	7.6	0.282 **B b**	7.5	0.283 **B b**	3.0
Maximum tensile strength (t) [kPa]	Kopecky	37,023 **A a**	46.6	32,731 **A a**	38.8	29,757 **A a**	31.9
	Koltay	33.730 **A a**	44.7	31,339 **A a**	37.8	25,237 **A a**	45.4
	I-214	26,133 **A a**	23.2	26,355 **A a**	26.7	28,957 **A a**	21.7
Modulus of elasticity (tension) [MPa]	Kopecky	2,234 **A a**	14.4	1,767 **AB a**	19.7	1,321 **B a**	31.3
	Koltay	2,452 **A a**	25.2	1,770 **B a**	19.6	1,017 **C a**	14.7
	I-214	1,910 **A a**	19.2	1,398 **B a**	18.2	1,272 **B a**	13.1

Differences among age groups within clone for each property are denoted by upper case letters. Differences among clones within age group for each property are denoted by lower case letter. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

Table 2.9. - Analysis of variance results of nested model for mechanical properties and their specific gravities of three poplar clones on Site 1.

Source of variation	Wood property								
	Df N=54	Specific gravity (bending, compression)	Modulus of rupture	Crushing strength	Modulus of elasticity (compression)	Df N=36	Specific gravity (tension)	Maximum tensile strength	Modulus of elasticity (tension)
Clone (among clones)	2	** (69.9%)$^+$	NS (12.2%)$^+$	NS -	* (15.7%)$^+$	2	** (65.4%)$^+$	NS -	NS (0.6%)$^+$
Tree (within clone)	15	NS (1.8%)	NS -	NS -	NS (3.8%)	9	NS (0.7%)	NS (14.2%)	NS -
Error (within tree)	36	(87.8%)	(87.8%)	(100%)	(80.5%)	24	(33.9%)	(85.8%)	(99.4%)

** - Statistically significant at the 1% level.

* - Statistically significant at the 5% level.

NS - Not significant at the 5% level.

( ) - Percent of the total variation.

$^+$ - Variance components x 10^2= R (repeatability)

Table 2.10. - Pearson correlation coefficients between mechanical properties and specific gravity based on the total data set (bottom left) and separately for each clone (top right).

Property	Clone	Specific gravity (bending, compression)	Modulus of rupture	Crushing strength	Modulus of elasticity (compression)	Maximum tensile strength	Modulus of elasticity (tension)	Specific gravity (tension)
Specific gravity (bending, compression)	Kopecky I-214 Koltay	1	0.357 -0.238 -0.304	0.663** -0.122 0.185	0.683** -0.253 0.500*	-	-	-
Modulus of rupture	Kopecky I-214 Koltay	0.235	1	0.597** 0.605** 0.215	0.595** 0.876** 0.058	-0.003 -0.102 0.056	0.564 0.607* 0.542	-
Crushing strength	Kopecky I-214 Koltay	0.223	0.480**	1	0.931** 0.769** 0.807**	0.108 -0.229 0.491	0.510 0.051 0.472	-
Modulus of elasticity (compression)	Kopecky I-214 Koltay	0.476**	0.551**	0.788**	1	0.040 -0.141 0.398	0.434 0.493 0.183	-
Maximum tensile strength	Kopecky I-214 Koltay	-	0.048	0.145	0.225	1	0.635* 0.368 0.684*	0.323 -0.356 0.092
Modulus of elasticity (tension)	Kopecky I-214 Koltay	-	0.558**	0.361*	0.366*	0.628**	1	0.323 0.107 -0.325
Specific gravity (tension)	Kopecky I-214 Koltay	-	-	-	-	0.100	0.134	1

*) Statistically significant at the 5% level.

**) Statistically significant at the 1% level.

FIGURES

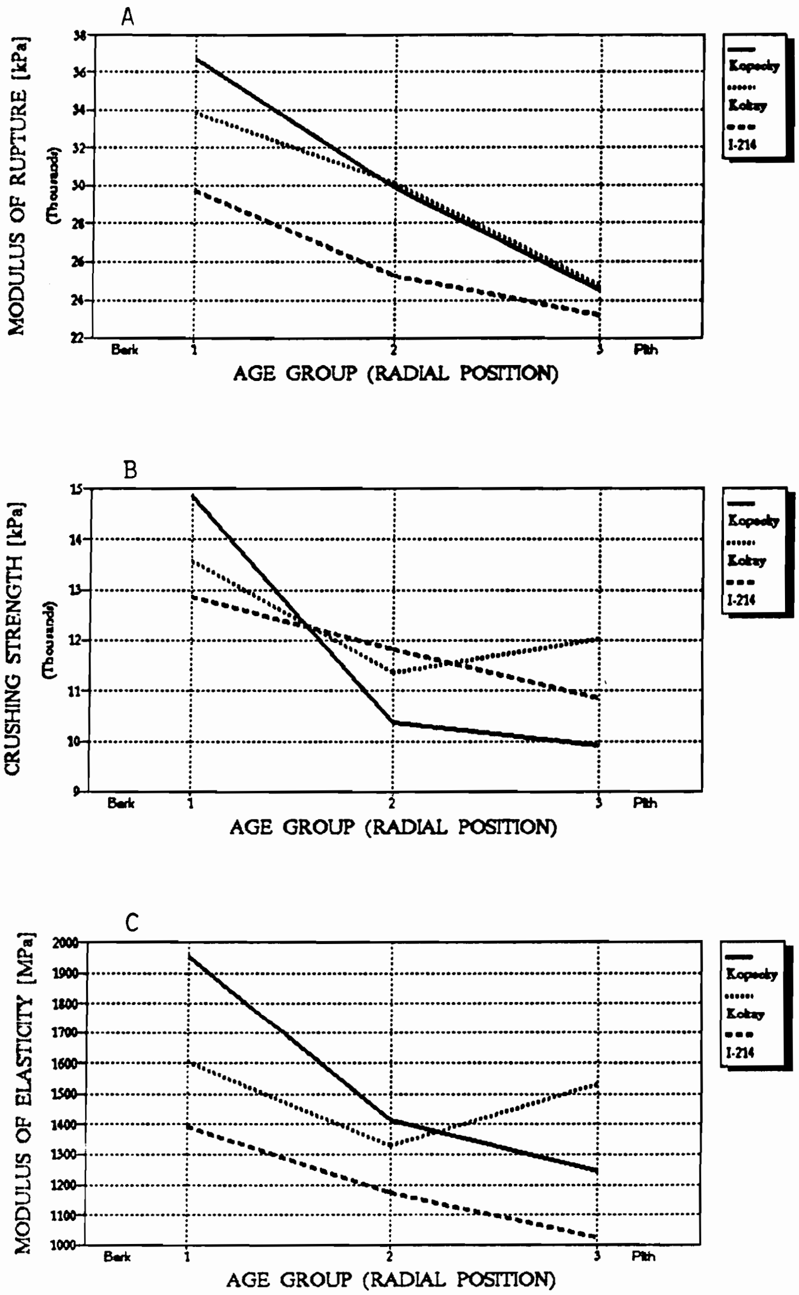

Figure 2.1. - Clone x radial position interaction for modulus of rupture (A), for crushing strength (B), and for modulus of elasticity (C) of the three poplar clones on Site 1.

SECTION 3.

Influence of Age and Growth Rate on Selected Anatomical and Physical Properties of *Populus x euramericana* Clones.

ABSTRACT

Clones investigated belong to the *Populus x euramericana* (Dode) Guinier hybrid group: the Italian I-214 and the Hungarian Kopecky and Koltay. Six trees from each clone were sampled at two sites in Hungary. The plantations were 15 years old and 10 years old. Disks were removed at breast height from each tree to examine the effect of age on variation of anatomical properties and specific gravity and the relation of these properties to growth rate. Along the eastern radius transverse microtome sections and specific gravity specimens were prepared from each growth ring.

Age had significant effect on growth rate, specific gravity, and on anatomical characteristics. Ring width increased in the first few years, then decreased toward the bark. Differences between clones were significant in the first few years and in the "good" years only. Specific gravity was high near the pith then each clone exhibited different radial patterns.

Anatomical properties along the radius showed a rapid change first, followed by a decreasing rate of change, finally a flat response for each clone on both sites. Segmented regression analyses of a quadratic model with plateau were conducted on the anatomical properties to estimate the demarcation between juvenile and mature periods. The maturation process was affected by site. The better site accelerated the maturation but with lower matured values. The ages of demarcation were not the same for all properties; however, the order of the maturation were the same on both sites. Fiber length and vessel lumen area were the last to become constant.

No consistent relationship were found between growth rate and specific gravity and between growth rate and anatomical properties when growth rings of the same age were compared.

INTRODUCTIONN

Environmental and genetic control of wood quality has been extensively studied over the years. The amount and distribution of genetic and environmental variations can be assessed at different levels. Evidently, variation among genera and species are present, but tree breeders are mostly interested in the category of variations that exist within species, such as the geographic (provenance) variation, site variation within provenances, stand variation within sites, variation among individual trees within stands, and variation among clones and within individual trees.

As Larson (1967) stated: "more variability in wood characteristics exists within a single tree than among trees growing on the same site or between trees growing on different sites. These patterns must be understood; they are always present and are hard to eliminate."

The presence of juvenile wood and its relative proportion to mature wood seem to be the most important causes of wood variation among trees. It is usually much more evident in conifers than in hardwoods. The juvenile wood concept has been widely studied and its direct relationship to the age of the cambium is accepted by many investigators (Paul 1960; Zobel and Kellison 1972; Pearson and Gilmore 1980; Zobel and Talbert 1984; Zobel and van Buijtenen 1989).

Due to improvements in forest management and genetics, accelerated growth may result in trees of a harvestable size at younger age and with a greater percentage of juvenile wood than wood produced by natural stands (Zobel et al. 1978; Bendtsen 1978). From a utilization standpoint, the principal interest is in the effects of age and growth rate on wood properties of trees from plantations.

Populus spp. and their hybrids are especially fast-growing, genetically improved and vegetatively propagated species. They have been planted extensively in the north temperate regions (Wright 1976). In Hungary, forest improvement has also been concentrated on these fast-growing broadleaved species. Nine percent of the forested area and more than twenty percent of the annual cut is represented by poplar hybrids (Molnar et al. 1990).

The objective of this study was to characterize the within tree variation of selected anatomical properties and specific gravity in radial direction as a result of age and growth rate effects.

LITERATURE REVIEW

Influence of tree age

Wood properties vary within trees, not only from the base to the top of a tree, but also from the pith to the bark. Properties of wood within the juvenile zone are characterized by rapid changes from the pith outward. In the mature zone, nearly all wood properties are much more constant. Literature regarding the radial pattern in wood properties is numerous and also controversial. Considering juvenile-mature wood relationship, changes of characteristics are not the same for all properties.

Specific gravity

There are several radial patterns of specific gravity in the hardwoods. It seems that the middle to high density diffuse-porous hardwoods generally have an increase in specific gravity from inside toward the bark. However, the low density diffuse-porous hardwoods, such as *Populus spp.*, have slightly higher density near the pith, decrease substantionally a short distance from the pith, then increase again in the mature wood zone after about 15th ring (Einspahr et al. 1972; Yanchuk et al. 1983, 1984). Some clones may have no change in wood density along the radius.

By comparison, Wheeler (1987) reported that ring-porous hardwoods tended to have a high density near the pith, which decreased and then increased to some extent outward, caused by changes in fiber wall thickness.

For *Populus*, Curro (1960), Gohre (1960), and Valentine (1962) found that the major portion of radial variation in specific gravity was related to distance from the pith. However, wood close to the cambium was more dense than near the pith but the correlation between juvenile and mature wood was weak, making early prediction of specific gravity unreliable (Farmer and Wilcox 1966). Blankenhorn et al. (1988) also reported that specific gravity decreased with increasing age of the wood.

In a study of 4 years old hybrid poplars, Murphey et al. (1979) reported no significant differences in specific gravity among years. Low level of association between specific gravity of juvenile and mature wood was found by Onilude (1982) investigating plantation grown cottonwood. Similarly, Bendtsen and Senft (1986) observed that the change in specific gravity with age was not very pronounced, accounting for only about a 10% increase from early juvenile to late mature wood in cottonwood. Investigating the relationship between specific gravity and age in quaking aspen, Ross et al. (1990) reported that specific gravity exhibited only a 15% difference between juvenile and mature wood.

Anatomical properties

Scaramuzzi (1958) found very little variability in the volume fraction of the different types of longitudinal anatomical elements across the radius of *Populus x euramericana clones* with ray volume showing the most variation. According to Isebrands (1972), percent of vessels increased but percent of fibers decreased with increasing age in eastern cottonwood. Cheng and Bensend (1979), Onilude (1982) and Kroll et al. (1992) all concluded that the vessels produced by the cambium during the mature age of trees were significantly larger and less numerous than those laid down during the juvenile years for poplar clones, cottonwood and balsam poplar, respectively.

Regarding fiber characteristics, Onilude (1982) found a slight trend of increasing fiber lumen area fraction and decreasing fiber wall area fraction and number of fibers per unit area. Nagai et al. (1984) for several hardwood and Bendtsen and Senft (1986) for eastern cottonwood reported that from pith to bark, fibril angle decreased rapidly to the 15-20th annual ring, and then remained fairly constant.

Cell length in poplars was observed as having a rapid increase in the first 10 to 20 years followed by a leveling off (Scaramuzzi 1955; Boyce and Kaiser 1961).

Nevertheless, increase of fiber length from the pith to the bark was reported by several investigators (Inokuma et al. 1956; Marton et al. 1968; Holt and Murphey 1978; Murphey et al. 1979; Cheng and Bensend 1979; Yanchuk et al. 1984).

In *Populus spp.* the percentage of ray cells is small since the rays are uniseriate. Uniform pattern of ray cells across the radius was observed by Cheng and Bensend (1979) for poplar clones and by Onilude (1982) for plantation grown cottonwood.

In general, radial variation in wood properties other than specific gravity was described by Zobel and van Buijtenen (1989) as confusing because many patterns could exist. But it is worth noting that site quality determines the variation patterns for each species. Fiber length shows the most consistency with usual increase from pith to bark.

Effect of growth rate

Any association between growth rate and wood properties depends on species, on sites and on how growth rate is expressed; namely, height, diameter, basal area or volume of a tree. Growth rate is commonly expressed by ring width. According to Larson (1972), anything that influences crown development, and thus the growth rate, may influence wood characteristics too.

Specific gravity

Bentsen (1978) in a study on rapid-grown plantation wood stated that wood from plantations had lower specific gravity and lower mechanical properties than those from the earlier generation natural forests. The same result was reported by Boone and Chudnoff (1972) as well as by Bower et al. (1976). However, it is conceivable that this effect was due to higher percentage of juvenile wood rather than to changes in anatomical properties. In a recent study of specific gravity and mechanical property - age relationship in red pine, Shepard and Shottafer (1992) observed equal to or greater wood property values for both juvenile and mature periods in two plantations than those for natural stands.

For diffuse-porous hardwoods, the effect of growth rate on wood properties appears complex and often controversial despite the very widespread interest and investigation over the years. No definite relationship was found between growth rate and specific gravity (Brown et al. 1949; Wangard 1950; Lamb 1968) or only minimal effect was reported (Panshin et al. 1964; Kazumi 1983). In *Populus*, the same pattern was stated by Gohre (1960), Einspahr and Benson (1967), Guiher (1968), and Marton et al. (1968). Nevertheless, Kennedy and Smith (1959) reported an increase in specific gravity with faster growth while negative correlation was found in most of the studies (Farmer and Wilcox 1966; Mutibaric 1967; Yanchuk et al. 1984; Jefferson and Yanchuk 1985; Beaudoin et al. 1992).

Anatomical properties

Investigations of wood properties other than specific gravity led to contradictory results. In general, no change has been found in fiber and tracheid length with increased radial growth, and no effect or slightly longer fibers and tracheids with increased height growth. For *Populus*, no change in proportion of wood elements with growth rate was reported by Scaramuzzi (1958) while Kennedy and Smith (1959) found longer fibers with faster growth due to the better sites. Yanchuk et al. (1983; 1984) also mentioned slightly positive correlation between fiber length and growth rate. However, Marton et al. (1968) observed negative but non-significant correlation between diameter growth and fiber length investigating poplar hybrids.

Similar arguments have been promoted among researchers. A serious and common cause of misinterpretation of the relationship between growth rate and wood properties is when the age of the cambium, as represented by the number of growth rings from the center, is ignored. It must be emphasized, that not the ring width but the age of the cambium at the time of the formation of growth increment is of key importance (Hiley 1955; Nicholls and Fielding 1964; Panshin et al. 1964; Larson 1969; Zobel and van Buijtenen 1989).

MATERIAL AND METHODS

Three *Populus x euramericana* (Dode) Guinier clones were collected from two different sites in Hungary. Fifteen years old plantations of three clone, the Italian I-214 and the Hungarian Kopecky and Koltay, were investigated in Daka (Site 1). However, only Kopecky and I-214 were available in Zalavar (Site 2) and the plantations were ten years old. Site 2 is considered more favorable for poplars because of its more evenly distributed rainfall and reduced extremes in temperature.

Six trees were randomly selected for this study from each clone in each site and tree height and diameter at breast height were recorded (*Table 3-1*). From each tree, disks about 100mm thick were cut at breast height. In order to avoid the effect of the prevailing wind, which may caused tension wood, transverse sections with a width of approximately 40mm were taken in the east-west direction. Each growth increment was measured and recorded together any visible defects.

For **anatomical measurements** transverse microtomed sections (20 μm) from each growth ring were prepared (Sass 1958). After staining with safranin and fast green to distinguish the normal fibers from the gelatinous fibers, anatomical characteristics from the mounted slides were measured using an image analyzer (IMAGE1, Universal Imaging Corporation 1990). One region from the early, three from the middle, and one from the late part of each growth increment were randomly selected for analyses. Vessel lumen diameter, vessel lumen area percentage, fiber lumen diameter, fiber lumen area percentage related to fiber wall area percentage, ray cell area percentage, and total cell wall area percentage were evaluated. Average of five measurements on each growth ring were used for further analysis.

Macerated materials were prepared to determine fiber length of the clones. Hydrogen peroxide of 30% and glacial acetic acid mixture with ratio of 1:1 were used to macerate thin wood sticks from each growth ring (Franklin 1945). After washing and staining the fibers, temporary slides were prepared for analysis with the image analysis system. Thirty-five unbroken cells were measured from each growth ring and their averages by growth increments were used for further analysis.

Specific gravity specimens were obtained from the same segments from which the microtome sections and the macerated material were cut. Rectangular strips were cut with thickness and width of about 5mm and with length of the whole radius, and then they were divided into specimens of growth increments using a razor blades. The maximum moisture content method (Smith 1954) was used to determine specific gravity of these small specimens. Five samples were measured from each growth ring and their averages were used for further analysis.

STATISTICAL ANALYSIS

Clonal and age effects

Analysis of variance was carried out on the data with significance given at the 95% probability level ($\alpha=0.05$) (SAS Institute Inc. 1985). For growth ring width, specific gravity, and anatomical properties the following statistical model was applied to evaluate the effects of clone and age:

$$Y_{jkln} = \mu + \beta_j + \gamma_{k(j)} + \delta_l + (\beta \times \delta)_{jl} + \epsilon_{jkln}$$

Where Y_{jkln} = property of interest,
μ = population mean,
β_j = effect of clone,
$\gamma_{k(j)}$ = effect of tree within clone,
δ_l = effect of age,
$(\beta \times \delta)_{jl}$ = clone x age interaction effect,
ϵ_{jkln} = random error, unexplained variation.

Type III mean square of between tree variation was specified as error term to test whether clone affected the measured properties significantly, and for the Duncan's procedure to compare clonal and age means (Hinkelmann 1992, personal correspondence).

Model of maturation

Each variable was plotted against age as the number of growth rings from the pith to the bark. The data showed the same pattern, first a rapid increase or decrease, followed by a levelling off and then a more or less constant value. Therefore, segmented regression analyses were conducted to describe the relation between the measured properties and age. Quadratic model with plateau was fitted to the data for each variable to estimate the perceptible point where the association between the two variables changed; in other words, to find the approximate age of demarcation between juvenile and mature periods. The segmented regressions were carried out by nonlinear regression techniques using the following theoretical approach:

$$Y = a + bx + cx^2 \quad \text{if } x \prec x_0$$
$$Y = p \quad \text{if } x \succ x_0$$

Where Y = property of interest,
x = age (number of growth rings from pith to the bark,
x_0 = age of demarcation,
a,b,c = parameters,
p = plateau.

Thus, for ages less than the critical age (x_0) the equation relating the measured properties to age is quadratic (parabola), and for ages greater than x_0, the equation is constant (horizontal line). Procedure of SAS NLIN (SAS Institute Inc. 1985) can fit such segmented model even when the joint point (x_0) is unknown.

Growth rate - property relationship

Pearson correlation coefficients were calculated between growth rate and the measured properties to test their relationships (Kleinbaum et al. 1988). Growth rate was expressed as tree height and diameter as well as growth ring width. Values of the two variables were always plotted against each other to test whether or not there are other than linear relationships between properties.

Each analysis was applied on data sets of the two sites separately. Assumptions based on the results of statistical analyses for one site were validated by results obtained from the other site.

RESULTS AND DISCUSSION

Tree parameters

Height and diameter at breast height of each sample tree are presented in *Table 3.1*. Regarding mean values from Site 1, Koltay had significantly higher height and diameter than Kopecky and I-214. Kopecky and I-214 exhibited similar average tree parameters on Site 2. Unfortunately no comparison could be made for Koltay because it was not available on Site 2. Clones on Site 1 had larger breast height diameters than those in Site 2 but significant difference was found only for Kopecky.

Means of tree heights were similar for Kopecky on both sites, while I-214 showed an even higher average value on Site 2 than on Site 1. This occurred in spite of the fact that the plantation on Site 2 was younger (10 years old) than on Site 1 (15 years old). Since height growth is strongly affected by environmental factors, Site 2 proved to be more favorable for these clones (Matyas 1983).

Investigating the three clones, Koltay on Site 1 and I-214 on Site 2 exhibited higher rate of growth, as represented by height and breast height diameter of the individual trees, than the other two clones. Nevertheless, when growth is the primary goal of a clonal selection, maximum production of stand per unit area should be considered rather than that of an individual tree because they are not identical (Matyas 1983). The largest tree should not be selected but that tree which utilizes growing space, light, and nutrients most effectively. In other words, trees with the best growth in relation to their leaf surface areas produce the greatest volume per hectare.

Growth ring width

Assessing wood properties, growth rate is usually expressed by ring width. *Table 3.2* contains the clonal averages of growth rate. Means of clones, based on the first ten growth rings, ranged from 7.9 mm to 10.0 mm on the two sites. On Site 1, the average yearly increment was lower based on 14 rings than that for the first 10 rings. Koltay had significantly wider growth rings with a mean value of 9.8 mm than I-214 with only 8.0 mm but did not differ significantly from Kopecky (8.7 mm). On Site 2, I-214 had significantly higher mean (10.0 mm) than Kopecky (7.9 mm).

Comparing clones from different sites, Kopecky showed similar ring widths in both sites (8.7 mm and 7.9 mm) but I-214 produced wider rings in Site 2 (10.0 mm) than in Site 1 (8.0 mm).

Effect of age on wood properties

Analysis of variance procedures were conducted to test the effect of clones and age on growth increments, specific gravity and selected anatomical properties of clones for the two sites separately. Results are compiled in *Table 3.3*. Regarding trees from Site 1, significant clonal effects were observed on specific gravity, fiber lumen area, ray area, and cell wall area. Age, referred to as ring number from pith to bark, affected each variable significantly. On Site 1, effect of age explained most of the total variations for ring width (79%), vessel lumen diameter (79%), vessel lumen area (59%), fiber lumen diameter (61%), fiber length (76%), and for ray area percent (52%). However, only a small percentage of the total variations was explained by age effect for specific gravity (18%), fiber lumen area (10%), and for cell wall area percent (27%). With regard to the effect of age, a similar trend was found for the variables measured on Site 2; nevertheless, ring width, specific gravity, and ray area percent significantly.

The hypothesis that there are no significant clone x age interaction effects was not rejected regarding fiber lumen area percentage and fiber length on Site 1, and for all variables except ring width and ray area on Site 2.

Radial changes of wood properties

Radial changes of wood properties involved in this investigation are depicted in *Figure 3.1 - 3.9* where clonal averages of six sample trees for each growth ring are showed from pith to bark.

Figure 3.1 presents the radial changes of **growth ring widths**. After the first few years, the clones responded similarly to climatic changes on Site 1. From the pith, the width of growth rings increased in the first 3-5 years then decreased toward the bark. Differences were significant in the first few years before canopy closure, and the "good" years only. The order of the clonal means became stable after the juvenile years (about 10 years). An increase of ring width during the first few years and then a subsequent decrease were detected from sample trees from Site 2 as well. However, there was no difference between clones during the first few years but after that I-214 produced wider rings than Kopecky.

Analyzing the radial variations in **specific gravity** of trees from Site 1, after the first three years Koltay became stable, I-214 exhibited slight fluctuation with the lowest values among clones. However, Kopecky was not stable, its specific gravity increased toward the bark *(Figure 3.2)*. Regarding specific gravity on Site 2, lower values were detected for I-214 than for Kopecky. The tendency of radial changes was not as obvious as on Site 1 possibly due to the younger age of the plantation.

The selected **anatomical properties** of the clones showed the same radial trends for both sites, that is a rapid increase or decrease, followed by a leveling off and then a more or less constant value *(Figure 3.3 - 3.9)*. Therefore, a segmented regression analysis was applied to describe the relationship between age as the independent variable and anatomical properties as dependent variables. A quadratic model with plateau was fitted to the observed data points of the clones from both sites to estimate the demarcation between juvenile and mature periods. An example of fitting the quadratic model with plateau on the data set is given in *Figure 3.10* for vessel lumen diameter. Segmented analysis fitting two straight lines on observed data points of wood properties proved useful in other studies (Ross et al. 1990; Shepard and Shottafer 1992). They estimated the maturation point where the data sets on juvenile and mature wood phases were separated by visual estimation. Regarding the value of this methods in determining the transition point (TP) and the point of maturation (POM), there is some disagreement among researchers (Bendtsen and Senft 1986; Senft et al. 1986). However, in this investigation on radial changes of anatomical parameters a quadratic curve with a plateau was a better fit for the data.

Results of the segmented regression analysis are presented in *Table 3.4* for Site 1 and Site 2, respectively. The estimated demarcation ages were not identical for all anatomical properties. However, the maturation order of properties was the same in both sites while the maturation ages were lower for sample trees from Site 2 than for those from Site 1. Fitting of the described segmented regressions was successful for for each property on both sites except for ray area percentage on Site 1.

First, the fiber lumen area percent became constant at ages of approximately 4-5 years on Site 1 and 3-4 years on Site 2; then cell wall area percent, fiber lumen diameter, and vessel lumen diameter became stable around 8-10 years on Site 1 and 4-6 years on Site 2. Finally, fiber length and vessel lumen area reached the maturation periods at the estimated ages of 12-13 years and 9-10 years for Site 1 and Site 2, respectively.

Not only did the maturation period of the clones start earlier on Site 2 but the matured values of the anatomical parameters were also lower. The results indicate that site influenced the maturation of these properties. The better site accelerated the maturation process and decreased the matured values for anatomical properties involved in this investigation. However, the order of the maturations of different anatomical traits were the same in both sites. This result indicates the influence of physiology on the maturation of the anatomical properties during the development of the stem and the crown.

Distribution of anatomical elements

Fractional area percentages of cell wall, vessel lumen, fiber lumen, and ray area along the radius from pith outward are illustrated in *Figure 3.11.* Cross sectional distribution of anatomical elements did not change much as the trees matured. However, a slight (8%) decrease in cell wall area percent was detected from the pith to the bark on both sites. It is apparent that these poplar clones had large cell lumens with thin cell walls. Less than 30% of the total cross sectional area was occupied by cell wall material.

Effect of growth rate on wood properties

Association between growth rate and wood properties is of practical importance to the tree breeders. Their objective is to achieve the highest yield of quality wood. However, this relationship is very complex, depending on several factors, such as species, sites, cause and measurement of growth rate. In general, growth rate and wood properties are not always directly related. The physiological stimulus generated by changes in the environment in which the tree grows and results in the differences in this growth (Zobel and van Buijtenen 1989).

Tree height and diameter growth:

Tree averages of specific gravity and selected anatomical properties were related to growth rate expressed as tree height and tree diameter at breast height *(Table 3.5).* Pearson correlation coefficients were calculated for each pair of variables to test whether there is a linear relationship between them. Furthermore, variables were plotted against each other to check the presence of non-linear association. Correlation analyses were carried out for the two sites separately to avoid the influence of age differences between plantations.

Based on this investigation, **tree diameter** had statistically significant positive correlation to vessel lumen diameter (0.816) only for Kopecky on Site 1. In other words, vessel lumen diameter increased with tree diameter. Ray area percent also showed significant correlation for the Koltay clone on Site 1 (0.820) and for the Kopecky clone on Site 2 (0.827). The other pairs of variables exhibited either positive or negative but not significant correlations.

Relating wood properties to **tree height**, statistically significant negative correlations were found for fiber length (-0.842) of Koltay on Site 1, and for vessel lumen area (-0.858) and fiber length (-0.961) for Kopecky on Site 2. Nevertheless, no general trends could be noted concerning the correlations between the other variables at the various levels. It can be concluded that sites and clones affected the relationships between growth characters of trees and the selected wood properties.

Every pattern occurred, such as positive, negative or no relationship between tree height and diameter growth and properties measured. Therefore, the controversy over the effect of growth rate on wood properties with regard to hardwoods was substantiated by this study as well.

Growth ring width:

Separate correlation analyses were conducted on growth rate as expressed by growth ring width and on the measured wood characteristics *(Table 3.6)* for both sites. Relationships between ring width and **specific gravity** were different for the three clones on Site 1. Kopecky exhibited significant negative correlation (-0.403); meanwhile, I-214 and Koltay did not demonstrate association between the two variables. On Site 2 both Kopecky and I-214 exhibited a significant negative relationship to growth rate. However, these results were opposite to those found for tree diameter growth where higher although not significant positive correlations were detected *(Table 3.5).*

Regarding **anatomical properties**, more or less similar trends were found for each clone, such as negative correlations between ring width and vessel lumen diameter, vessel lumen areas, fiber lumen diameter and fiber length; positive correlations between ring width and ray and cell wall area; and no correlations for ring width and fiber lumen area on Site 1. Similar associations were detected on Site 2, except that ring width correlated positively to fiber lumen diameter and negatively to cell wall area. The trends found here did not correspond to those observed for tree diameter growth.

The question may be asked, which methods show properly the relationship between wood properties and growth rate? Regarding tree parameters, the correlations may show the real relationships because trees of the same age were involved. However, the analysis resulted in non-significant correlation coefficients probably because of the small sample size. Only six trees from each clone on each site were involved in this calculation.

On the other hand, the results of the correlation analysis between growth ring width and the various wood properties did not show a true association because the influence of the age of the rings was ignored. The correlation coefficient reflected the tendency of the changes in ring width and in the properties with age; therefore, it can be misleading. Ring width is generally reduced as the tree ages. That is why the basal area of the tree is the real measure of growth rate. Basal area becomes larger as the square of the radius of the tree. Nevertheless, growth rate is commonly expressed by ring width; thus, comparisons must be done between ring widths of the same age to avoid incorrect assessment of the effect of growth rate (Zobel and van Buijtenen 1989).

Therefore, an adjusted correlation analysis was performed on wood properties of these poplar clones. The influence of age of the growth increment was taken into account by relating growth rate as ring width to specific gravity and anatomical characteristics of rings which were produced at the same age of the cambium. The correlation coefficients between ring width and wood properties of a specific growth ring were inconsistent and mainly non-significant. This can be partly explained by the few number of observations because the calculations were made on only six trees for each ring of each clone on both sites.

Based on this study, no consistent and significant relationships between growth rate, as defined by either tree parameters or growth ring width, and wood characteristics measured existed for the three poplar clones on two sites. This result suggested that growth rate may be increased without influencing specific gravity and the anatomical properties of poplar clones. However, the age of the cambium has an influence on wood properties which has to be considered in decisions on rotation age and on clonal selection because variation in wood properties were higher within a tree than among the clones.

CONCLUSIONS

The following conclusions were reached on the basis of results obtained through the analysis on influence of age and growth rate on selected wood properties of three poplar clones from two sites in Hungary:

1. Variation in wood properties measured within trees, from pith to bark were statistically significant. Age had a significant effect on growth ring width, specific gravity and anatomical characteristics.

2. Ring widths increased in the first few years, then decreased toward the bark. Differences between clones were significant in the first few years and in the "good" years only. Furthermore, their order seemed to stabilize after ten years which has to be considered when selecting clone for growth rate.

3. Specific gravities of the three clones were high at the pith then each exhibited different radial patterns. After the first three years, Koltay clone became constant. So did I-214 but with slight fluctuation of the lowest values. However, the specific gravities of Kopecky increased toward the bark.

4. Along the radius, anatomical properties at first showed a rapid change, followed by a decreasing rate of change, and finally a flat response. Segmented regression analysis fitting a quadratic model with a plateau proved useful to estimate the demarcation between juvenile and mature periods of anatomical characters.

5. Maturation process of anatomical properties were affected by site. The better site accelerated the maturation but with lower matured values. The ages of demarcation were not the same for all properties; however, the order of the maturation were the same in both sites indicating the influence of tree physiology on the aging process. Among the measured anatomical properties, fiber length and vessel lumen area were the last to become constant at the estimated ages of 10-13 years on Site 1 and 9-10 years on Site 2.

6. Distribution of cross sectional area of cell wall, vessel and fiber lumen, and ray area exhibited only slight changes along the radius. Vessel and fiber lumen area increased approximately 8% from pith to bark.

7. No consistent relationship was found between growth rate (expressed by either tree height, tree diameter or growth ring width) and wood properties of the three clones from two sites.

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TABLES

Table 3.1. - Characteristics of poplar clone sample trees.

SITE	Code of tree	Clone					
		KOPECKY		I-214		KOLTAY	
		DBH [cm]	Height [m]	DBH [cm]	Height [m]	DBH [cm]	Height [m]
Site 1. (Daka) Age: 15 years	0	30.0	18.4	28.0	17.7	29.0	19.7
	1	27.8	16.3	29.0	16.2	33.0	20.7
	2	24.0	17.9	21.3	13.5	28.0	19.4
	3	23.5	16.7	22.0	15.5	30.5	18.5
	4	26.5	18.4	27.8	17.7	34.5	19.7
	5	29.5	18.9	22.0	18.0	31.0	19.5
	Mean cv%	**26.9 B a** 10.2	**17.8 B a** 5.9	**25.0 B a** 14.3	**16.4 B b** 10.5	**31.0 A** 7.8	**19.6 A** 3.6
Site 2. (Zalavar) Age: 10 years	0	16.2	16.6	24.5	18.8	-	-
	1	20.3	19.8	22.0	17.0	-	-
	2	22.5	19.6	19.2	18.1	-	-
	3	15.5	15.6	24.3	18.9	-	-
	4	23.7	18.9	24.7	18.7	-	-
	5	16.8	16.6	19.5	18.0	-	-
	Mean cv%	**19.2 A b** 18.2	**17.9 A a** 10.1	**22.4 A a** 11.3	**18.3 A a** 3.9	- -	- -

Differences among clones within site for DBH and height are denoted by upper case letters. Differences between sites within clone for DBH and height are denoted by lower case letters. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

Table 3.2. - Mean growth ring width, and the coefficients of variations for the three clones on two sites.

SITE	Growth ring (n)	CLONE					
		KOPECKY		I-214		KOLTAY	
		mean	cv%	mean	cv%	mean	cv%
Growth ring width [mm]							
Site 1	14	7.1 **AB**	56.0	6.7 **B**	51.7	8.1 **A**	53.3
	10	8.7 **ABa**	40.5	8.0 **B b**	41.4	9.8 **A**	41.0
Site 2	10	7.9 **B a**	49.1	10.0 **A a**	41.7	-	-

Differences between clones within sites for growth ring width are denoted by upper case letters. Differences between sites within clones for growth ring width are denoted by lower case letter. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

Table 3.3. - Analysis of variance results for growth ring width, specific gravity, and anatomical properties of clones on each of the two sites.

Source of variations	Df	Property								
		Growth ring width	Specific gravity	Vessel lumen diameter	Vessel lumen area	Fiber lumen diameter	Fiber lumen area	Fiber length	Ray area	Cell wall area
Site 1 (N=252)										
Clone	2	NS	**	NS	NS	NS	**	NS	*	**
Tree(Clone) (Error I.)	15	**	**	**	**	**	**	**	**	**
Age	13	** (79%)	** (18%)	** (79%)	** (59%)	** (61%)	** (10%)	** (76%)	** (52%)	** (27%)
Clone x Age	26	**	**	**	**	*	NS	NS	*	**
R^2 [%]	-	91.3	79.5	93.3	79.7	84.6	64.8	92.4	72.4	66.2
Site 2 (N=120)										
Clone	1	*	**	NS	NS	NS	NS	NS	*	NS
Tree(Clone) (Error I.)	10	**	**	NS	**	**	**	**	NS	**
Age	9	** (72%)	** (27%)	** (64%)	** (67%)	** (68%)	** (30%)	** (91%)	** (74%)	** (45%)
Clone x Age	9	**	NS	NS	NS	NS	NS	NS	**	NS
R^2 [%]	-	90.2	80.2	70.1	82.2	84.9	79.8	94.5	82.3	80.9

** - Statistically significant at the 1% level.
* - Statistically significant at the 5% level.
NS - Not significant at the 5% level.
( ) - Percent of variation explained by the effect of age.

Table 3.4. - Results of the non-linear segmented analysis of a quadratic model ($Y=a+bx+cx^2$) with plateau ($Y=p$) for an estimate of the maturation age (x_0) for anatomical properties of clones on each of the two sites.

Estimated parameter	Property						
	Vessel lumen diameter	Vessel lumen area	Fiber lumen diameter	Fiber lumen area	Fiber length	Ray area	Cell wall area
Site 1 (N=252)							
a	49.5299	25.1869	12.4881	48.8808	0.7167	The model was not applicable (The Jacobian was singular).	37.0945
b	9.0010	1.8965	1.0496	2.4324	0.0920		- 1.8236
c	- 0.4689	- 0.0758	- 0.0552	- 0.2801	- 0.0038		0.1050
x_0	9.60	12.51	9.50	4.34	12.01		8.68
p	92.73	37.05	17.47	54.16	1.27		29.17
Site 2 (N=120)							
a	43.8792	18.3348	9.7310	40.8797	0.6212	12.6923	45.87
b	12.4093	2.7997	2.6430	10.2031	0.1245	- 1.1634	- 7.0911
c	- 0.9938	- 0.1407	- 0.2636	- 1.5436	- 0.0065	0.0578	0.7581
x_0	6.24	9.95	5.01	3.30	9.52	10.07	4.68
p	82.62	32.26	16.36	57.74	1.21	6.84	29.29

Table 3.5. - Pearson correlation coefficients between tree growth parameters and selected wood properties of the three clones on each of the two sites.

Tree growth parameters	Clone	Property							
		Specific gravity	Vessel lumen diameter	Vessel lumen area	Fiber lumen diameter	Fiber lumen area	Fiber length	Ray area	Cell wall area
Site 1									
Breast height diameter	Kopecky	0.599	0.816*	-0.353	-0.112	-0.483	0.542	0.218	0.622
	I-214	0.126	0.434	0.026	0.455	0.057	-0.356	0.050	-0.076
	Koltay	0.534	-0.575	0.303	-0.313	0.307	-0.458	0.820*	-0.643
Height	Kopecky	0.404	0.683	-0.123	0.327	0.242	0.125	0.624	-0.152
	I-214	-0.161	0.743	-0.139	0.536	0.482	0.579	-0.632	-0.447
	Koltay	0.043	-0.534	0.766	-0.510	-0.400	-0.842*	0.363	-0.137
Site 2									
Breast height diameter	Kopecky	0.334	-0.011	-0.776	0.523	0.534	-0.769	0.827**	-0.359
	I-214	0.049	0.132	-0.290	-0.694	-0.457	-0.157	0.233	0.513
Height	Kopecky	0.394	-0.260	-0.858*	0.112	0.214	-0.961**	0.668	0.020
	I-214	-0.441	-0.197	0.202	-0.168	0.231	0.664	-0.568	-0.272

** - Statistically significant at the 1% level.

* - Statistically significant at the 5% level.

Table 3.6. - Person correlation coefficients between growth ring width and selected wood properties of the three clones on each of the two sites.

Growth rate	Clone	Property							
		Specific gravity	Vessel lumen diameter	Vessel lumen area	Fiber lumen diameter	Fiber lumen area	Fiber length	Ray area	Cell wall area
Site 1									
Growth ring width	Kopecky	-0.403**	-0.357**	-0.583**	-0.348**	0.022	-0.614**	0.489	0.214*
	I-214	-0.032	-0.223*	-0.404**	-0.184	0.140	-0.253*	0.387	0.098
	Koltay	0.144	-0.498**	-0.640**	-0.395**	0.155	-0.590**	0.591	0.349**
Site 2									
Growth ring width	Kopecky	-0.368**	-0.167	-0.604**	0.064	0.379**	-0.553**	0.434**	-0.160
	I-214	-0.429**	-0.031	-0.334**	0.187	0.196	-0.145	0.283*	-0.051

** - Statistically significant at the 1% level.
* - Statistically significant at the 5% level.

FIGURES

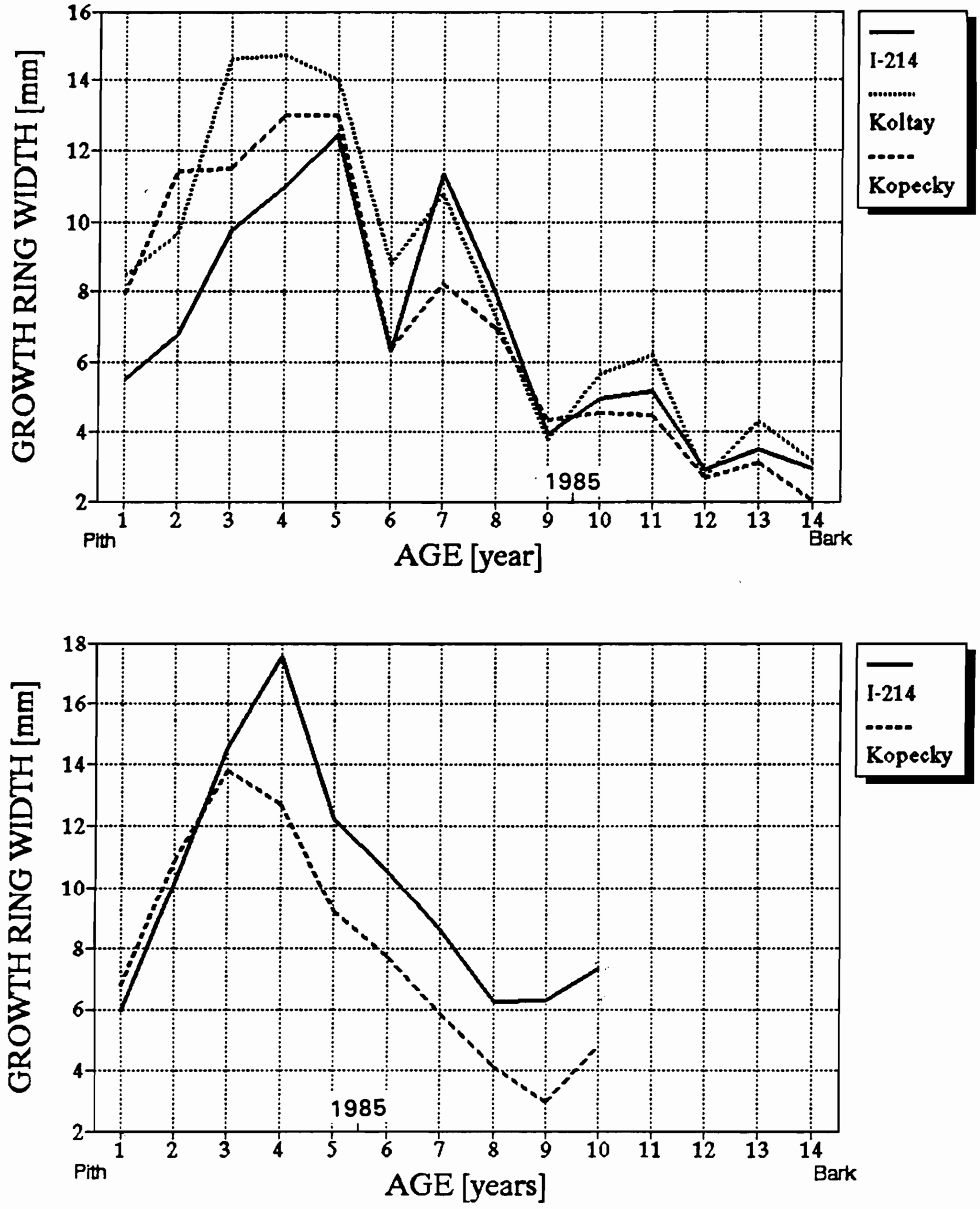


Figure 3.1. - Radial changes of growth ring width. Top: for three clones on Site 1 (15 years old). Bottom: for two clones on Site 2 (10 years old).

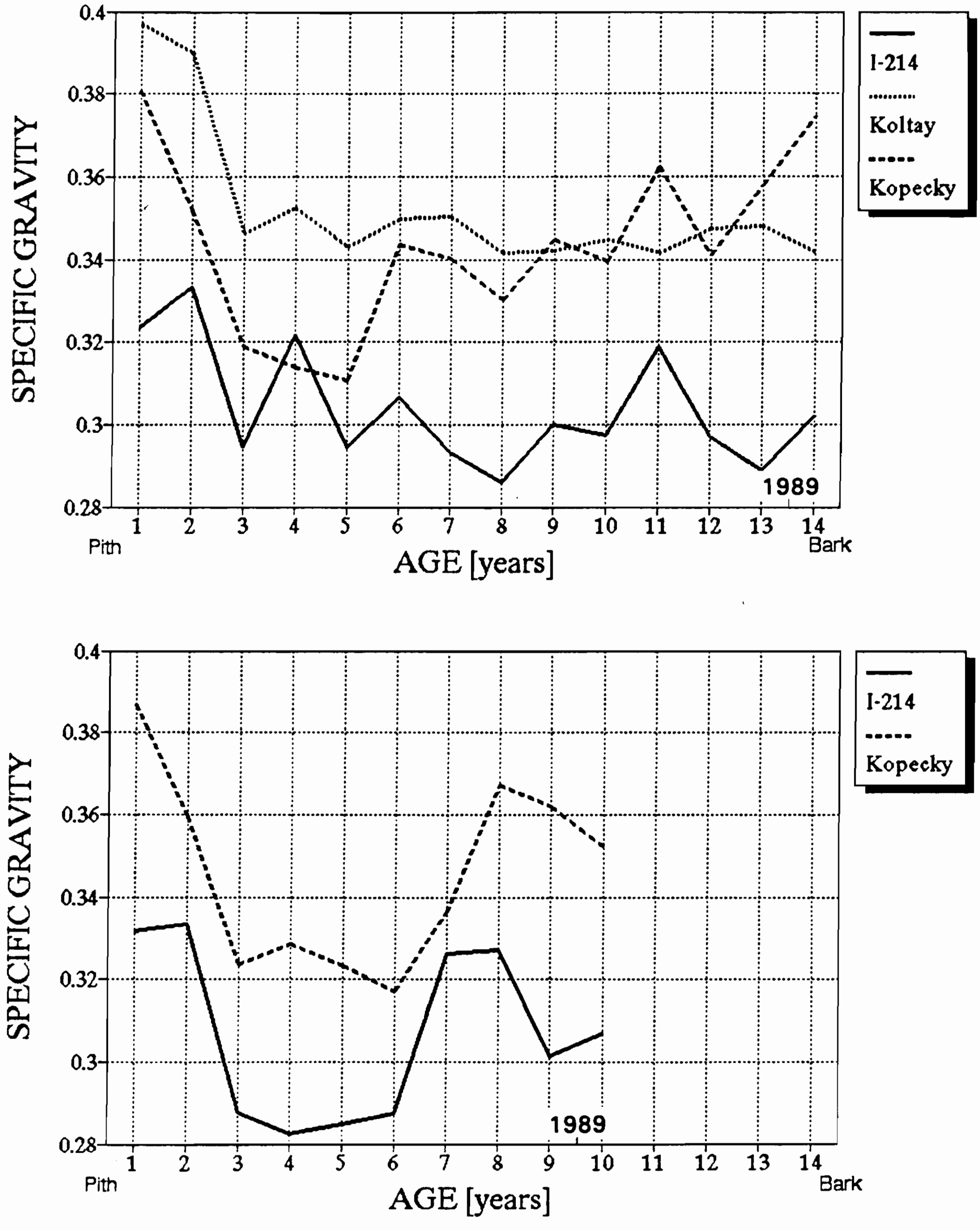
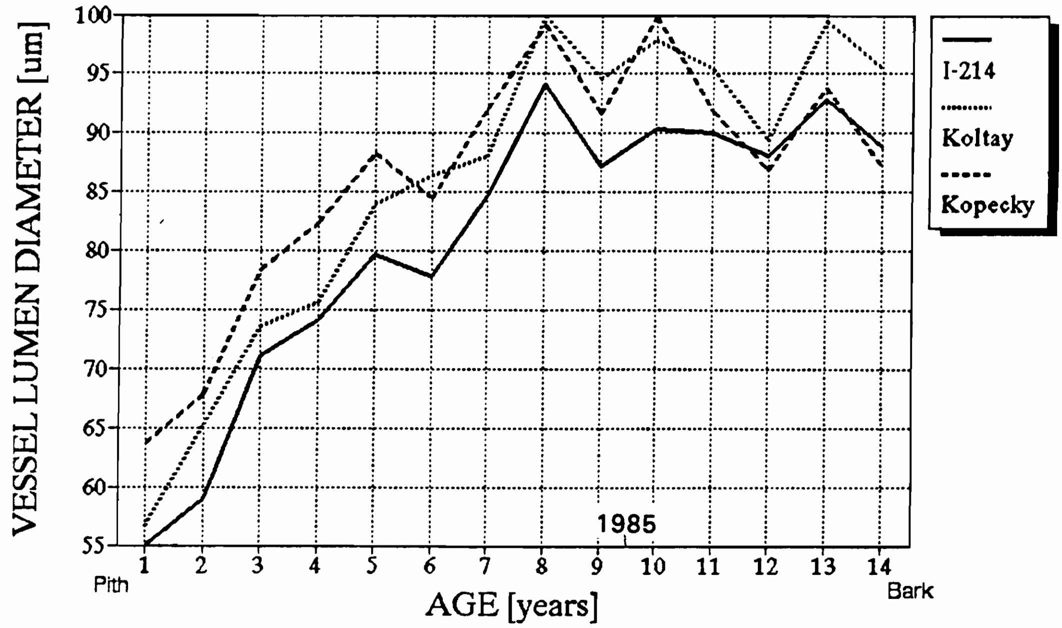


Figure 3.2. - Radial changes of specific gravity. Top: for three clone on Site 1 (15 years old). Bottom: for two clones on Site 2 (10 years old).



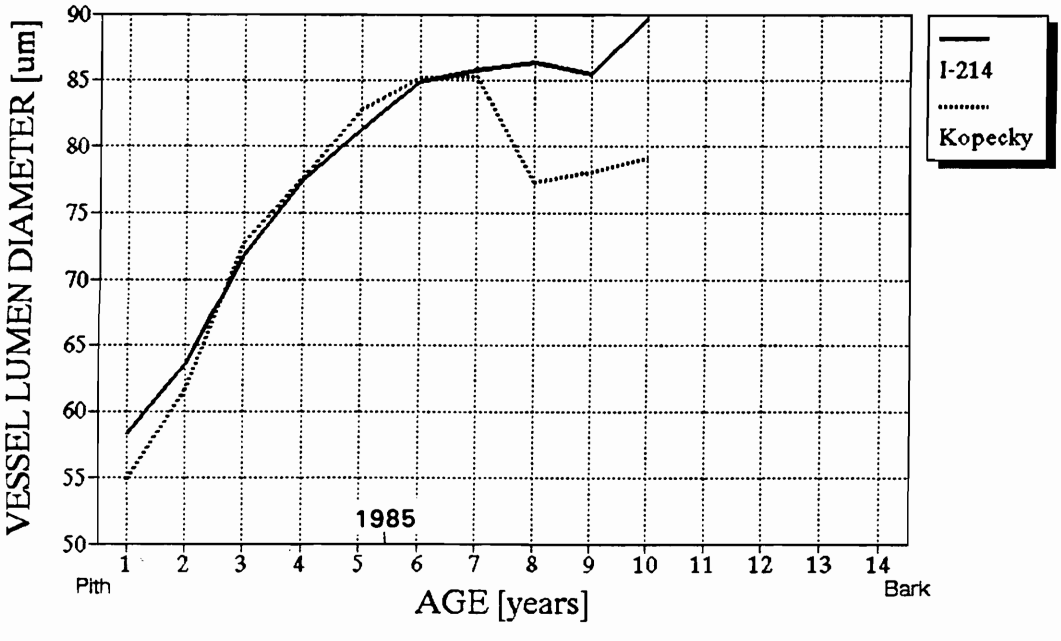
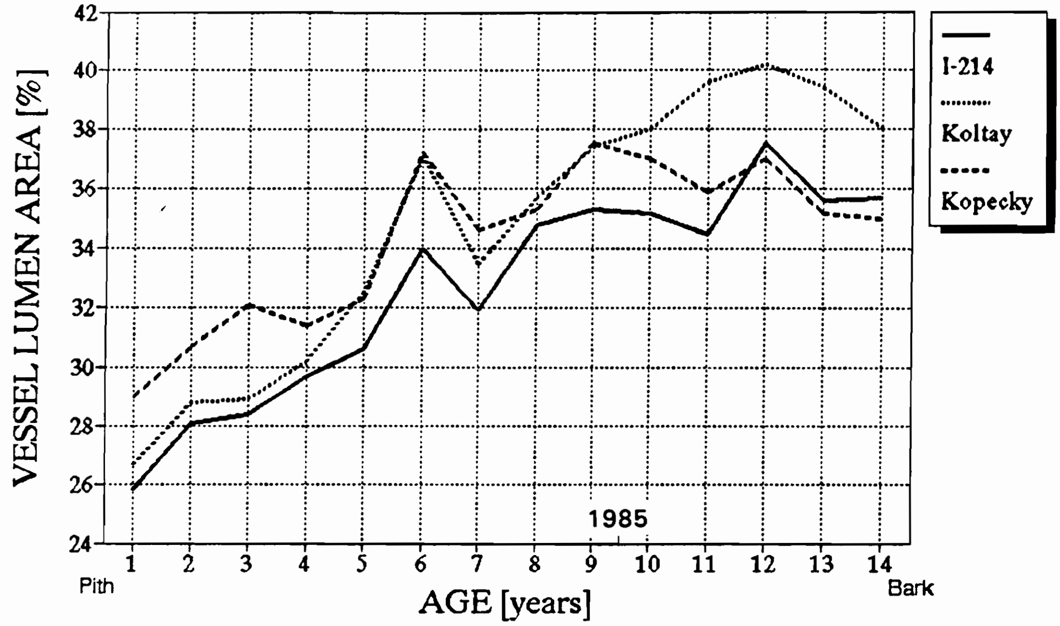


Figure 3.3. - Radial changes of vessel lumen diameter. Top: for three clones on Site 1 (15 years old). Bottom: for two clones on Site 2 (10 years old).



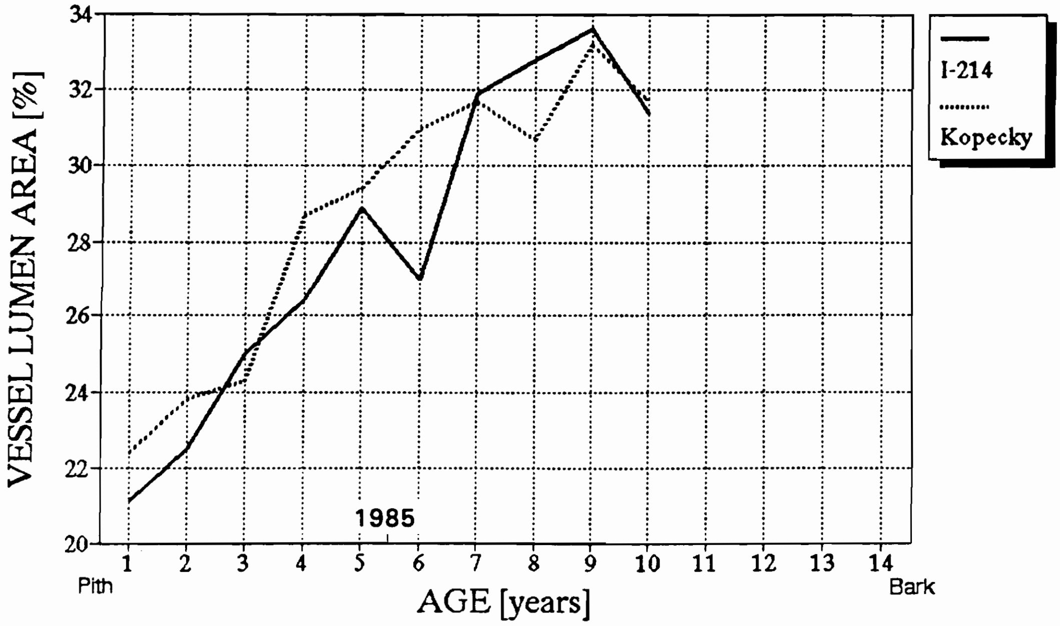
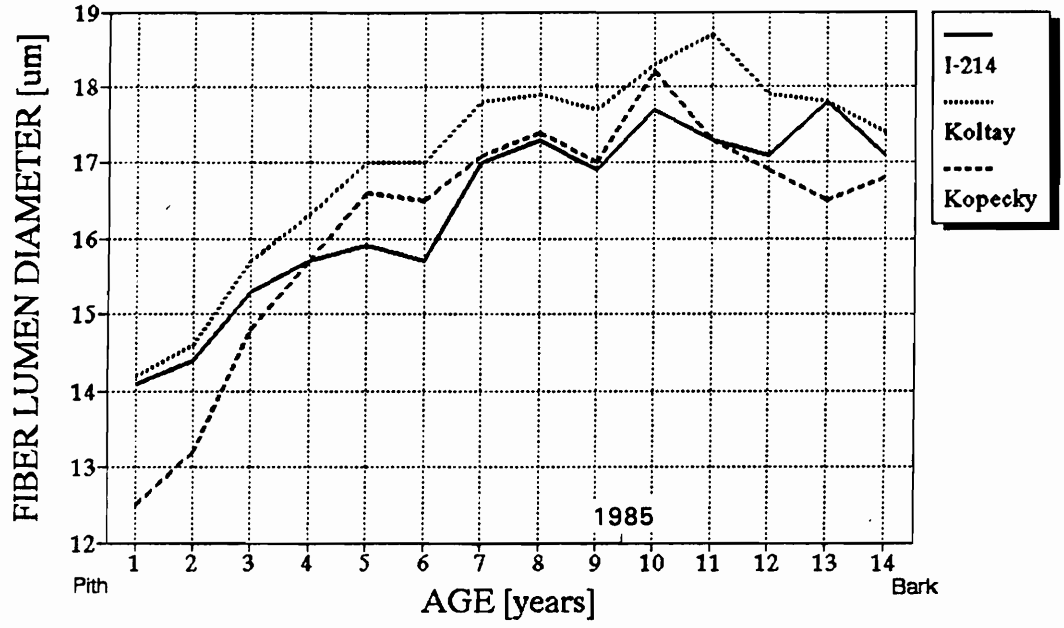


Figure 3.4. - Radial changes of vessel lumen area. Top: for three clones on Site 1 (15 years old). Bottom: for two clones on Site 2 (10 years old).



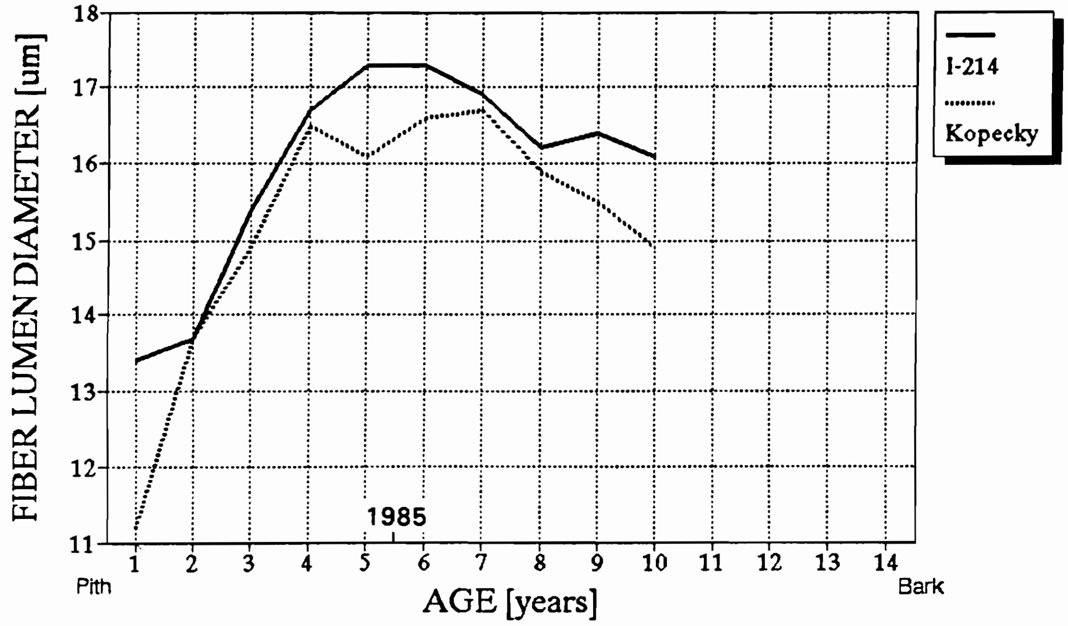
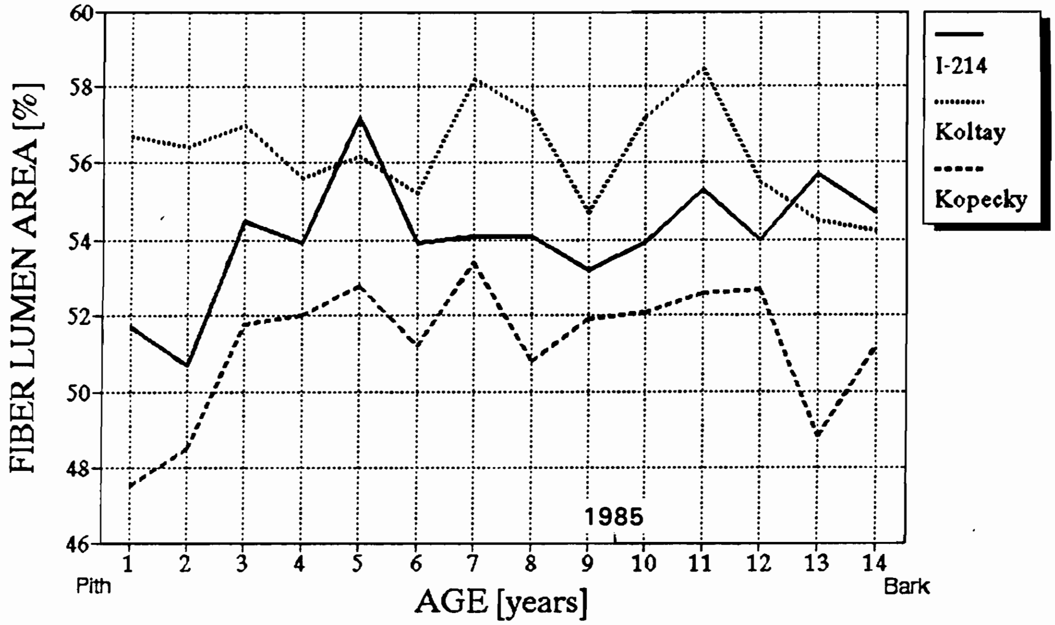


Figure 3.5. - Radial changes of fiber lumen diameter. Top: for three clones on Site 1 (15 years old). Bottom: for two clones on Site 2 (10 years old).



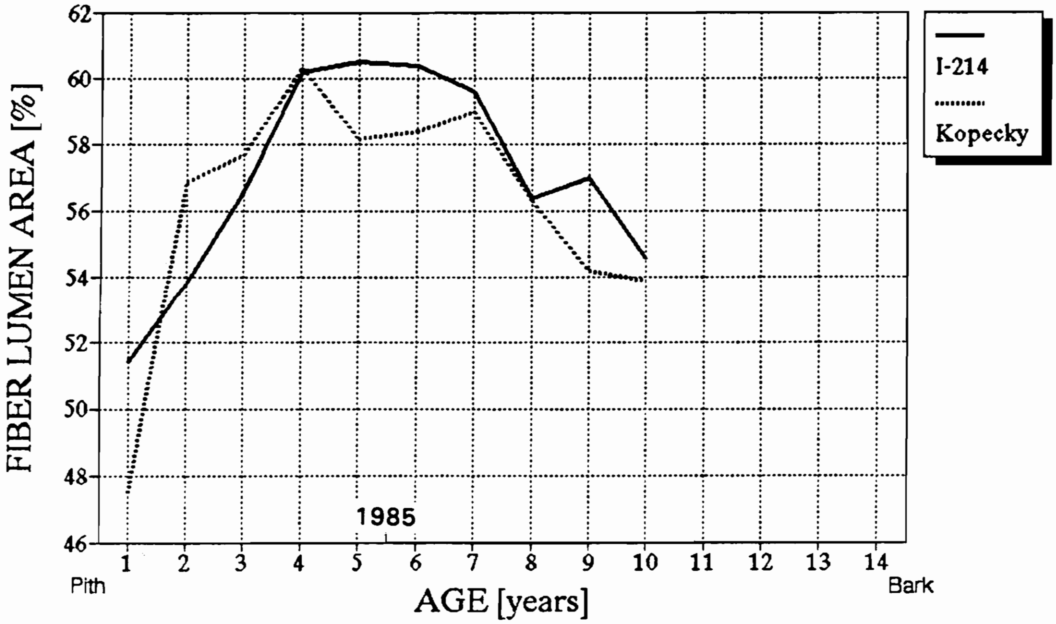


Figure 3.6. - Radial changes of fiber lumen area. Top: for three clones on Site 1 (15 years old). Bottom: for two clones on Site 2 (10 years old).

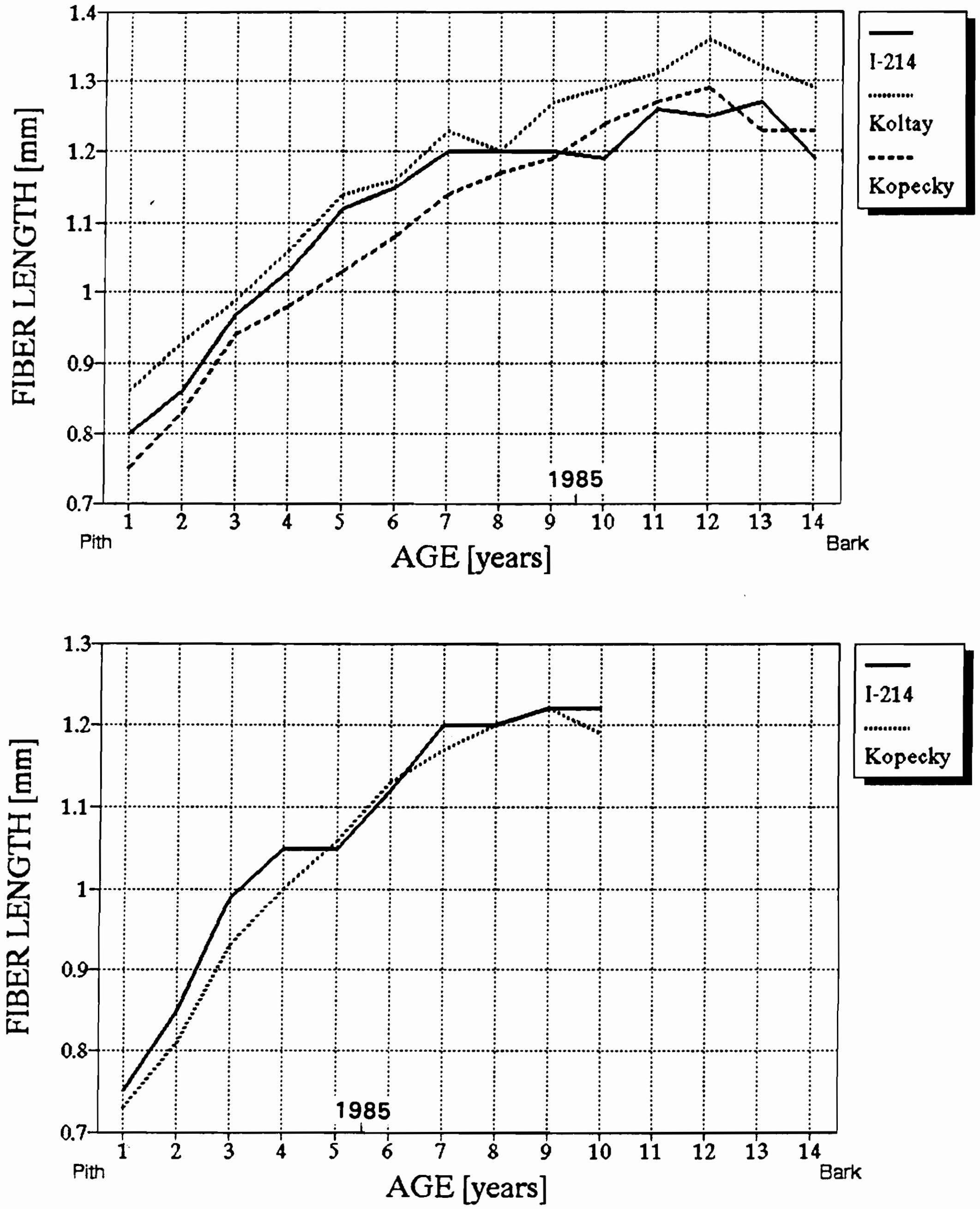
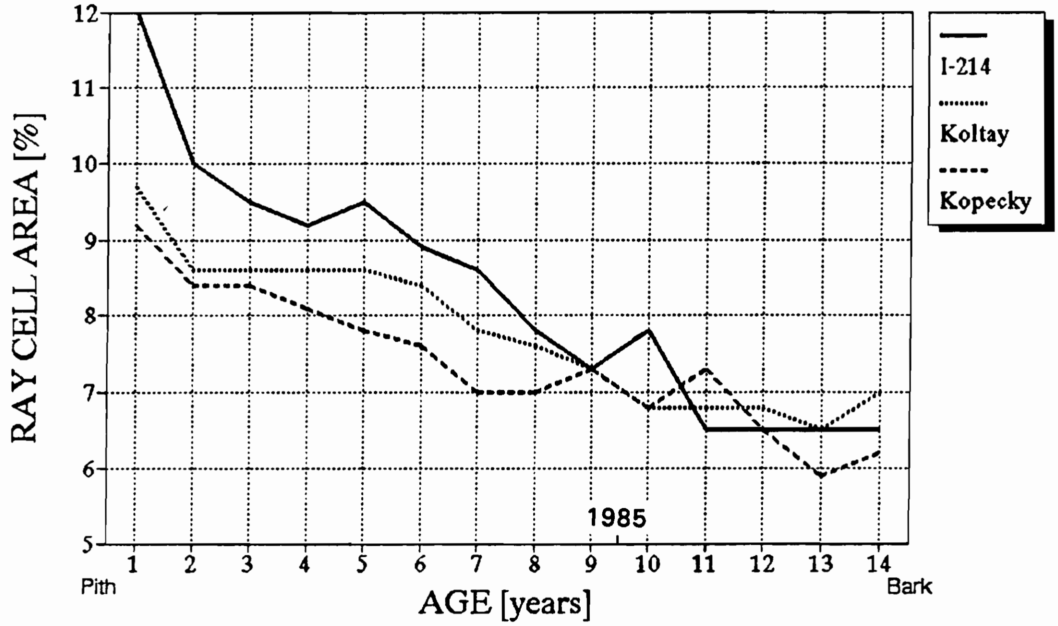


Figure 3.7. - Radial changes of fiber length. Top: for three clones on Site 1 (15 years old). Bottom: for two clones on Site 2 (10 years old).



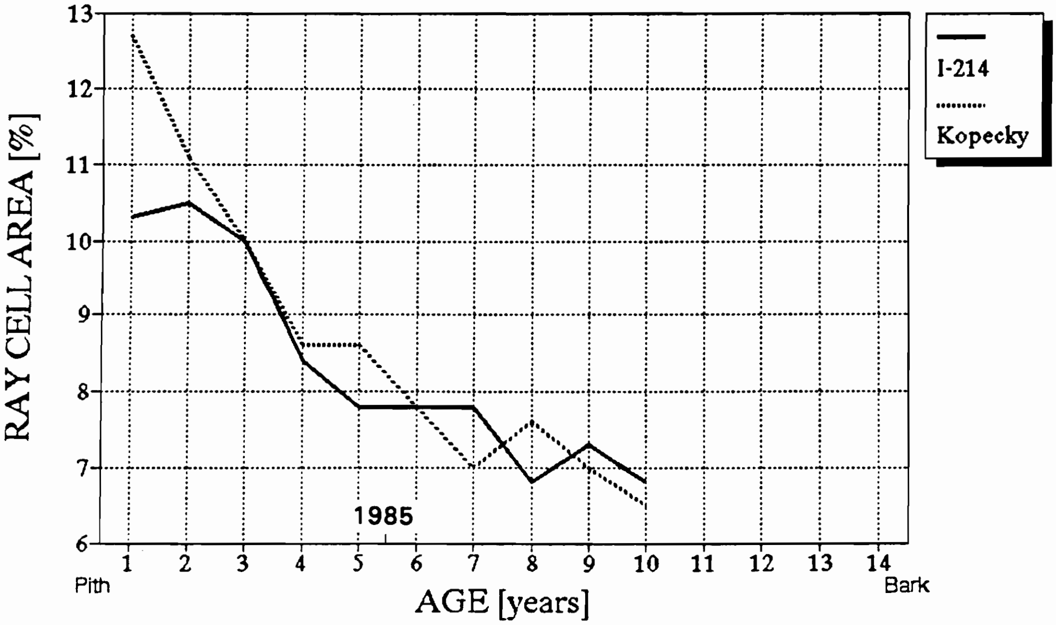
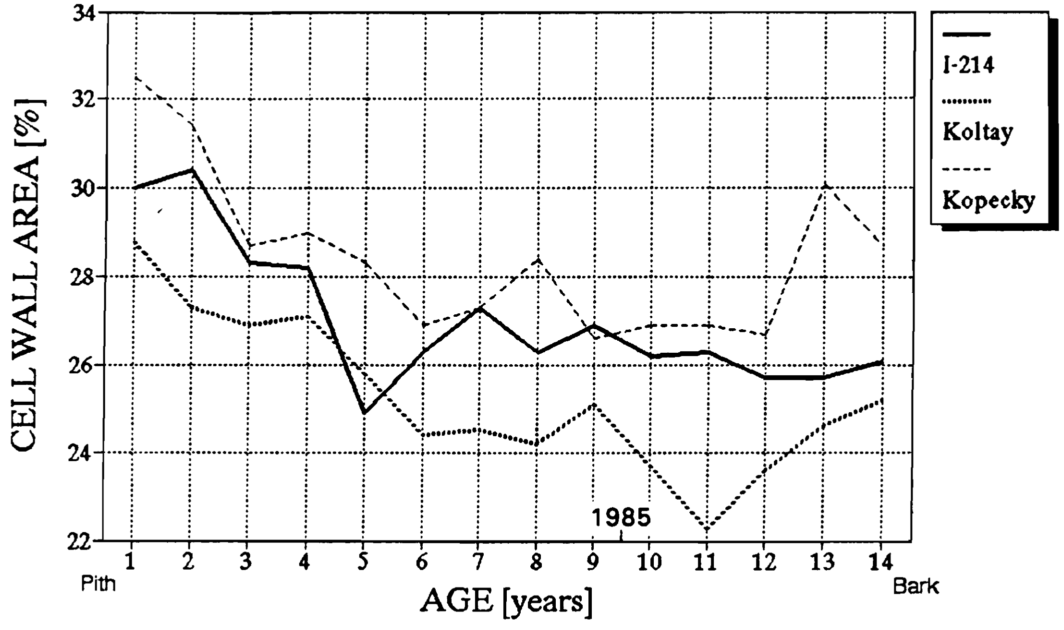


Figure 3.8. - Radial changes of ray area. Top: for three clone on Site 1 (15 years old). Bottom: for two clones on Site 2 (10 years old).



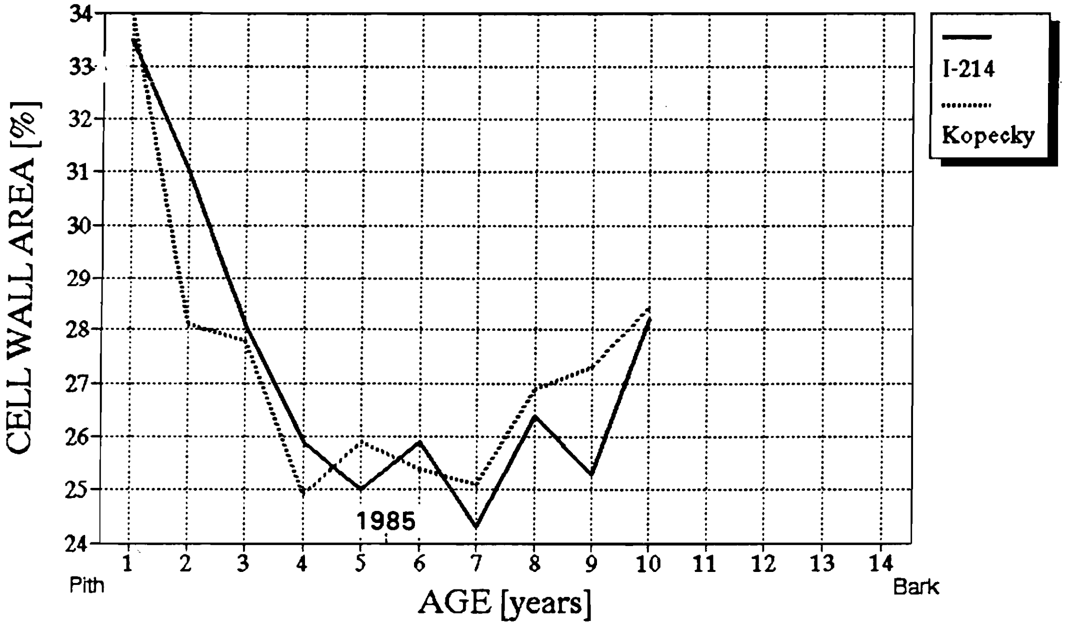
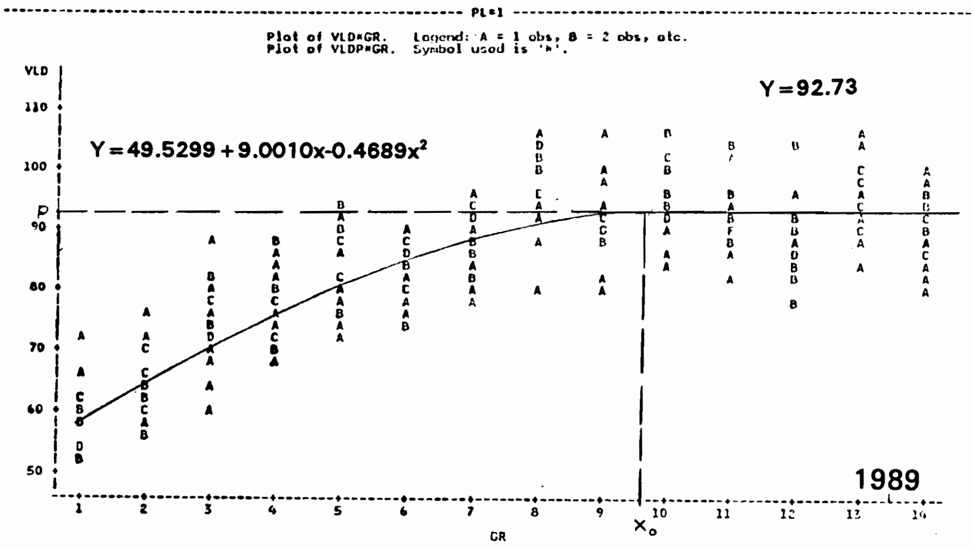


Figure 3.9. - Radial changes of cell wall area. Top: for three clones on Site 1 (15 years old). Bottom: for two clones on Site 2 (10 years old).



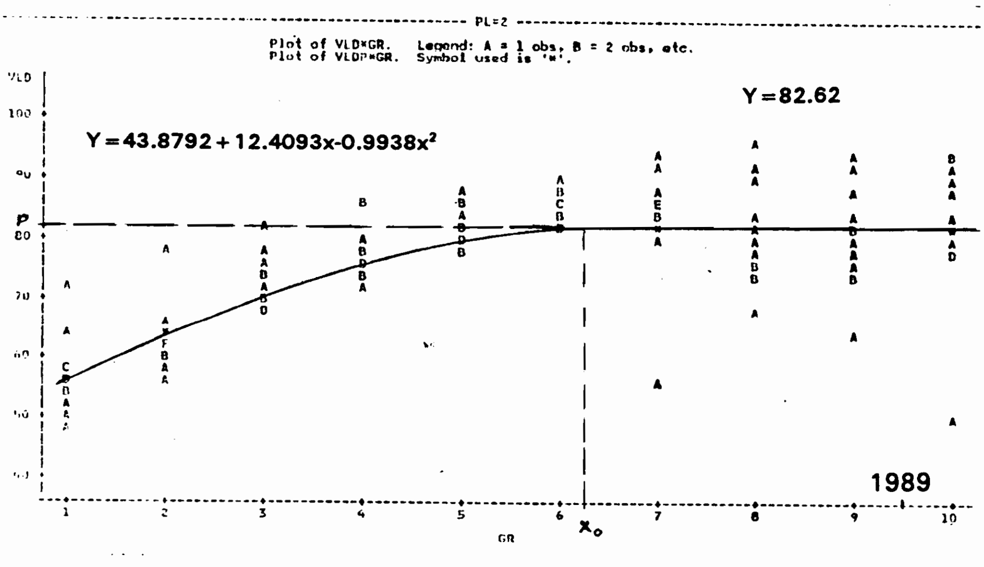


Figure 3.10. - An example of fitting quadratic model with plateau on the data of anatomical parameters. Top: radial changes of vessel lumen diameter of three clones on Site 1 (15 years old). Bottom: radial changes of vessel lumen diameter of two clones on Site 2 (10 years old).

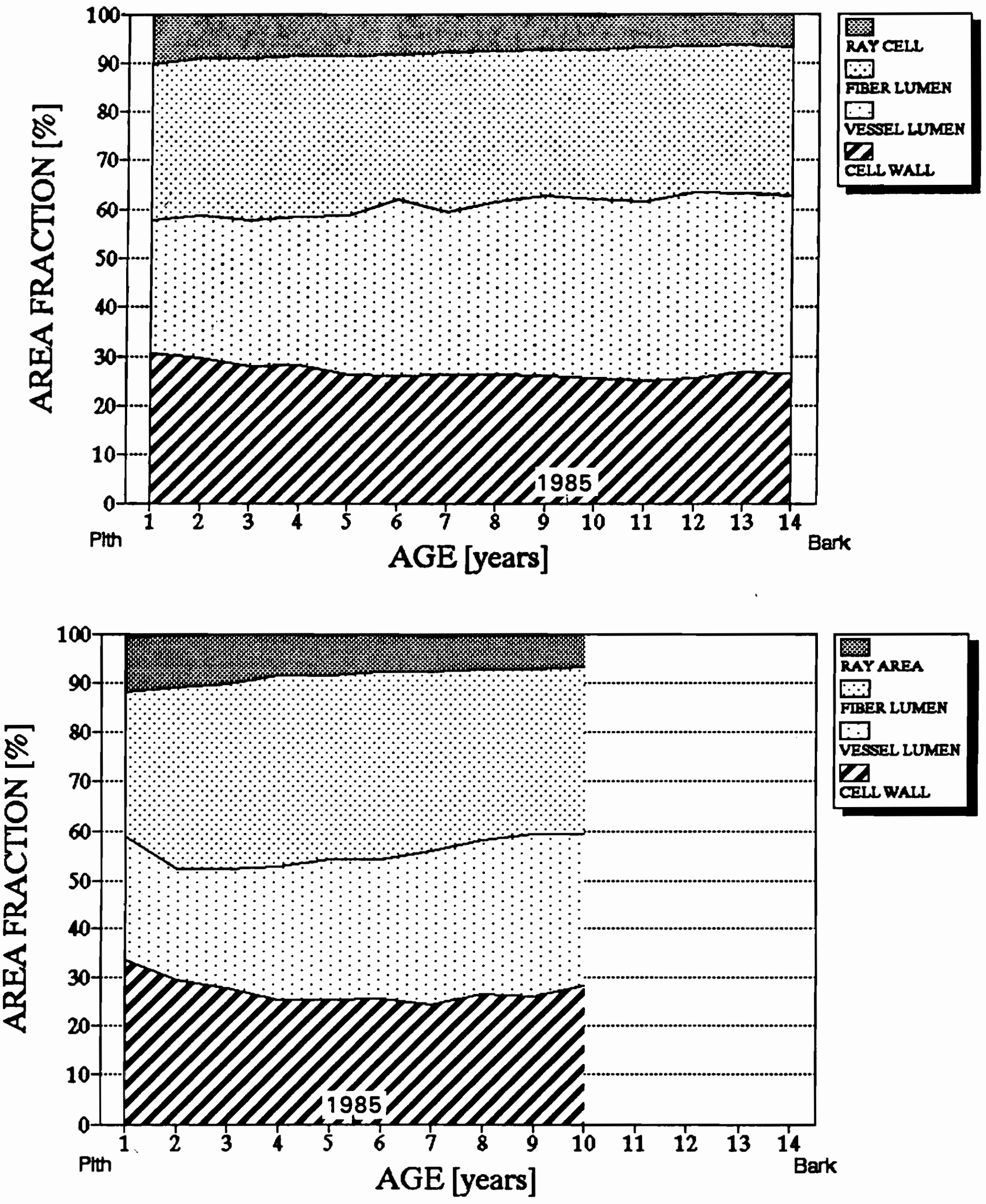


Figure 3.11. - Radial changes of distribution of anatomical elements. Top: based on three clones on Site 1 (15 years old). Bottom: based on two clones on Site 2 (10 years old).

DISSERTATION DISCUSSION AND CONCLUSIONS

The objective of this dissertation was to determine selected anatomical, physical, and mechanical properties and characterize their variation for three Populus x euramericana clones grown in Hungary. Since Hungary has had a serious shortage of timber, a tree improvement program has been concentrating on poplar hybrids, as fast-growing, genetically improved, and vegetatively propagated species. Information on wood properties of the poplar plantations is important for the further clonal selections, for maintaining the existed forests, for decisions on rotation ages, and for better utilization of the clonal material.

This investigation presented an opportunity to evaluate anatomical, physical, and mechanical property variations of the same material in relation to site, clone, age, and growth rate. Since the anatomical properties were determined using an image analyzer and thus thousands of anatomical elements were measured, the results are reliable. However, the disadvantage of this experimental design was that the sample size of mechanical property measurements was limited. Furthermore, if more clones had been involved from more sites and with the same plantation ages, the results could have been more broadly interpreted.

In this dissertation, three research papers, the three sections, address the results of the investigations. In the first section, the anatomical properties of the clones were determined and compared, and the influence of site and clone on the variables measured were evaluated. Site, clone and/or their interaction affected significantly one or more of the anatomical parameters except fiber length. However, the site and clonal differences were small and may be negligible from practical standpoint. Variations of anatomical properties between sites and among clones were statistically significant. However, most of the variations occurred within tree. This is probably due to the increase in size of the cambial initials with age and is closely related to the development of the stem and the crown of a tree. The aging process caused larger variations in anatomical properties than the site and the genetical differences. This is especially true for fiber length and has to be considered at a clonal selection for pulp and paper production.

Specific gravity and mechanical properties were investigated in the second section. Although only three clones were involved in this study, highly significant clonal effect but no-significant site effect were found for specific gravity. This is not surprising, because among wood properties specific gravity is considered to be under genetic control. Despite the fact that specific gravity values of the clones were different, mechanical properties were not significantly different, and there were not significant correlations between specific gravity and mechanical properties. This is probably due in part to the small sample size and the narrow range of specific gravity values. However, at low specific gravity , strength may not be determined by the amount of cell wall material, but rather by factors reflecting the quality of cell wall, such as gelatinous fibers and fibril angle.

Gelatinous fibers were found in almost every clone sample as scattered cells or groups without specific pattern. Based on visual estimates, the proportion of gelatinous fibers varied among trees and was higher near the pith than near the bark, but was not related to site, clone, or growth rate. However, the presence of gelatinous fibers possibly affected the anatomical properties and may have caused bias in measurement as the gelatinous layers occluded the fiber lumens. Gelatinous fibers may have also affected the physical and the mechanical properties. For example, mechanical properties were higher near the bark than close to the pith except for maximum tensile strength. This pattern was the inverse of the changes in the amount of gelatinous fibers present in the samples.

Since anatomical and specific gravity measurements were conducted on each growth ring, the effect of the age was also investigated and is presented in the third section together with the analysis on the effect of growth rate. Differences in growth ring widths among the clones were significant in the "good" years only, and the rankings of the clones became stable after about ten years. Specific gravity values were high in the first three growth rings for each clone, then each clone exhibited different trends. In the first few years, the high specific gravity is possibly due to the planting shock, the needs of a thin stem with few leaves, and the high content of gelatinous fibers. However, after the canopy closure, specific gravity exhibited the trend which characterizes a certain clone. The Koltay and the I-214 clones had more or less constant values, while specific gravity of the Kopecky clone increased toward the bark. From a breeder point of view, the best situation is if the specific gravity remains constant, it does not change with the changes in the environment, growth rate, or age.

Along the radius, anatomical properties for all the three clones on both sites showed a rapid change first, followed by a decreasing rate of change, finally a flat response. The diameters of the cells became larger and the cell wall area decreased with increasing years. Segmented regression analyses of a quadratic model with plateau were used to estimate the demarcation between juvenile and mature periods. The better site accelerated the maturation but with lower values. The size of a cell produced by division of the cambial initial depends mainly on the size of that cambial initial. If the growth rate is fast, it is possible that the mother cell (produced from the cambial initial) may receive a stimulus for further division before it could grow larger.

The demarcation age between juvenile and mature zones were not the same for each anatomical property, but the order of the maturation of the characteristics were the same for both sites. This indicates the physiological control on the maturation process of the anatomical properties which is determined by the needs of the stem and the crown during the growth of a tree. Fiber length and vessel lumen area were the last to become constant, and this information could be important to set the rotation of a plantation for specific utilization.

It is important to emphasize that there were no consistent relationship between growth rate and specific gravity and anatomical properties when growth rings of the same age were compared. In other words, increasing rate of growth may not decrease the specific gravity of these poplar clones.

From among the clones, the Kopecky clone seemed to have slightly better properties than the other two clones, such as longer fibers, higher growth rate, relatively high specific gravity, higher (but not significantly) mechanical properties. Unfortunately, it was available from one site only. Even if the differences among the clones for a property were statistically significant, the differences were very low, and may be negligible from a utilization standpoint. Since the variations among clones were lower than the within-tree variations, this factor has to be considered before giving preference to a clone calculated solely on its average wood properties.

In summary, utilization of this clonal material is limited based on their properties investigated in this study. These clones are not suggested for any solid wood structural applications because of their low strength properties; furthermore, if the wood products have esthetics functions, they are not suitable for them either. All sample trees had discoloration and several pith flecks as well. The high gelatinous fiber content can cause difficulties in drying and in machining. However, they can be used as internal parts for furniture, as wood composites for different boards, and for pulp and paper production because of their relatively long fibers with thin cell walls. Not for timber production, but as an important fiber source, these hybrid poplar clones with rapid growth and high productivity could be considered for short rotation intensively managed plantations.

The following conclusions were reached on the basis of the results in the investigation of three *Populus x euramericana* clones grown on two sites in Hungary:

1. Analysis of variance indicated that significant differences existed among clones on two sites for most of the measured anatomical characteristics. However, the differences detected are small and may be negligible from a practical standpoint. Consequently, other selection criteria than anatomical properties should be considered for poplar clones.

2. Sites, clones and/or their interactions affected significantly one or more of the anatomical parameters except fiber length. Nevertheless, only a small percent of the total variation was explained by the specified models. This indicates the importance of another factors, such as age of cambium and crown closure, in influencing the anatomical properties.

3. Based on statistical analysis, fiber lumen area percentage was found under moderate genetic control. In addition, significant tree-to-tree variation, referred to as environmental effect, was found for all variables but vessel lumen diameter. However, the highest variation was detected within trees suggesting that the age effect is much stronger than clonal and environmental effects and should be of major concern.

4. Distribution of anatomical elements for the three clones on two sites resulted in slight but statistically significant differences. In general, the cell wall material production of poplar clones was very low, less than one-third of the total cross sectional area.

5. Statistically significant and complex but not clonal specific intercorrelations were found between anatomical properties in this study. Clonal selection for longer fibers may result in larger fiber lumens with thinner cell walls and larger vessel diameters and vessel lumens as well. In general, the correlations between wood properties (not just anatomy) have to be explored in order to achieve improvement in several traits simultaneously in clonal selection.

6. Analysis of variance for three poplar clones on two different sites indicated that site did not affect specific gravity; however, significant differences existed between clonal means. The highest specific gravity was found for Koltay, the lowest for I-214 while specific gravity of Kopecky was between them.

7. The effect of clones on specific gravity variation within Site 1 accounted for more than 50% of the phenotypic variation indicating strong genetic control on this property. No significant variation existed between trees within clones, but the within-tree variation was significant. This suggests that besides genetics, the age of the cambium influenced the specific gravity and not the environment.

8. Regarding modulus of rupture, crushing strength, maximum tensile strength and modulus of elasticity measured in tension, no significant clonal effect was found for the samples on Site 1. Strength values were low for each clone.

9. There were significant differences between age group means. The mechanical properties were higher near the bark than close to pith, except for ultimate tensile strength. Clonal means of strength properties were significantly different close to the bark, but they were not significantly different near the pith.

10. Based on nested analysis of variance for strength properties, no significant clonal and between tree (within clones) variations were tested. High within trees (between age groups) variation proved the importance of age of trees rather than clonal or environmental influences on mechanical properties of poplar clones.

11. No significant correlations were found between specific gravity and bending and tensile strengths of clones. However, the relationship was clonal specific in compression. Kopecky exhibited significant associations between specific gravity and both crushing strength and modulus of elasticity but the other two clones did not. Therefore, specific gravity did not prove to be the most important single factor influencing strength properties and can not be used to predict mechanical behavior of *Populus* clones.

12. Variation in wood properties measured within trees, from pith to bark were statistically significant. Age had a significant effect on growth ring width, specific gravity and anatomical characteristics.

13. Ring widths increased in the first few years, then decreased toward the bark. Differences between clones were significant in the first few years and in the "good" years only. Furthermore, their order seemed to stabilize after ten years which has to be considered when selecting clone for growth rate.

14. Specific gravities of the three clones were high at the pith then each exhibited different radial patterns. After the first three years, Koltay clone became constant. So did I-214 but with slight fluctuation of the lowest values. However, the specific gravities of Kopecky increased toward the bark.

15. Along the radius, anatomical properties at first showed a rapid change, followed by a decreasing rate of change, and finally a flat response. Segmented regression analysis fitting a quadratic model with a plateau proved useful to estimate the demarcation between juvenile and mature periods of anatomical characters.

16. Maturation process of anatomical properties were affected by site. The better site accelerated the maturation but with lower matured values. The ages of demarcation were not the same for all properties; however, the order of the maturation were the same in both sites indicating the influence of tree physiology on the aging process. Among the measured anatomical properties, fiber length and vessel lumen area were the last to become constant at the estimated ages of 10-13 years on Site 1 and 9-10 years on Site 2.

17. Distribution of cross sectional area of cell wall, vessel and fiber lumen, and ray area exhibited only slight changes along the radius. Vessel and fiber lumen area increased approximately 8% from pith to bark.

18. No consistent relationship was found between growth rate (expressed by either tree height, tree diameter or growth ring width) and wood properties of the three clones from two sites.

VITA

The author, daughter of Margit and Sándor Peszlen, was born in Sopron, Hungary on September 11, 1955. She received a diploma in Wood Engineering from the University of Forestry and Wood Sciences, Sopron, Hungary, a degree of Master in Higher Education from the University of Gödöllő, Hungary, and a Ph.D. in Wood Sciences and Forest Products from the Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A. She was previously employed as a research associate for the Department of Wood Technology and later the Department of Botany, University of Forestry and Wood Sciences, and the Research Institute of Furniture Industry, Budapest, Hungary. She received a Fulbright Scholarship to study wood science at Virginia Tech. Currently, she is an assistant professor in the Department of Wood Sciences, University of Forestry and Wood Sciences. Her professional activities include teaching and research in wood anatomy and the relationship of structure to properties. She is a member of the Hungarian Wood Research Association (FATE), the International Association of Wood Anatomists (IAWA), and the Forest Products Society (FPS).

Ilona Peszlen

Ilona Peszlen