THE BASIC DENSITY OF SCOTCH PINE, NORWAY SPRUCE, COMMON BIRCH AND WHITE BIRCH IN SOUTHERN FINLAND

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THESIS

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By

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Preface

In spring 1962 the Small-Sized Timber Research Commission offered to finance a study on the wood density of different timber assortments if this could be done at the Forest Research Institute. The Forest Technology Department of the Forest Research Institute considered it most expedient to establish first how and why wood density varies within the stem and between stems. It was thought that the calculation of the wood density of different timber assortments could be done as an application of the basic data obtained. This plan was accepted by the Small-Sized Timber Research Commission, and the field work was started in the same spring. The Small-Sized Timber Research Commission then financed the investigation for three years.

Professor, Dr. Paavo Aro, Chief of the Forest Technology Department, played a decisive role in the successful outcome of the study, and participated closely in all the phases of the work. He supported and speeded up the performance of this study in many ways. Associate Professor, Dr. Veijo Heiskanen, then Director of Research of the Small-Sized Timber Research Commission, offered valuable guidance, especially in drawing up the research project and again in the final phases of the study. In later stages, the course of the work was tutored by Professor, Dr. Kalle Putkisto from the Department of Logging and Utilization of Forest Products, University of Helsinki.

When the field work of the study had already progressed for two summers I was awarded through the agency of the National Research Council for Agriculture and Forestry a fellowship of the W. K. Kellogg Foundation. This enabled me to study in the Department of Forest Products at Michigan State University under the direction of the Chairman of the Department, Professor, Dr. A. J. Panshin, and

Professor, Dr. Aubrey E. Wylie many aspects of wood technology, including wood density. After my return to Finland, Professor Panshin and Professor Wylie continued to provide assistance in conducting this study. The valuable instruction at Michigan State University had an appreciable effect on the final form of this study.

The statistical treatment of the material was possible only with the assistance given by the Computer Centre, University of Helsinki. The computer programme was drawn up by Mr. Pekka Kilkki, B.For.

The manuscript was checked and corrected by Professors Paavo Aro, Veijo Heiskanen, A. J. Panshin and Aubrey E. Wylie.

The translation from Finnish into English was made by Miss Päivikki Ojansuu, M. A., and checked by Mr. L. A. Keyworth, M. A. (Cantab.).

I extend my sincere thanks to all persons and institutes mentioned in the foregoing.

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LIST OF SYMBOLS USED IN THE TEXT

The following abbreviations are used in the text and in the figure and table legends.

B	birches combined
CB	common birch
cm	centimetre
cu.m	solid cubic metre
dbh	breast height diameter above the bark
$\bar{d}$	mean of the differences of paired observations
kg	kilogram
m	metre
mm	millimetre
n	number of observations
P	Scotch pine
R	coefficient of correlation in simple and multiple linear regression
R^2	coefficient of determination correspondingly (This value indicates the proportion of the total variation in the dependent variable that is explained by the regression)
S	Norway spruce (in the figures)
S	sample standard deviation
S^2	sample variance
Sd	standard deviation of the differences of paired observations (Guenther 1964)
Sy.x	standard deviation of the dependent variable associated with the regression
WB	white birch
X_1-X_{23}	see pages 29-31
$\bar{X}$	sample mean
..	no observation

I. Introduction

1. THE NEED FOR A WOOD QUALITY INVENTORY AND THE FEASIBILITY OF MAKING ONE

"Quality is the resultant of physical and chemical characteristics possessed by a tree or a part of a tree that enable it to meet the property requirements for different end products" (M i t c h e l l 1961). The quality of wood is thus a concept bound with the use of wood.

It is of primary importance in industrial planning to know not only the volume but also the quality of the raw material inventories. Only when the quality of the raw wood obtainable is known can it be utilized to the best advantage, and only then is there a basis for forecasts of raw material consumption and the quality of the end product. When this goal has been achieved, it is possible to price the raw wood equitably by taking the quality of the timber into consideration separately in each individual case. A fair price, again, is the only way of making the wood producer conscious of quality considerations in growing forest. At the same time, the chances are increased of directing forest tree improvement activity more towards development of the quality of wood side by side with the present activity which is aimed chiefly at increasing the volume of growth.

As there is no unit by which the quality of wood can be expressed directly, the end must be attained by a roundabout route. One property or several properties of wood indicative of the suitability of wood for a certain use are measured. These properties are called wood quality indicators. To be serviceable, a wood quality indicator should meet the following requirements.

- The indicator must give an idea of the suitability of the wood for various uses.
- The indicator must be a sentitive measure of the variation in wood quality.
- The indicator must allow accurate measuring at reasonable cost.

- The indicator must be easy to interpret and use, not only in scientific research but also in practical forestry.
- The indicator must be applicable to all species of wood.

Defects in wood affect essentially the quality of several kinds of timber. The amount, distribution and size of knots give an idea of the suitability - or unsuitability - of wood as raw material for, say, lumber from a certain tree species. The utilization value of wood is influenced also by the occurrence of reaction wood, decay, blue stain and other defects. The purpose of a general inventory of wood quality, however, is to elicit just the basic starting point, the quality of defect-free wood and its variation.

The symbol of the quality of wood employed in the case at issue must thus be a characteristic of clear, defect-free wood. It would be preferable if a property visible to the naked eye could be used. Such properties are the growth rate and uniformity of growth illustrated by the ring width. The growth rate is expressed by the average ring width, but the uniformity of growth is more difficult to depict. The ring width can be determined by simple methods and can often be seen clearly by the naked eye. Its significance is easy to understand and it can be influenced by silvicultural treatment. In addition, the ring width varies over a wide range.

There is a negative correlation between ring width and pulp yield (W e g e l i u s 1949). Ring width can be used also for assessing the quality of sawlogs and lumber. According to the stress-grading rules for Finnish structural lumber, the average ring width of pine and spruce lumber may be a maximum of 3 mm in the first and a maximum of 5 mm in the second grade (S i i m e s 1952). There are corresponding restrictions in several countries, e.g. in the grading rules for southern yellow pine and Douglas fir lumber in the U.S.A. (Standard Grading Rules for Southern Pine Lumber, 1963 and Standard Grading and Dressing Rules for Douglas Fir..., 1962). It has also been shown that a positive correlation prevails between the

average ring width and the knottiness of the sawlog and lumber (H e i s k a n e n 1954).

When the concept of juvenile wood became known, earlier opinions about the correlation between the growth rate, i.e. the ring width, and the quality of wood had to be revised. According to R e n d l e (1960), "juvenile wood refers to the secondary xylem produced during the early life of the part of the tree under consideration and characterized anatomically by a progressive increase in dimensions and corresponding changes in form, structure, and disposition of the cells in successive growth layers". Concurrently with these changes, there generally occurs also a narrowing of the ring from the pith towards the cambium.

It was concluded earlier that there is a fixed correlation between the quality of wood and the ring width. It has been found later that this correlation is in many cases smaller than had been assumed except in the zone of juvenile wood where some wood properties change concomitantly with the ring width. The juvenile wood zone within which the annual ring narrows from the pith towards the cambium at the same time as certain other properties of the tree change towards higher quality is, however, fairly narrow. The time during which a tree grows juvenile wood varies from species to species, but may be correlated with the normal life span of the tree (R e n d l e 1959).

The correlation between ring width and certain other properties of wood is considerably weaker outside than in the juvenile wood zone itself (H i l e y 1955, R e n d l e 1959). Juvenile wood has been studied chiefly in pines, and its occurrence in Norway spruce and birches is still unclarified. However this may be, it is evident that ring width alone is not a sufficiently accurate standard of quality for pine, spruce and birch wood.

The proportion of summerwood volume to springwood volume, which is denoted as percentage summerwood, is another property to be considered in selecting an indicator of wood quality. In M o r k's (1928) definition, summerwood includes tracheids in which the common cell wall in tangential direction between two cells is exactly half or over half of the radial width of the lumen. If the joint width of two cell walls is less than this, the tracheids are considered to belong to springwood. Mork's definition was intended originally for spruce, but it is used commonly for other softwoods as well.

As summerwood by definition consists of thicker-walled cells, the unit volume of wood contains more wood substance the higher the percentage summerwood. When the percentage summerwood increases, the strength properties of wood are improved (J a l a v a 1933). Percentage summerwood is used in the grading of southern yellow pine and Douglas fir lumber in the U.S.A. The requirement for lumber of high grade strength properties, so-called dense lumber, is that there are "on either one end or the other, not less than 6 annual rings per inch and not less than 1/3 summerwood. Pieces averaging less than 6 annual rings per inch and not less than 4 meet dense requirements if averaging 1/2 or more summerwood" (Standard Grading Rules for Southern Pine Lumber, 1963 and Standard Grading and Dressing Rules for Douglas Fir..., 1962). The requirement concerning the amount of summerwood is more important than that applying to ring width (Short Course in Grading, 1963). The percentage summerwood of both pine and spruce in Finnish structural lumber of strength class I must be a minimum of 24. The corresponding figure for calss II is 17, whereas for lumber of strength class III there is no minimum percentage summerwood (S i i m e s 1952).

Both spring- and summerwood cells have their advantages and disadvantages in paper making, and thus the presence of both cell types in a certain ratio in pulp is desirable. According to D a d s w e l l and W a r d r o p (1959), the wood contained by Australian plantation-grown softwoods should contain 15-50 per cent of summerwood if high-grade pulp is desired.

The use of percentage summerwood as an indicator of wood quality is limited above all by its unsuitability for hardwoods, because the transition between spring- and summerwood is indistinct in diffuse-porous hardwoods. In softwoods, particularly in those that have pronounced summerwood bands, percentage summerwood affects not only the amount and quality of the pulp yield and the strength of the wood, but also its weight, appearance and workability. Percentage summerwood denotes, however, only the proportion of the xylem that meets the minimum requirement mentioned in the definition of summerwood, and it gives no indication of the quality of springwood and summerwood which also varies.

In addition to growth rate and percentage summerwood, there are several other properties that may be considered as wood quality indicators. They are properties of which no idea can be obtained without laboratory apparatus. Fibre length, cell wall thickness, fibril orientation and the chemical composition of wood are indicators illustrating the quality of wood used as raw material in pulp and paper making (D a d s w e l l and W a r d r o p 1959). Fibril orientation also influences the properties of lumber (Forest Products Laboratory 1960). The latter, however, is so difficult to determine that the practical performance of the work alone prevents its selection as an indicator for inventories of wood quality.

None of the properties enumerated above meet fully the demands to be made of a wood quality indicator. A more serviceable indicator is the d e n s i t y o f w o o d which denotes the dry-matter weight per unit volume of wood: wood density is usually expressed in grams per cubic centimetre, in kilograms per solid cubic metre or in pounds per cubic foot. If the volume of a piece of wood is measured when the moisture content of the wood is above the fibre saturation point, the term b a s i c d e n s i t y of wood is used for the density value obtained. When the volume of absolutely dry wood is used, the oven-dry density or d r y d e n s i t y of wood is obtained; it is higher than the former value on account of the shrinkage of wood.

When the wood density is divided by the water density at a water temperature of + 4^{o}C, the s p e c i f i c g r a v i t y o f w o o d is obtained. This is a unit-less quantity and consequently independent of the measuring system. Specific gravity of wood must be distinguished from specific gravity of cell wall substance. The former depends on the volume of the cell walls, the specific gravity of cell wall substance and the amount of extractives, cell lumina and intercellular spaces. The latter is practically constant, about 1.53 (Brown, Panshin and Forsaith 1949).

The density and the specific gravity depend primarily on the ratio between the volume of the cell walls and the volumes of the intracellular and intercellular spaces, since the specific gravity of the cell wall substance is practically constant. A disturbing factor, however, is the extractives in wood which increase wood density.

2. DENSITY AS A WOOD QUALITY INDICATOR

Density denotes the weight of the wood contained in a unit volume. Weight itself is a factor affecting wood properties. Knowledge of the weight of timber is of especial importance in connection with transport because the load size, the transport charges and the buoyancy of wood in floating depend on the weight of the timber. It should also be known when the wood is used as building material. When the traditional method of volume scaling and weight scaling are used concurrently, wood density is an essential link which must be known for comparison of the volume and weight measurements.

Wood density also gives a picture of the mechanical properties of wood. There is an especially strong correlation between density and the strength properties of wood such as the tensile, bending, compression and shearing strength and hardness (Siimes and Liiri 1952). When the density increases, certain strength properties increase, too. Wood hardness is directly proportional to density to the power of 2 1/4 (Markwardt and Wilson 1935). The strength properties of high-density Scotch pine are twice those of low-density pine (Siimes and Liiri 1952).

The ratio of the strength to the density of wood is taken into consideration in stress grading. When Finnish structural lumber is divided into three strength classes, the density [1)] of pine must be a minimum of 500 kg/solid cu.m in class I and a minimum of 450 kg/solid cu.m in class II. The corresponding figures for spruce are 470 kg/solid cu.m and 420 kg/solid cu.m (S i i m e s 1952). "Density can be used in the selection of high-grade piling, transmission poles, and other products where high strength is of major importance" (M i t c h e l l and W h e e - l e r 1959).

In the production of structural plywood, density is an essential factor (H e s s 1965, O r t h 1965). It is also important to select the outermost boards from strong and stiff lumber in making laminated beams and arches. On the other hand, it is possible to place weak lumber between the outermost boards. By placing the pine boards in the beam in the right way, beams are obtained that are 60 % stronger and 45 % stiffer than those in which the low-density boards are placed in the outer parts of the beam (S i i m e s 1965).

Density also affects the liquid absorption, swelling and shrinkage properties of wood. Low-density wood absorbs more water than heavy. The consumption of preservatives is highest in low-density wood with some preservation methods and can be calculated when the density of wood is known. In pine wood the tangential, radial and volumetric shrinkage and swelling are directly proportional, while the shrinkage and swelling in the longitudinal direction of the tree are inversely proportional to the density of the wood (S i i - m e s 1938).

The pulp yield per unit volume of wood depends on the wood density: a unit volume of wood contains more fibre the higher the density of wood. For instance, there is a linear correlation between the sulphate pulp yield and the density of Scotch pine (E r i c s o n 1962a) and southern yellow pines (M i t c h e l l and W h e e l e r 1959). Correspondingly the sulphite pulp yield in kg/solid cu.m of Norway spruce wood can be expressed with the following

[1)] Volume measured at 15 per cent moisture content.

equation: yield = 20 + 433 · specific gravity + 8 · chlorine number (K l e m 1949).

The correlation between the pulp yield of a given unit weight of wood and the wood density is weak, in contrast. It has been noted, however, that the cellulose yield per unit weight of wood is smaller from juvenile wood than from adult wood (Z o b e l and M c E l w e e 1958).

Wood density can also be used to predict the quality of the paper obtained from wood. Density gives an indication of the cell wall thickness compared with lumen diameter, for dense wood is composed on the average of thickwalled cells. Thanks go their stiffness, thicker-walled fibres retain their original rounded cross-section form in paper-making, while thin-walled fibres collapse and become ribbon-like in form, which facilitates the bonding of the fibres (R u n k e l 1942).

This behaviour of the fibres affects the paper properties decisively. Paper made of thin-walled cells is dense and opaque and has high tensile and bursting strength. But the tearing strength, which is an important property especially in kraft paper, is highest in paper made of thick-walled cells (M i t c h e l l 1961). Proliferation of the number of thick-walled cells also lengthens the beating time necessary in the pulp production and makes sheet formation more difficult. Simultaneously, the paper surface becomes rougher and the folding endurance of paper weakens (D a d s w e l l and W a r d r o p 1959). Because of their pale colour, thin-walled springwood fibres require less bleaching to reach a desirable degree of whiteness (E d l i n 1965).

The most suitable fibres for a given occasion depend on the type of paper and its intended use. In fact one cannot speak of a pulp that is univerally good for all paper qualities. However, D a d s w e l l, W a t s o n and N i c h o l s (1959) thought it desirable that the thickness of the cell wall should be less than half of the lumen diameter.

If a great bursting strength is required of paper, a low wood density is advantageous, but for a great tearing strength dense wood is desirable (H i e t t, B e e r s and Z a c h a r i a s e n 1960). The effect of the density of the wood on the tearing strength is, however, considerably less with spruce sulphite pulp than with pine sulphate pulp (S t o c k m a n 1962). If the smoothness and closeness of a sheet of paper are the primary considerations, it helps if a relatively high proportion of the fibres are thin-walled (C u r r a n 1938). In the manufacture of many types of papers, including newsprint and thin translucent papers with high resistance to folding and bursting and with good tensile strength, low-density wood is often preferred (E d l i n 1965).

In the viscose process low-summerwood pulps have certain advantages. They have been found for example to show better filterability of the viscose. This is not of great importance in practice, however, as the percentage summerwood of spruce wood used as raw material is relatively low (H e d i n, M a l m and W e n n e r b l o m 1963).

Wood of low density is the most suitable for the production of groundwood pulp (S c h a f e r 1961). Some types of paper made of groundwood pulp need such thin-walled fibres that low-density wood may be suitable despite the smaller yield (B e s l e y 1962).

Both the fibre yield and the quality of paper thus depend on wood density. High-density wood improves the quality of some types, while low-density wood is good for other types, but this does not detract from the usefulness of density as an indicator of the quality of pulpwood. It is important to know, on the one hand, what kind of wood is suitable for a certain use and, on the other hand, where wood of certain kind is to be had.

The quality of the raw material of particle boards depends primarily on wood density, and the usefulness of different tree species can be compared on that basis. For a constant density of particle board, its tensile strength perpendicular to surface and bending strength decrease and the moisture absorption, linear swelling and thickness swelling increase when the wood density increases (L i i r i 1964). Particle boards of the best quality are thus obtained from low-density wood. A wood density of 300 kg/

solid cu.m is ideal for the strength and stiffness of the board, its dimensional stability and weight (M i t c h e l l 1961). However, in manufacturing particle board of a fixed weight the consumption of raw material is greater, the lower the density of wood employed.

Wood density also indicates the quality of fuelwood, for the heat value of wood for each tree species is directly proportional to the wood density. The heat content of a unit volume depends principally on its dry weight and moisture and to some extent on the tree species (H e i s - k a n e n and J o k i h a a r a 1960).

Wood density is expressed in most Finnish studies as dry density. For this determination, the volume of the test piece is measured when the wood is absolutely dry. In closer correspondence to real conditions is the basic density of wood. To determine this, the volume of the test piece is measured when the moisture of wood is above the fiber saturation point. The density values were determined in the present study as basic densities, although the term density is used for the sake of brevity in lieu of basic density. When density values are taken from earlier studies in which the dry density was used, mention will be made of this. In accordance with the general practice the term t r e e d e n s i t y or average tree density is used for the average wood density of the stem in the present study.

When extractives are removed from wood the density of the extracted wood can be determined; this value may give a better idea of, say, the paper properties than that based on unextracted wood (B a r e f o o t, H i t - c h i n g s and E l l w o o d 1964). The most important Finnish tree species, however, contain relatively small amounts of extractives. The average acetone extract content of Scotch pine is 2.6 per cent in southern and 4.9 per cent in northern Finland, of Norway spruce 1.5 and 1.9 per cent, respectively, and of birches 1.6 and 2.6 per cent (Finnish Pulp and Paper Research Institute 1949 a and 1949 b). As the removal of such amounts of extractives cannot appreciably increase the accuracy of using density as an indicator of wood quality, no effort was made in the present work, which is restricted to southern Finland only, to remove the extractives from wood prior to the determination of density. In the heartwood of Scotch pine the amount of extractives may sometimes be considerable, however (cf. J a l a v a 1952).

3. ARRANGEMENT AND LIMITATION OF THE TASK

The ultimate object in planning the present study was a national inventory of the wood density. However, it was obvious from the outset that it would be more practical to limit the first phase to a geographically small area in southern Finland, extending it later to cover the country as a whole. The purpose of the study was thus, first, to clarify the variation in wood density and the influence of different factors on it in a selected investigation area and, second, to evolve a serviceable method for a wood density inventory in which standing trees could be used. The following investigation targets were set for the realization of these aims.

1. The variability of density within the stem;
2. The variability of density between stems with special attention to the effect of environment;
3. The density of the most important types of timber;
4. Evolving a method for the performance of a nation-wide study of wood density using standing trees.

The tree species selected for study were Scotch pine (*Pinus silvestris* L.), Norway spruce (*Picea abies* (L.) Karst.), and the two botanical species of birch, the common birch (*Betula verrucosa* Ehrh.) and white birch (*Betula pubescens* Ehrh.). These tree species account for 97.7 per cent of the total growing stock in Finland (I l v e s - s a l o 1956).

The investigation was confined to clear stem wood. Defects such as knottiness, reaction wood and decay were disregarded. The values given here for the density of pine, spruce and birch wood thus illustrate the basic density of completely clear, defect-free wood.

This phase of investigation was concentrated on a small geographical area. An endeavour was made, however, to collect the sample in such a way that conclusions could be drawn on the basis of the results for the whole of southern Finland, until the study of the whole country could be performed. The representativeness of the sample will definitely be checked in later studies of the geographical variation of wood density.

It has become increasingly obvious since the present study was started that ensuring future wood production in Finland calls for a more intensive silvicultural programme in which artificial regeneration and fertilization of forests will be of decisive importance. It was therefore tried to find out, partly by means of literature reviews, the changes to be expected in the density of wood produced by the future forests, compared with that of the existing forests.

II. Material and methods

1. MATERIAL

The material for the study was collected in 1962-1964 from the experimental areas of the Forest Research Institute of Finland at Vilppula, Vesijako and Punkaharju, from private forests between the experimental areas of Vilppula and Vesijako, and from the Evo forest district of the State Board of Forestry. These places are included in a geographically narrow area about 100 km long north-south and about 250 km across in an east-west direction. The location of the most important places appears from Figure 1 and from below.

Locality	Location		
	Northern latitude	Eastern longitude	Height above sea level, m
Vilppula	62° 02′	24° 22′	110
Vesijako	61° 23′	25° 03′	110
Evo	61° 12′	25° 08′	130
Punkaharju	61° 47′	29° 18′	110

The climatic conditions of the places are representative of the important forest regions in southern Finland. As the weather conditions of the growing season may be of significance for wood quality, Table 1 gives information on the temperature and precipitation in the localities under investigation. The data are based on publications by the Finnish Meteorological Office (1964) and by H e i - k i n h e i m o.

The sample plots had to be restricted to stands in which any tree whatsoever could be felled as a sample tree. At Vesijako and Evo, stands recently flattened by storm were also used. The distance between plots of similar tree species, forest site type and age class was a minimum of one kilometre. In the stands thus available for the research task, the greatest possible number of sample plots were chosen. The stand density, mean height, mean age and composition of tree species were determined for each sample plot.

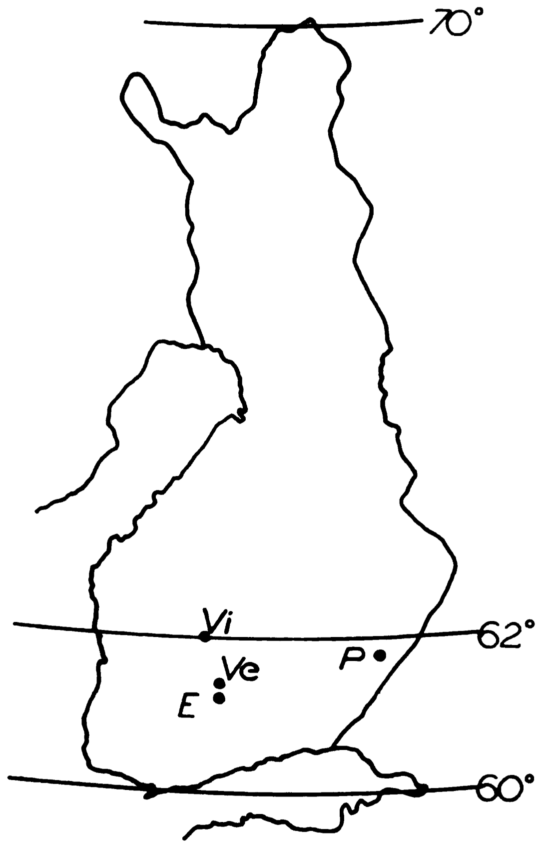


Figure 1. The location of the investigation places (Vilppula, Vesijako, Evo and Punkaharju).

Table 1. Information on the average weather conditions of the investigation localities. (Padasjoki and Hattula represent Vesijako and Evo).

Locality	Period	Month V	VI	VII	VIII	IX	Whole year
		Mean temperature, centigrades					
Vilppula	1921-50	8.3	14.1	16.1	14.9	10.3	3.5
Hattula	1921-50	9.2	13.5	16.9	15.0	9.9	3.9
Punkaharju	1921-50	8.5	13.2	16.9	15.2	9.9	3.2
		Precipitation, mm					
Vilppula	1921-50	44	63	74	75	69	596
Padasjoki	1931-60	40	44	65	71	65	542
Punkajarju	1931-60	38	53	67	72	61	566

Sample trees were collected from mineral soils and undrained swamps. The forest site types of mineral soils which were included in the investigation are *Oxalis-Myrtillus* type (OMT), *Myrtillus* type (MT), and *Vaccinium* type (VT) [1]). The forest site type was determined by using plant cover analyses. Undrained swamps irrespective of their quality were accepted for swamp sample plots, but for pine the selection was limited to pine swamps and for spruce and birch to spruce swamps. Ten stems were taken from each sample plot.

The material was grouped according to the tree age, using the following classification: 21-40, 41-60, 81-100 and 101-120 years. For birch the last class was omitted as unnecessary.

The material was small for OMT pine and VT birch and the youngest age class of the poorest sites. However, they represent cases which are encountered fairly infrequently in the practical harvesting of timber. The material also included pine and spruce of over 120 years, especially trees growing on swamps. Table 2 gives an idea of the nature of the sample trees.

Table 2. Average measurements and properties of sample trees.

Property	Pine	Spruce	Common birch	White birch
Dbh, cm	13.9	14.5	15.1	11.5
Tree length, m	13.4	13.3	17.1	13.4
Crown proportion*)	43.6	67.6	53.1	52.5
Age, years	68	78	57	54

*) Crown proportion = crown length as a percentage of the total tree height (N y y s s ö n e n 1954).

Table 3. The diameter distribution of sample trees according to the diameter above the bark at breast height.

Species	Dbh, cm								Total
	3-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	
	Number of stems, per cent of the total material								
Pine	6	28	28	21	11	5	1	0	100
Spruce	3	29	29	23	11	3	1	1	100
Birches	6	34	31	17	9	2	1	-	100

[1]) OMT is the moistest and most fertile of the mineral soil forest site types mentioned, VT the driest and poorest. According to the National Forest Inventory, the average annual growth at various sites in the southern half of Finland is as follows: OMT 4.5, MT 4.0, VT 2.9, undrained spruce swamps 1.9, and undrained pine swamps 0.8 solid cu.m/hectare (I l v e s s a l o 1963).

Average measurements alone do not give a sufficiently accurate picture of the sample. Table 3 gives information on the distribution of sample trees into diameter classes, the main part of the material being 6-25 cm in diameter.

No attention was paid to the botanical species in collecting the birch sample trees. Common birch and white birch were thus included in the sample in the ratio in which they occurred in the sample plots. The moister the site in question, the higher was the proportion of white birch. This affects the average density of birchwood measured at various sites.

Site	Birch species Common	 White	 Total
		Number of trees	
OMT	69	71	140
MT	92	67	159
VT	66	4	70
Swamp	22	168	190
Total	249	310	559

From six to ten increment cores were taken from each tree at different stem heights. Additional cores were taken from the saw timber part of the tree to establish the density of sawmill waste from slabs. The primary sample thus included the following quantities of trees and cores extending from stem surface to pith.

Species	Number of trees	Number of cores
Pine.....................	785	7 700
Spruce...................	751	7 890
Common birch.............	249	2 240
White birch..............	310	2 390
Total	2 095	20 220

In addition to the primary sample, different secondary samples had to be collected to decide special questions that arose in the course of the investigation. Only the most important of these are mentioned here.

To establish the accuracy of the mercury immersion method used in determination of the density of the increment cores, a sample was collected which contained a total of 652 paired observations from different species of trees. Each pair consisted of an increment core and an adjacent disk. Correction equations for the densities determined from the increment cores were calculated on the basis of this material.

A number of increment cores were selected by lot from the primary sample to establish the dependence of wood density on the percentage summerwood and the ring width. The average properties of this sample were as follows.

Species	Number of cores	Ring width mm	Percentage summerwood
Pine	336	1.41	24.5
Spruce	356	1.59	17.3
Common birch ...	502	1.57	..

For these cores, in addition to density, measurements were taken of the ring width, and of the percentage summerwood except for birch. To determine the effect of the juvenile wood phenomenon, measurements were also taken of the age of the core.

2. METHODS USED IN INVESTIGATION

21. Collection of samples

Ten healthy sample trees were felled in each sample plot. Leaning trees were not taken because they contain an exceptional amount of reaction wood. Age, breast height diameter above the bark, tree height, and crown proportion were determined for each stem. In addition, tree class was determined in accordance with the following classification: the height of the trees in the second tree calss is 80-90 per cent, of the third 70-80 per cent and of the fourth a maximum of 60-70 per cent of the length of the dominant trees of the stand, i.e. trees of the first tree class (I l v e s s a l o 1928).

The felled sample trees were divided into timber assortments according to the generally used grading rules (cf. Tapion Taskukirja 1959). The following table shows the minimum top diameters under the bark of the timber assortments included in the study. The pine and spruce logs were intended for the production of lumber (cf. H e i s - k a n e n and S i i m e s 1960). The birch logs were destined for the preparation of veneer and plywood (cf. Yleiset vanerikoivujen... 1961).

Timber assortment	Pine	Spruce	Birch
	Minimum top diameter		
Logs	5"	5"	6"
Pulpwood	8 cm	8 cm	8 cm
Small-diameter pulpwood	5 cm	5 cm	..
Fuelwood	..	..	5 cm

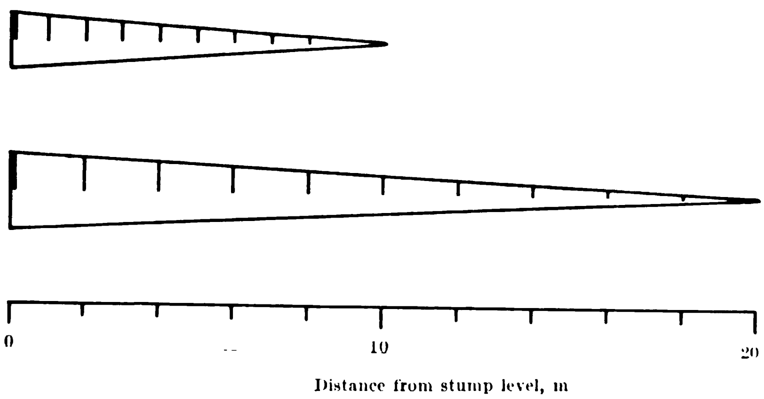


Figure 2. The sampling method in 10 and 20 m trees.

There were two types of samples to choose from: a disk sawn from the stem and a core taken by an increment borer. The disk method gives greater accuracy, because the disk is many times the size of a core and in it the inner and outer parts of the stem are weighted in exactly the correct ratio (E r i c s o n 1959). In a core the inner parts of the stem are over-represented.

One of the objects of the present study, however, was to evolve a method for performing a study of wood density in the country as a whole. Such a study is possible only when standing trees are used. Moreover, as transport and storage of the material limit the sample size in a comprehensive study, the most practical procedure was to

collect the density samples as increment cores extending from the stem surface to the pith. The inner diameter of the bore was 5.5 mm.

An endeavour was made, by taking several increment cores per stem, to establish the variability of density at different stem heights, the density of the timber assortments prepared from the different parts of stem, the average density of the stem and the possibility of determining the average tree density from a single core. The points in the stem from which samples were taken were related to the height of the tree. The first sample was taken at stump height (cf. I l v e s s a l o 1948), i.e., at the relative height 0 per cent. The following samples were always taken from there at distances equal to 10 per cent of the stem height (Figure 2). For tall trees, the last sample was taken at a height of 90 per cent of the tree length. No samples were taken from tops with a diameter smaller than 3-4 cm. Thus, in the smallest trees, a core taken from a height of 50 per cent was sometimes the last one.

The core length and the type of timber which the core represented was noted for every core. From saw logs, two cores were taken from every sampling point. The average density of the cross-section surface was determined in the usual way from one of the cores. The other core was divided into two parts so that the length of the inner part was equal to the top diameter of the log divided by two. This part was supposed to represent lumber. The outer part represented approximately the sawmill waste from slabs that accumulates from the log.

22. Determination of density

The density of wood can be determined in many different ways. Summaries of the methods employed have been published in the literature (e.g. M a r k w a r d t and P a u l 1946, J a l a v a 1952, E r i c s o n 1959 and 1966 a, F o r e s t B i o l o g y S u b c o m m i t t e e 1963) and it is unnecessary to repeat them here in detail. In some methods wood density is determined without measuring at all the weight or volume of the sample. Such methods are the maximum moisture content method (S m i t h 1954 and 1955), the photometric measurement (M ü l l e r - S t o l l 1949, G r e e n and W o r r a l l 1964), microscopic measurement of the amount of cell wall substance (T s o u m i s 1964, S m i t h 1965) or the use of beta or gamma rays (B e r s e n e v and F o k i n a 1958, P h i l l i p s 1960, S a n d e r m a n n, S c h w e e r s and H o h e i s e l 1963, H o l l o w a y 1965, etc.).

The most commonly applied method of determining wood density is by measuring separately the weight and volume of the sample. The weight is obtainable easily with the help of a balance meeting the accuracy requirements. The volume can be measured in many different ways.

The simplest method of determining the volume of the sample is to calculate it from the dimensions. This requires a sample which is regular in form like a faultless increment core. The core volume is calculated from the length and diameter. The diameter value may be the bore diameter, as is the practice in the U.S. Forest Products Laboratory (M i t c h e l l 1958). Measuring the true diameter of the core by a micrometer instead of using the bore diameter will, however, give a more accurate result (W a l t e r s and B r u c k m a n n 1964).

Determination of the core volume from its length and diameter presupposes that the core surface is unbroken and even. It was noted when collecting the material that small fragments tend to break off the cores and thus the true volume of the core is smaller than the volume calculated on the basis of the diameter measured at the unbroken point. This was especially noticeable with rapidly growing spruce. For this reason, a method was chosen which does not necessitate an even core surface.

The volume of the increment cores was determined in the present study by the mercury immersion method evolved by Ericson. The volume of the core is determined by immersing it with a needle in a bowl of mercury placed on a M e t t - l e r K 7 T balance and reading the weight of the mercury displaced by the wood sample off the optical scale of the balance. E r i c s o n (1959) has described the method in detail.

As the densities reported in the present study are basic densities, the core volumes were measured when the wood was wet. However, practical facilities were lacking for volume determinations of green cores. They were therefore allowed to dry to prevent decay. Before volume measurement, the cores were soaked in water until they sank. Soaked cores give practically the same accuracy as green cores (L a r s o n 1957, W a l t e r s and B r u c k m a n n 1964, E r i c s o n 1966 a).

The accuracy of the mercury immersion method used for the volume measurements was established with a control material of pairs of samples consisting of a 4 cm thick disk and an increment core. The disk densities were determined by the method described by N y l i n d e r (1953 b) in which the disk volume is obtained by measuring the amount of water displaced by the wet disk. The densities thus determined from the disks were regarded as correct values and the core densities were compared with them. The volumes obtained by this method differed from stereometrically determined volumes in Nylinder's studies by no more than 0.1 $\pm$0.7 per cent.

The inner part of the stem is over-represented in comparison with the outer part in a core. If the density around the pith is denoted by a and at the cambium by b, it can be shown by simple calculus that the average density of the part of the stem in question is $(a + 2b)/3$ provided that density changes linearly from pith to cambium. However, the core gives a density value of $(a + b)/2$, weighting the inner part excessively. To improve the accuracy of the result, the core may be divided into several parts. The density can then be determined separately for each part and the average density calculated by weighting each part of the core in correspondence to the cross-section area represented by it.

In the present study, cores over 4 cm long were divided into three parts as recommended by E r i c s o n (1959). The places at which the cores were cut, starting from the pith, were core length/$\sqrt{10}$ and core length/$\sqrt{2}$. The relative areas represented by the core parts were, correspondingly, starting from the pith, 10, 40 and 50 per cent of the total cross-section area. It was thus possible to eliminate the greatest part of the above error. Using the same symbols, we obtain the following expression as the average density (D) of the core.

$$D = \left[15\ a + 5\ b + \frac{9\ (b-a)}{\sqrt{2}} + \frac{5\ (b-a)}{\sqrt{10}}\right] / \ 20$$

Table 4. Comparison by cores and stems of the densities determined from increment cores by the mercury immersion method (M) and from disks by the water immersion method (W).

Species	Difference W-M, kg/cu.m $\bar{d} \pm Sd$		t-value
	Comparison by cores		
Pine	+ 18	± 21	t_{222} = 12.50*
Spruce	+ 14	± 23	t_{277} = 10.41*
Birhes	+ 18	± 22	t_{150} = 12.29*
	Comparison by stems		
Pine	+ 18	± 11	t_{21} = 7.41*
Spruce	+ 16	± 12	t_{30} = 7.14*
Birhes	+ 19	± 8	t_{17} = 9.79*

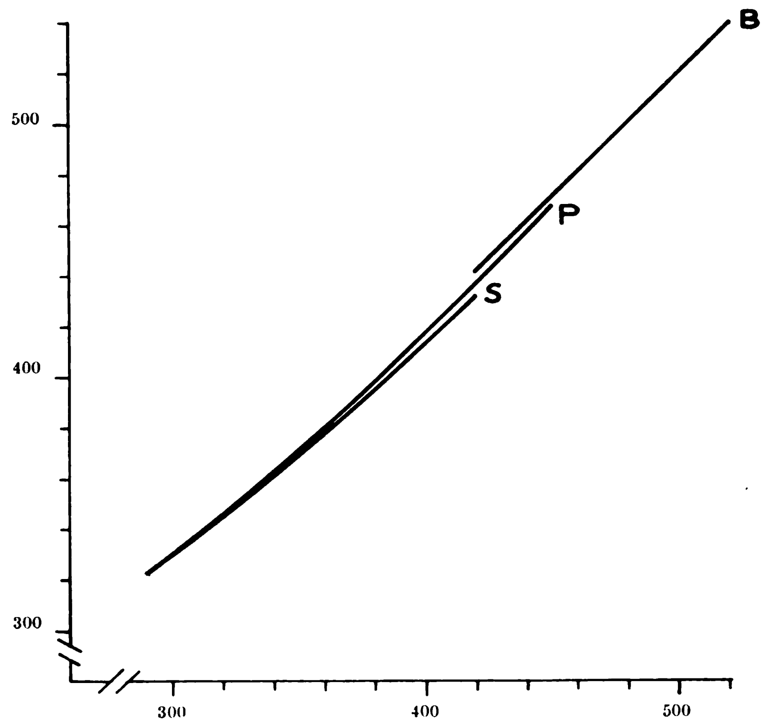
The magnitude of this particular systematic error associated with the method can be calculated from the formulas. If density increases linearly from pith towards cambium the systematic error decreases to one seventh of the original error when the core is divided into three parts as described above.

Short cores (2.5-4.0 cm in length) were cut for density calculations into two parts only, representing volumes of 30 and 70 per cent. Cores shorter than 2.5 cm were treated whole. The difference between the pith and the outer part in such short cores is small and consequently a small source of error.

It is assumed in the formulas that density changes linearly between the pith and the surface. In fact, the increase or decrease in density is rapid at first but slows down increasingly when moving from the pith towards cambium. Hence, the formulas presupposing linear correlation contain maximum errors which are bigger than the expected errors. It can be calculated from the foregoing formulas that this systematic error should not be greater than 2 kg/solid cu.m. However, the control material showed that the total error was considerably greater.

The magnitude of the systematic error of the method employed can be seen in Table 4. The densities obtained by the mercury immersion method from cores were on an average 4.1 per cent smaller than the values regarded as correct. M a r k w a r d t and P a u l (1946), S p u r r and H s i u n g (1954) and E r i c s o n (1959) also reported that densities measured from cores were smaller than densities measured from larger cubiform bodies or disks. W a h l g r e n and F a s s n a c h t (1959) did not find any significant differences between the average core and disk values. They pointed out, however, that the relationship was not in a 1:1 ratio at all levels of density.

Correted tree density, kg/cu.m.



Uncorrected tree density, kg/cu.m.

Figure 3. Correction of tree density values measured by the mercury immersion method.

In the present study, the error was obviously caused partly by the failure of the mercury to cover the core surface completely because air bubbles tended to stay on it. "The condition of the wood surface is certainly of great importance for determining the occurrence of systematic errors" (E r i c s o n 1966 a). This increased the amount of mercury displaced by the core and the volume registered was too big. The unevenness of the core surface was more pronounced the lighter the weight of the wood. The mercury therefore covered most poorly cores of low density. The error in the core volume measurement was thus dependent on the core density.

The magnitude of the correction can be arrived at from regression equations which show the true density of the sample as a function of the measured core density. The correlation between the variables conforms fairly well with the straight line, but when the samples in question are of very light weight the error grows at an increasing rate while the true density diminishes. A semi-logarithmic equation resulted in fact in a significantly bigger correlation coefficient for pine and spruce than a straight line. These equations were used to correct the density values measured by the mercury immersion method (Figure 3).

All the per-stem densities were determined from uncorrected core values and then corrected by the below-mentioned equations before the data processing. Core densities were corrected by their own equations when used for other purposes than to calculate per-stem densities.

Species	Correction equation	R^2	Sy.x
Pine	Log Y = 2.21932 + 0.00100 X	0.9106	11.2
Spruce ...	Log Y = 2.22260 + 0.00098 X	0.8368	11.2
Birches ..	Y = 33.1 + 0.970 X	0.9312	8.4

Y = corrected average tree density, kg/cu.m

X = average tree density measured by the mercury immersion method, kg/cu.m

The unexplained variation connected with the formulas is caused by several reasons. A part of the unexplained variation must be attributed to the inaccuracy of the density values determined from disks, a greater proportion to the increment core method. Another factor causing unexplained variation is the method of collecting the increment cores. Cores from the same tree were always collected from the same side of the stem. Although an endeavour was made to avoid abnormal wood insofar as this could be judged with the naked eye, the presence of compression and tension wood and other defects was a source of error in the results.

23. Statistical procedures

The data processing was performed with an IBM 1620 computer at the Computer Centre, University of Helsinki. The most important of the statistical procedures used in this investigation is regression analysis. The regression program computed among other things the following data.

- Mean of each variable
- All possible sums of squares and products of up to 14 variables
- Simple correlation coefficients for all possible pairs of variables (Table 5)
- Regression of the dependent variable on all possible linear combinations of up to ten independent variables ($Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \text{-----------} \beta_n X_n$)
- Standard deviation and t-value of each constant of the regression equations
- Simple or multiple correlation coefficient for each equation
- Standard deviation of the dependent variable associated with each fitted equation
- F-value of each fitted equation

Tree density was always as the dependent variable in the analysis (Y). The independent variables (X_i) included in the regression analysis were as follows.

X_1 = density at breast height, kg/solid cu.m

X_2 = density at 25 per cent height, kg/solid cu.m

X_3 = $X_1 \times X_{10}$ = interaction between density at breast height and tree length

X_4 = age, years

X_5 = age squared

X_6 = logarithm of age
X_7 = reciprocal of age
X_8 = breast height diameter above the bark, centimetres
X_9 = $X_8/X_4 = X_8 \times X_7$ = interaction between breast height diameter and tree age
X_{10} = tree length, metres
X_{11} = X_8/X_{10} = breast height diameter divided by tree length
X_{12} = crown proportion
X_{13} = tree class (1-4)
X_{14} = tree class squared
X_{15} = stand density (0.1-1.0)

$$\left.\begin{array}{ll} X_{16} & \text{: if the site is OMT, } X_{16}=1, \text{ otherwise } X_{16}=0 \\ X_{17} & \text{: if the site is MT, } X_{17}=1, \text{ otherwise } X_{17}=0 \\ X_{18} & \text{: if the site is VT, } X_{18}=1, \text{ otherwise } X_{18}=0 \\ X_{19} & \text{: if the site is swamp} X_{19}=1, \text{ otherwise } X_{19}=0 \end{array}\right\} \text{site quality}$$

$$\left.\begin{array}{ll} X_{20} & = X_{16} \times X_7 = X_{16}/X_4 \\ X_{21} & = X_{17} \times X_7 = X_{17}/X_4 \\ X_{22} & = X_{18} \times X_7 = X_{18}/X_4 \\ X_{23} & = X_{19} \times X_7 = X_{19}/X_4 \end{array}\right\} \text{interaction between tree age and site quality (pine and birches)}$$

X_{20} = $X_{16} \times X_4 = X_{16}/X_7$ interaction between tree age and site quality (spruce)
X_{21} = $X_{17} \times X_4 = X_{17}/X_7$
X_{22} = $X_{18} \times X_4 = X_{18}/X_7$
X_{23} = $X_{19} \times X_4 = X_{19}/X_7$

The calculations concerning density variation within the stem, density of different timber assortments, and the secondary samples were performed without computer help.

In all tests of this investigation the level of significance is 0.05. An asterisk after a test value indicates that the result of the test is significant at the five per cent level.

Table 5. Simple correlation coefficients for some pairs of independent variables.

Variable	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
	Simple correlation coefficient											
	Pine											
X_1	1.00	.85	.48	.53	.44	.59	-.61	.22	-.34	.30	-.07	-.30
X_2	-	1.00	.24	.47	.39	.52	-.54	-.00	-.48	.07	-.11	-.28
X_3	-	-	1.00	.35	.25	.44	-.49	.82	.31	.97	-.08	-.35
X_4	-	-	-	1.00	.97	.97	-.89	.39	-.51	.26	.34	-.31
X_5	-	-	-	-	1.00	.89	-.77	.35	-.48	.18	.40	-.23
X_6	-	-	-	-	-	1.00	-.97	.43	-.50	.36	.27	-.37
X_7	-	-	-	-	-	-	1.00	-.44	.45	-.41	-.19	.41
X_8	-	-	-	-	-	-	-	1.00	.50	.85	.43	-.06
X_9	-	-	-	-	-	-	-	-	1.00	.43	.20	.27
X_{10}	-	-	-	-	-	-	-	-	-	1.00	-.07	-.33
X_{11}	-	-	-	-	-	-	-	-	-	-	1.00	.43
X_{12}	-	-	-	-	-	-	-	-	-	-	-	1.00

(to be continued)

(cont.)

Table 5. Simple correlation coefficient for some pairs of independent variables.

Variable	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
					Simple correlation coefficient							
					Spruce							
X_1	1.00	.91	.01	.44	.43	.43	-.40	-.24	-.55	-.20	-.18	-.28
X_2	-	1.00	-.05	.40	.39	.39	-.36	-.26	-.55	-.23	-.17	-.30
X_3	-	-	1.00	.44	.39	.47	-.48	.90	.39	.97	.04	.00
X_4	-	-	-	1.00	.98	.97	-.90	.35	-.50	.34	.12	-.33
X_5	-	-	-	-	1.00	.91	-.80	.31	-.48	.29	.13	-.29
X_6	-	-	-	-	-	1.00	-.97	.37	-.50	.37	.09	-.36
X_7	-	-	-	-	-	-	1.00	-.38	.47	-.39	-.08	.37
X_8	-	-	-	-	-	-	-	1.00	.56	.94	.40	.13
X_9	-	-	-	-	-	-	-	-	1.00	.51	.27	.37
X_{10}	-	-	-	-	-	-	-	-	-	1.00	.08	.05
X_{11}	-	-	-	-	-	-	-	-	-	-	1.00	.26
X_{12}	-	-	-	-	-	-	-	-	-	-	-	1.00

(cont.)

Table 5. Simple correlation coefficients for some pairs of independent variables.

Variable	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
					Simple correlation coefficient							
					Common birch							
X_1	1.00	.80	.50	.40	.37	.41	-.41	.25	-.06	.28	.19	.04
X_2	-	1.00	.38	.43	.40	.46	-.47	.20	-.18	.21	.16	.00
X_3	-	-	1.00	.42	.35	.48	-.51	.82	.47	.97	.47	.14
X_4	-	-	-	1.00	.98	.98	-.91	.43	-.35	.37	.40	.08
X_5	-	-	-	-	1.00	.93	-.83	.37	-.35	.29	.37	.06
X_6	-	-	-	-	-	1.00	-.98	.47	-.33	.43	.40	.09
X_7	-	-	-	-	-	-	1.00	-.47	.32	-.46	-.37	-.10
X_8	-	-	-	-	-	-	-	1.00	.63	.85	.84	.37
X_9	-	-	-	-	-	-	-	-	1.00	.53	.55	.31
X_{10}	-	-	-	-	-	-	-	-	-	1.00	.47	.49
X_{11}	-	-	-	-	-	-	-	-	-	-	1.00	.14
X_{12}	-	-	-	-	-	-	-	-	-	-	-	1.00

(cont.)

Table 5. Simple correlation coefficients for some pairs of independent variables.

Variable	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
	Simple correlation coefficient											
	White birch											
X_1	1.00	.83	.37	.30	.26	.32	-.32	.09	-.14	.15	.03	-.06
X_2	-	1.00	.23	.34	.32	.35	-.34	.05	-.20	.05	.06	-.03
X_3	-	-	1.00	.35	.29	.39	-.42	.81	.49	.97	.32	.08
X_4	-	-	-	1.00	.98	.98	-.92	.38	-.38	.31	.37	.02
X_5	-	-	-	-	1.00	.92	-.84	.34	-.38	.25	.35	.02
X_6	-	-	-	-	-	1.00	-.98	.41	-.36	.35	.39	.01
X_7	-	-	-	-	-	-	1.00	-.43	.32	-.38	-.39	-.01
X_8	-	-	-	-	-	-	-	1.00	.66	.85	.77	.30
X_9	-	-	-	-	-	-	-	-	1.00	.55	.50	.29
X_{10}	-	-	-	-	-	-	-	-	-	1.00	.35	.41
X_{11}	-	-	-	-	-	-	-	-	-	-	1.00	.10
X_{12}	-	-	-	-	-	-	-	-	-	-	-	1.00

III. Results

1. DENSITY VARIATION WITHIN THE STEM

11. Variables causing density variation within the stem

As mentioned before, percentage summerwood is one of the most important factors affecting the density of softwoods, for summerwood density is 2-3 times the density of springwood. Trendelenburg and Mayer-Wegelin (1955) reported a number of studies in which the ratio of the dry densities for summerwood and springwood was 2.3-3.0 for Scotch pine and 1.9-2.8 for Norway spruce.

Spring- and summerwood are not distinguishable with equal clarity in diffuse-porous hardwoods, but the wood forming in them at the beginning of the growing season does differ from the wood that grows later in the summer. The relative volume of vessels compared with other cells decreases towards the outer margin of the annual ring, especially in ring-porous but also in diffuse-porous hardwoods. There is, on the other hand, a negative correlation between birch wood density and the vessel area (Walldén 1934).

In the present investigation, 53 per cent of the density variation of the increment core in pine wood and 40 per cent in spruce wood can be attributed to variation in percentage summerwood when the dependence between density and percentage summerwood is denoted by a straight line. The change in percentage summerwood affects density more sharply in spruce wood than in pine wood (Figure 4), for the slope of the regression line is significantly steeper in the equation for spruce than in the equation for pine ($t_{690} = 4.46^{*}$).

Species	Regression equation	R^2	Sy.x
Pine	Y = 307.3 + 3.49 X	0.5279	27.3
Spruce	Y = 296.9 + 4.61 X	0.4019	32.3

Y = wood density of increment core, kg/solid cu.m

X = percentage summerwood

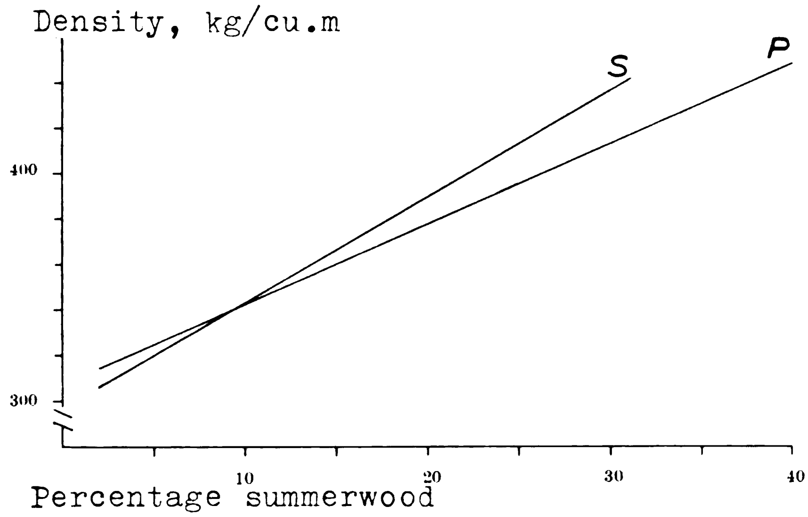


Figure 4. Correlation between wood density and percentage summerwood of the increment core.

In Larson's (1957) study 60 per cent of the variation in the density of Pinus Elliottii could be attributed to percentage summerwood, and Schafer (1949) succeeded in giving the corresponding explanation for 72 per cent of the density variation of pulpwood bolts made of southern yellow pines. In Pillow's (1954) study on Pinus taeda the comparable figure was 38 per cent. Van Buijtenen (1964) determined the regression between density and percentage summerwood in Pinus Elliottii separately for adult wood and juvenile wood. The value 0.79 was established for the coefficient of determination for the former, while the value for juvenile wood was only 0.27.

In the present study, using the density variation of the increment core, a smaller proportion of the total variation than in some other studies could be explained by the variation in percentage summerwood. However, it is evident that a considerable part of the wood density variation is caused by the variation in percentage summerwood.

All wood density variation cannot be explained by percentage summerwood for, in addition to the proportions of springwood and summerwood, the density of springwood and of summerwood also varies, depending on different factors. "Density of summerwood in the annual ring is related to summerwood tracheid characteristics. Negative genotypic and phenotypic correlation exists between summerwood density and tracheid radial lumen diameter, radial

Table 6. Percentage summerwood of pine and spruce in annual rings of different ages.

Ring age, years	Pine	Spruce
	Percentage summerwood	
	$\bar{X} \pm S$	$\bar{X} \pm S$
1 - 5	16.3 ± 5.1	14.7 ± 6.9
6 - 10	23.7 ± 5.9	16.2 ± 5.9
11 - 15	26.7 ± 6.3	18.1 ± 5.7
16 - 20	28.7 ± 6.5	19.5 ± 4.9
21 - 30	28.6 ± 6.0	21.5 ± 4.5
31 - 40	30.6 ± 6.6	22.6 ± 4.6
41 - 50	29.5 ± 9.8	22.7 ± 4.9
51 - 60	27.7 ± 9.2	23.5 ± 5.2

width, and tangential width. Double-wall thickness is phenotypically and positively correlated with density but no genotypic correlation is indicated. In springwood radial lumen diameter, tracheid radial width, and tracheid tangential width are phenotypically and genotypically correlated with density in a negative direction. Double-wall thickness is phenotypically and genotypically correlated with density in a positive direction" (G o g g a n s 1962).

There is a general tendency for both the density of summerwood and its percentage in the annual ring to increase year by year up to a certain ring age (R e n d l e 1959). This causes variation in the wood density in the radial direction of the stem. The change in percentage summerwood in pine and spruce from pith to cambium can be seen in Table 6.

The percentage summerwood of Scotch pine is exceptionally low in the vicinity of pith. It increases from the pith with age (S i r é n 1959, D i e t r i c h s o n 1964). The proportion of summerwood increases to 28-29 per cent within the first 15-20 annual rings.

The percentage summerwood on pine in southern Finland seems to remain at 28-29 per cent from the 20th year until at least the 60th. But several investigations have shown that the percentage summerwood of many tree species decreases at a later tree age (L a r s o n 1957). The percentage summerwood of pine in southern Finland is 28.2 according to J a l a v a (1934 b) and 21.9 according to S i i m e s (1938).

The increase in percentage summerwood from pith to cambium is also evident in spruce. The change is not equally abrupt as in pine, but it seems to continue longer.

There is a causal relationship between the low percentage summerwood in the vicinity of pith and juvenile wood formation. Juvenile wood is characterized by thin cell walls, less dense summerwood, a gradual transition from spring- to summerwood and a small proportion of summerwood (R e n d l e 1960). The density of juvenile wood is therefore low. A progressive increase in cell dimensions from pith to cambium occurs within the juvenile wood zone. The consequence is an increase in density in the radial direction.

In pines the gradual transition from juvenile wood to adult wood causes a quite distinct increase in density in the area of the first annual rings. The juvenile wood zone, however, is narrow, 5-8 annual rings in *Pinus Elliottii* and 8-11 in *Pinus taeda* (Z o b e l, W e b b and H e n s o n 1959). For Scotch pine, the width of the juvenile wood zone has not been established, but as it is a longer-lived tree species its juvenile wood zone can be assumed to contain slightly more numerous annual rings (cf. R e n d l e 1959). According to an anonymous investigation (1957), the annual ring of Scotch pine generally attains the normal adult pattern between the tenth and the twentieth years.

Almost all studies of juvenile wood have been concerned with pine species. Its significance may be smaller for certain other tree species.

Wood density increases from pith to cambium also outside the juvenile zone. The following regression equations show the dependence of the average density of the increment core on the core age. The age of pine and spruce cores in the sample was 4-100 years and that of common birch cores 4-75 years.

Species	Regression equation	R^2	Sy.x.
Pine	$Y = 344.8 + 2.220\ X - 0.01477\ X^2$	0.4049	27.2
Spruce	$Y = 358.8 + 0.828\ X - 0.00376\ X^2$	0.0704	40.1
Common birch	$Y = 424.5 + 2.999\ X - 0.02400\ X^2$	0.2715	34.2

Y = wood density of increment core, kg/solid cu.m

X = increment core age, years

The best coefficients of correlation were obtained from the above equation models. Even then, in spruce wood it was possible to relate only 7 per cent of the variation in the average density of the increment core to age. In pine wood the variation explainable by core age was 40 per cent of the total variation.

The average density of a pine increment core is at its maximum when the core is some 80 years of age, after which the density begins to decrease. The corresponding point of culmination is reached in spruce a few decades later, in common birch a little earlier (Figure 5).

It can be assumed from the foregoing that the average density of a whole tree also reaches its maximum at a certain age. However, this age limit must be considerably higher for the whole tree than for an individual increment core.

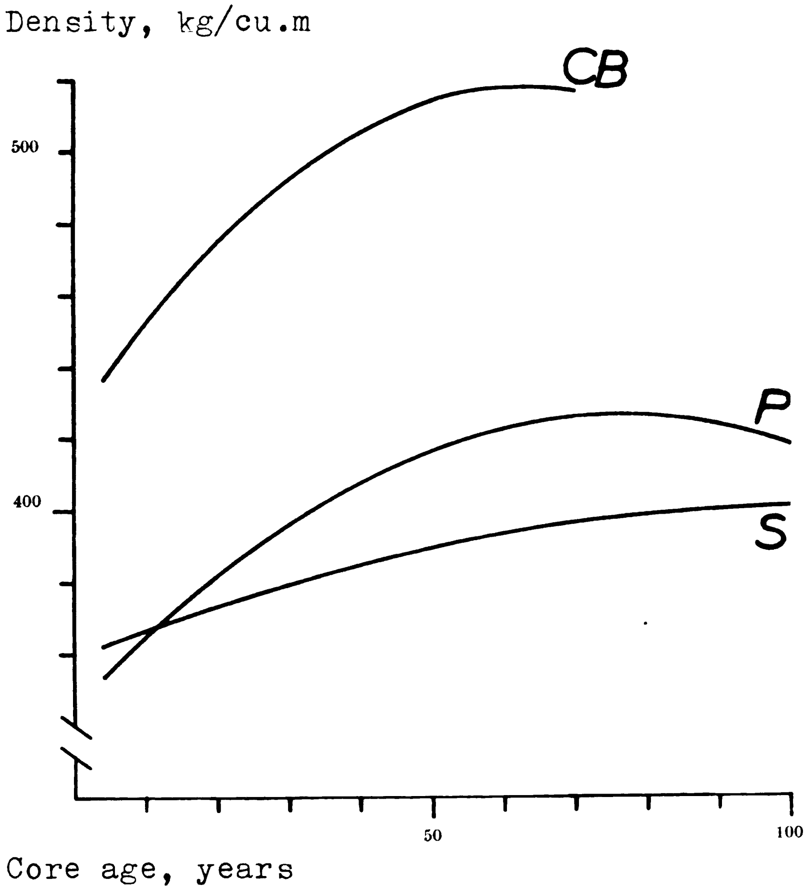
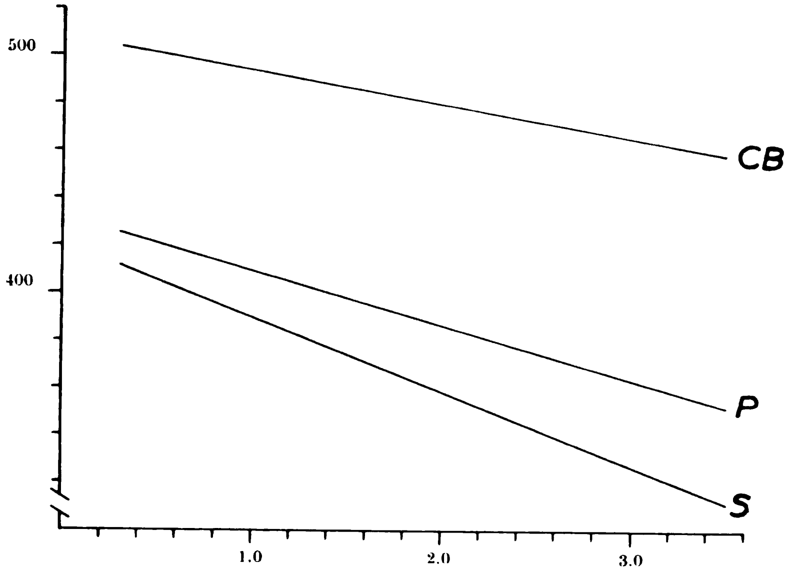


Figure 5. Correlation between wood density and core age.

The question of the effect of ring width on wood density has aroused a great deal of controversy. Knowledge of this matter is of primary importance for practical silviculture, but opinions on the subject are still contradictory. The discovery of juvenile wood formation has given rise to new points of view, but there is no unanimity.

Numerous investigators have concluded that there is a negative correlation between density and ring width in pine and spruce wood. For Scotch pine only, this view is advocated by H a r t i g (1884), K i n n m a n (1923), L u n d b e r g (1928), V o l k e r t (1941), B u r g e r (1948), Y l i n e n (1951), M o l t e s e n (1957), E c h o l s (1958) and N y l i n d e r (1961a), and for Norway spruce by H a r t i g (1884), C i e s l a r and J a n k a (1902), K i n n m a n (1923), V o l k e r t (1941), K l e m (1944), W e g e l i u s (1949), N y - l i n d e r and H ä g g l u n d (1954), A l d r i d g e

Density, kg/cu.m



Ring width, mm

Figure 6. Correlation between wood density and ring width of the increment core.

and H u d s o n (1955 and 1958), M o l t e s e n (1957), H a l e (1962) and B e r n h a r t (1964). On the other hand, it has been observed in some studies that the density of Scotch pine is small when the annual rings are very narrow. According to S i i m e s (1938), the density of pine is thus highest when the width of the annual ring is 1.0-1.2 mm, and according to Š k r i p e ň and R i a s o - v á (1958) when it is 1.4 mm.

In the present work, the correlation between wood density and ring width was calculated from a material in which the ring width was 0.3-3.5 mm and the increment cores were under 100 years old. The regression was denoted by a straight line.

Species	Regression equation	R^2	Sy.x
Pine	Y = 434.6 – 29.7 X	0.2823	33.7
Spruce	Y = 410.7 – 21.5 X	0.1743	37.8
Common birch	Y = 507.1 – 19.6 X	0.0969	42.1

Y = wood density of increment core, kg /solid cu.m

X = ring width, mm

The existence of the juvenile wood phenomenon was not taken into consideration above, However, naked eye examination of the cross section of the wood reveals that the annual rings are wider than the average in the vicinity of pith. The only exceptions are trees which, when young, have grown slowly in the shade of large trees, such as undergrowth spruces. As wide annual rings are often a feature of juvenile wood, juvenile wood formation must also be considered in analysing density and ring width.

According to T u r n b u l l (1947), the density of *Pinus patula* increases outwards from the pith in proportion to the age or number of rings from the pith. As ring width nearly always decreases in the same direction, "there appears to be a relation between narrow rings and high density, but this relation is primarily accidental". "The failure to recognize the existence and the properties of juvenile wood has led to many of the conclusions where rate of growth has been found to be strongly related to wood density" (G o g g a n s 1961).

A surprising change occurs in the structure of regression equations when the effect of juvenile wood is eliminated by excluding from the material the pith part of cores cut into three (Figure 6). The correlation between wood density and ring width is then smaller in pine and birch wood but considerably greater in spruce wood than the above.

Species	Regression equation	R^2	Sy.x
Pine	Y = 432.1 - 23.0 X	0.1098	37.7
Spruce	Y = 420.6 - 31.1 X	0.4242	27.3
Common birch ...	Y = 508.2 - 14.7 X	0.0650	40.2

Y = wood density of increment core, kg/solid cu.m

X = ring width outside the juvenile wood zone, mm

Studies in which the juvenile wood phenomenon has been taken into consideration have generally established that the correlation between the wood density of pines and the annual ring width is smaller than previously assumed. V o l k e r (1941) assumed that this correlation may be only ostensible. The correlation was later found to be fairly weak for several pine species (C o c k r e l l 1944, S p u r r and H s i u n g 1954, B a n k s 1955, B a n k s and S c h w e g m a n n 1957, L a r s o n 1957, C o o p e r 1960).

The present investigation shows, however, that no conclusion regarding the properties of spruce wood can be drawn on the basis of the juvenile wood formation of pines. If the wood in the vicinity of the pith is disregarded, the wood density of spruce increases as the ring width narrows. This is supported by the regression equations given by T a m m i n e n (1962 and 1964) which show the correlation between sapwood density and percentage summerwood and the ring width. The coefficient of determination obtained from the equations is 0.40 for spruce, but only 0.22 for pine.

The negative correlation between spruce wood density and ring width is largely dependent on the negative correlation between percentage summerwood and ring width (W e g e l i u s 1946, N y l i n d e r 1953 b, K l e m 1957). In contrast, the corresponding correlation is weaker for pines (L a r s o n 1957). However, R i s i and Z e l l e r (1960) found no correlation between the wood density and ring width of Picea mariana. It is worth of mentioning that the average ring width of spruce pulpwood in a study of the 1930s was 1.96 mm in the area in question here (V u o r i s t o 1937).

12. Density variation in the radial direction of the stem

The objective set was to find patterns in accordance with which wood density varies within the tree. The problem was divided into two parts: variation in density in the radial direction of the stem, and variation in density in the longitudinal direction of the stem. However, as these part tasks are interlinked, they are inevitably discussed concurrently from time to time.

Table 7 shows the density variation in different parts of the stem in pine, spruce and birches. The material was divided into three age classes. These classes are not fully comparable because the youngest contains a higher proportion of trees that have grown on good sites than the older age classes. Three values are given for each relative height. The first represents the inner part of the stem which contains 10 per cent of the stem volume atthe heigth in question. The third value represents the surface of the stem, and correspondingly, 50 per cent of the stem volume. The middle value denotes the density of the part of the stem between other two parts.

The density of pinewood increases from pith to cambium. This is seen most clearly in the middle age class of the material and, again, at the relative height of 10 per cent. An exception may be the butt part of old stems on account of extractives that develop in heartwood (cf. J a l a v a 1952).

A density increase from pith to cambium is in fact characteristic of most softwoods (G o g g a n s 1961). It has been established for Scotch pine by W i j k a n d e r (1897), H e l a n d e r (1918), T r e n d e l e n b u r g (1939), J a l a v a (1946), N y l i n d e r (1953 a) and T a m m i n e n (1962). The change is similar in several other pine species (O r m a n 1952, S p u r r and H s i u n g 1954, B a n k s 1955, Y a n d l e 1956, K e l s e y and S t e e l e 1956, J a y n e 1958, etc.).

Table 7. Density of pine, spruce and birch wood in different parts of the stem.

Relative stem height, per cent	Tree age, years: - 40			41 - 80			81 +		
	Part of the core: Inner	Middle	Outer	Inner	Middle	Outer	Inner	Middle	Outer
	Density, kg/solid cu.m								
	Pine								
0	390	402	424	427	443	470	481	476	478
10	343	371	414	363	408	459	405	444	465
20	334	353	395	360	392	436	390	420	443
30	333	343	382	354	384	424	378	404	429
40	330	344	365	350	379	406	374	394	413
50	334	345	364	354	376	397	370	389	399
60	333	341	344	357	368	382	374	385	384
70	..	..	..	345	363	364	374	378	376
	Spruce								
0	386	353	363	396	370	384	415	401	404
10	349	344	361	369	366	387	386	398	407
20	341	338	352	356	362	385	379	391	402
30	338	338	353	354	361	377	371	383	397
40	342	332	349	356	360	375	372	382	389
50	349	335	347	365	368	373	372	380	382
60	352	334	344	359	359	369	374	377	377
70	..	..	..	361	358	366	375	376	369
	Birches								
0	456	487	519	468	498	517	490	516	521
10	440	471	503	458	488	512	488	515	527
20	441	468	495	454	486	504	472	505	518
30	445	460	490	452	485	499	474	505	520
40	439	465	485	454	483	497	471	502	517
50	429	454	471	462	486	499	473	501	508
60	438	436	464	453	476	503	487	503	494
70	..	..	..	449	473	467	469	494	499

The change in the density of Scotch pine is sharpest in the area of juvenile wood, but continues outside this zone as well. The density of forming wood depends appreciably on the percentage summerwood and on the stem age at the height in question, but the width of the annual ring is also significant. The average density of the cross section of pine seems to reach its maximum when the tree age at the stem height in question is about 80 years.

The wood density of spruce changes a little more irregularly in the radial direction of the stem. It is relatively high in the immediate vicinity of pith, higher than in Scotch pine. The density decreases first towards the cambium, contrary to the situation with the pine, but, a few annual rings later, begins again to increase towards the cambium. No endeavour was made in this connection to establish the point where the change takes place. Owing to the sampling method employed, the above change in density can be established in Table 7 only in the youngest age class. In a study by N y l i n d e r (1953 b), the density of wood in a spruce plantation was at its minimum five annual rings from the pith. In *Picea sitchensis* the corresponding point was 10-15 rings from the pith (B r y a n and P e a r s o n 1955).

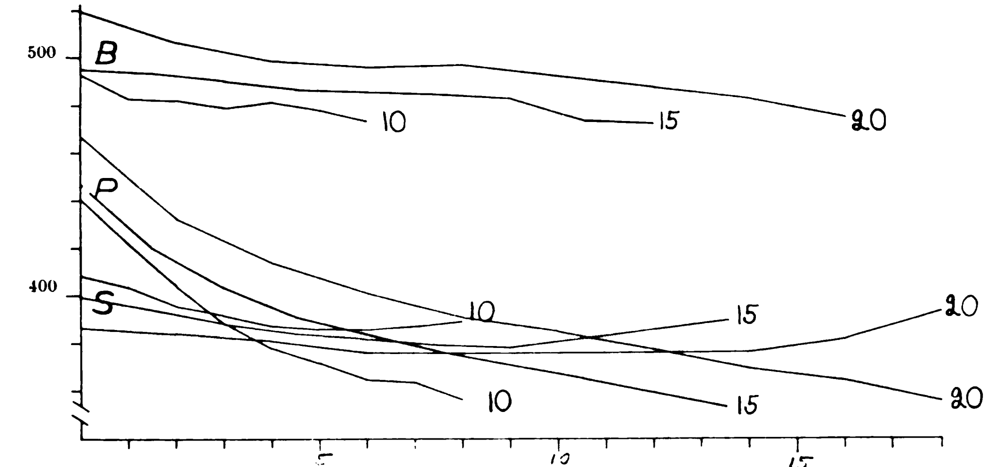
The wood density in spruce does not apparently greatly depend on the ring distance from the pith. On the other hand, percentage summerwood and ring width appear to be of great significance. It may be assumed from the last-mentioned factor that silvicultural treatments may affect wood quality particularly strongly in spruce wood.

The wood density of birches increases regularly from pith to cambium. This has been established also by S t a u f f e r (1892), W a l l d e n (1934), J a l a v a (1946) and K u j a l a (1946). However, the changes in birches are smaller than those in Scotch pine and the effect of ring width in particular on wood density is weak.

13. Density variation in the longitudinal direction of the stem

Density variation in the longitudinal direction of the stem is important for the value ratios of timber assortments. As the density variation within the stem is usually greater than the inter-stem density variation, it is important for the timber user to be familiar with it.

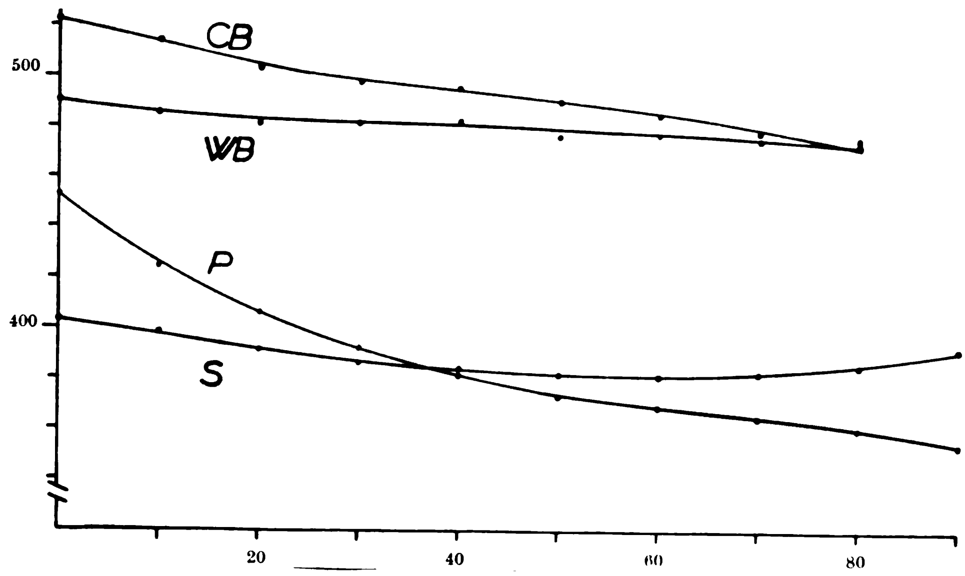
Density, kg/cu.m



Distance from stump level, m

Figure 7. Density of 10, 15 and 20 m pines, spruces and birches at different stem heights.

Density, kg/cu.m



Relative stem height, per cent

Figure 8. The variation pattern of wood density in the longitudinal direction of the stem.

Density variation in the longitudinal direction of the stem depends on the tree size. It is greatest in a long stem, but sharpest in a short stem. Figure 7 shows that the average wood density of pine and birches increases with tree length. For spruce, the situation is reversed. In pine and birches, the difference in the density of stems of varying sizes in influenced more by positive correlation between density and age, in spruce by the negative correlation between density and rate of growth. In harvesting spruce, small stems are obtained mostly from the slow-growing trees of the suppressed tree classes.

The density variation in the longitudinal direction in stems of varying sizes can be illustrated by a single curve when the absolute heights are converted to relative heights. This gives variation patterns of general applicability for each tree species, and these are shown in Figure 8 fitted with the naked eye. It is possible with the help of these patterns to compare the different tree species.

Density of pinewood decreases from the butt towards the crown, at first more sharply, but within the living crown more slowly. S p u r r and H s i u n g (1954) listed a number of studies showing that this trend prevails not only in pines but also in many other softwoods.

The variation pattern of density in the spruce stem differs from most of the other tree species. The density of the butt end at first decreases on moving towards the crown, but from the middle of the stem it begins to increase again. A similar conclusion was drawn by B e r t o g (1895) according to whom the wood density of spruce decreases from the butt to the lower limit of the living crown but increases again within the crown towards the top of the tree. This result was arrived at by B e r n h a r t (1964) as well. Some authors are of the opinion that density of spruce wood in the longitudinal direction of the stem is relatively constant (T u r n - b u l l 1942, J a l a v a 1946). The density of *Picea sitchensis* decreases towards the crown according to one report (B r y a n and P e a r s o n 1955), while a contrary trend was noted in Picea glauca in another study (H a l e and F e n s o m 1931).

The density of birches decreases from the butt towards the crown. This has been reported also by S t a u f f e r (1892), J a l a v a (1946) and K u j a l a (1946). Wood in the butt is 30 kg/solid cu.m heavier in common birch than in white birch. However, the density of common birch decreases more sharply towards the crown, and the wood density in these two birch species is the same at the relative height of 90 per cent.

"Springwood formation is associated with active crown growth, and on the main trunk the bulk of the springwood is produced during the period of terminal elongation. Proximity of the crown assures a high production of springwood in the stem" (L a r s o n 1962). Therefore the springwood portion of the annual ring tapers downward and the summerwood portion tapers upward (T u r n - b u l l 1937).

As the living crown of the tree recedes from the butt, the effect of auxin that develops in the crown on the butt end of the cambium, and via it on the properties of the wood that develops in the butt end of the tree, decreases. It is partly for this reason that the density of the pine and birch wood which develops at a certain height increases with age, as was shown by the regression equations presented earlier.

The development is different in the spruce stem. The living crown does not contract equally rapidly as in the pine and birches. The crown of spruce trees in the investigation material comprised an average of 68 per cent of the total stem length, while the comparable figure for pine was 43 and for birches 50 per cent.

A considerable proportion of spruce wood develops within the crown. The wood forming in the different parts of the stem is thus fairly even in density. This concurs well with the strength requirement made of the stem because, since the crown reaches far down, the wind pressure is distributed more evenly over the different

parts of the stem than in the pines. The different density gradient of common birch and white birch may also be caused partly by the different self-pruning of the stem. The self-pruned part of the stem is generally longer in common than in white birch (H e i s k a n e n 1957).

The variation of wood density in the longitudinal direction of the stem shows that the densities of timber assortments prepared from different parts of the stem differ. This question, which is of especial interest to the pulp and paper industry, is discussed in Chapter 3. The density variation in the longitudinal direction of the stem must be taken into consideration also in the collection of density samples. The following chapter deals with its effect on the sampling method.

14. Estimating the average tree density

When the present investigation was begun it was known that several wood density studies would be needed in the next few years. The tasks will be such that the samples must be collected by increment borer from standing trees. No such method has been used so far in Finnish conditions. However, V u o k i l a (1960) proved that the average tree density of *Larix sibirica* can be measured most accurately from samples taken at the height of 4–5 m. N y l i n d e r (1961 a and 1961 b) established that at 10 per cent height the density of pine is 7 per cent and of spruce 2 per cent higher than the average tree density. The difference was not constant, but depended on, for instance, the tree age.

The development of an effective sampling method for the research tasks in question was one of the problems of the present work. By the time the investigation was commenced W a h l g r e n and F a s s n a c h t (1959), U.S. Forest Products Laboratory, had worked out regression equations for southern yellow pines. These equations showed the average tree density as a function of the reciprocal of the density of an increment core taken at breast height. The best of the coefficients of determination given by these equations was for *Pinus* taeda, 0.53, and the poorest that for Pinus Elliottii, 0.25. Multiple regression analyses did not increase appreciably the proportion of explained variation. It had also been shown in young Pinus taeda and Pinus Elliottii trees that there is a very close association between the density of juvenile wood at breast height and that of the entire zone of juvenile wood (Z o b e l, W e b b and H e n s o n 1959).

The density of Scotch pine, Norway spruce and birches is higher at breast height than the average tree density (Table 8). But, despite the fact that the density at breast height tends to give too high average tree density, it does not alter the density ranking of the trees (B a r e f o o t, H i t c h i n g s and E l l w o o d 1964).

Table 8. Density (kg/solid cu.m) at breast height and average tree density.

Species	Density at breast height $\bar{X} \pm S$	Average tree density $\bar{X} \pm S$	Diffe-rence	t-value
Pine	432.4±44.3	408.6±32.8	23.8	$t_{1568}=11.59^{*}$
Spruce	392.4±33.8	386.8±30.0	5.6	$t_{1500}= 3.36^{*}$
Common birch	509.8±37.4	496.9±31.2	12.9	$t_{496}= 4.18^{*}$
White birch	484.5±33.5	481.9±29.2	2.6	$t_{618}= 1.03$
Birches, combined	495.8±37.4	488.6±31.0	7.2	$t_{1116}= 3.50^{*}$

A sample taken at breast height, thus, permits comparison of the average tree density for a certain tree species.

When the average tree density is determined from a sample taken at breast height, the result will be too high unless corrected. The correction is best performed by using a regression equation which gives the average tree density as the function of density measured at breast height. In addition to simple linear regression, multiple linear regression was also tested for different tree species.

The results of the regression analysis are given in Table 9. Variables anumerated on p. 25 were tested as independent variables. The table gives the best equations for one, two and three independent variables and for comparison with some earlier studies equations, in which X_1 and X_8 are independent variables. The following variables appear in the table.

Y = average tree density. It was calculated as the weighted mean of increment cores taken from the stem. The mean was corrected for the error caused by the mercury immersion method.

X_1 = density at breast height. As no increment core was taken at breast height, this value was obtained by interpolation from the densities of the increment cores taken both sides of the 1.3-metre height. The value obtained was corrected as above.

$X_3 - X_{10}$: See page 25.

Density at breast height was thus determined by using two increment cores. This involved interpolation in which the increment core taken at 10 per cent height generally had more weight. If the stem height was exactly 13 m, the value was obtained solely from an increment core taken at 10 per cent height. The average height of all the tree species was roughly 13 m.

Table 9. Regression of the average tree density on the on the density at breast height.[1)]

Species	Regression equation	R^2	Sy.x
Pine	$Y = 129.0+0.648X_1$	.7663	15.9
	$= 129.0+0.682X_1-1.039X_8$	.8053	14.5
	$= 170.0+0.589X_1-67.8X_9$	.8138	14.2
	$= 155.8+0.634X_1-46.7X_9-0.738X_{10}$	.8224	13.9
Spruce	$Y = 66.4+0.817X_1$	.8471	11.7
	$= 79.4+0.799X_1-0.409X_8$	.8541	11.5
	$= 73.6+0.818X_1-0.00145X_3$	.8560	11.4
	$= 89.9+0.779X_1-15.2X_9-0.429X_{10}$	.8571	11.4
Common birch	$Y = 122.8+0.734X_1$	.7716	15.0
	$= 122.2+0.737X_1- 0.074X_8$	.7718	15.0
	$= 162.1+0.682X_1-630X_7$	.7905	14.3
	$= 168.2+0.700X_1-982X_7-0.00028X_3$	.7922	14.3
White birch	$Y = 95.1+0.798X_1$	.8414	11.6
	$= 95.1+0.798X_1+0.000X_8$	.8414	11.6
	$= 98.5+0.777X_1+0.128X_4$	.8477	11.4
	$= 36.1+0.907X_1+1.249X_4-0.00232X_3$	.8501	11.4
Birches, combined	$Y = 118.5+0.746X_1$	.8134	13.4
	$= 117.4+0.753X_1- 0.146X_8$	.8141	13.4
	$= 126.3+0.746X_1-30.5X_9$	.8248	13.0
	$= 143.4+0.722X_1-23.7X_9-338X_7$	.8299	12.8

1) Density at breast height (X_1) was obtained by interpolation from the densities of the increment cores taken both sides of the 1.3-metre height.

The coefficients of determination obtained from the equations are high for all the tree species, especially for spruce and white birch in which the wood density changes fairly little in the longitudinal direction of the stem. For comparison, mention may be made of the equations employed in the southern and western wood density surveys in the U.S.A. (U.S. Forest Service 1965a and 1965b) which give the average tree density on the basis of the density of an increment core taken at breast height and the breast height diameter. In the former case the best coefficient of determination, 0.59, pertains to *Pinus longifolia*, and the poorest, 0.44, to *Pinus*

Elliottii (M i t c h e l l 1965). The comparable figures in the western wood density survey were 0.70 for Tsuga heterophylla and 0.44 for Larix occidentalis (W a h l g - r e n 1965). At least the following factors contributed to the higher accuracy achieved by the equations presented in this investigation.

Table 10. Density (kg/solid cu.m) at 25 per cent height and the average tree density.

Species	Average tree density $\bar{X} \pm S$	Density at 25 per cent height $\bar{X} \pm S$	Difference	t-value
Pine	408.6±32.8	408.5±36.1	0.1	$t_{1568}=0.02$
Spruce	386.8±30.0	386.3±32.5	0.5	$t_{1500}=0.37$
Common birch	496.9±31.2	495.9±33.5	1.0	$t_{496}=0.36$
White birch	481.9±29.2	481.9±32.5	0.0	$t_{618}=0.00$
Birches, combined	488.6±31.0	488.1±33.7	0.5	$t_{1116}=0.24$

Present investigation	American wood density surveys
- Density at breast height determined by interpolation from densities measured from two increment cores.	- Density at breast height determined from one increment core only.
- The increment core was divided into three parts for the density determination	- Increment core treated as a whole.
- Increment core volume measured by the mercury immersion method. Systematic error was corrected.	- Increment core volume measured on the basis of the core length and the diameter of the increment borer.

E r i c s o n (1966 b) developed the corresponding equations for Scotch pine and Norway spruce in Sweden. The coefficient of determination was 0.59-0.93 in different cases and for spruce higher than for pine.

The accuracy increases with the number of cores taken from the tree (T a r a s and W a h l g r e n 1963, K r a h m e r and S n o d g r a s s 1965). As it is the intention to take only one increment core at breast height in later studies, it is probable that the average tree density cannot be calculated as accurately as in Table 9. T a r a s and W a h l g r e n (1963) were able to reduce the standard deviation for the equation of *Pinus longifolia* from 21 kg/solid cu.m to 18 kg/solid cu.m when instead of one increment core two cores were taken at breast height and both were divided into three parts for the density measurement.

It was shown by N y l i n d e r (1961 a) that the density of Scotch pine at 25 per cent height is approximately the same as the average tree density. This is valid for spruce, common birch and white birch as well (Table 10).

It appears from Table 10 that average tree density can be determined from a sample taken at 25 per cent height with even greater accuracy than from a sample taken at breast height (cf. Table 8). Although the practical importance of such a sampling method is insignificant, some regression equations are presented here for the sake of comparison. In these equations, the 25 per cent height density is used. It was calculated as the arithmetic mean of the densities of cores taken at 20 per cent and 30 per cent heights, with the systematic error of the mercury immersion method eliminated from the mean as described in the chapter on the method. Table 11 shows that this procedure really gives a higher accuracy. The use of the method, however, is restricted to materials collected from felled trees.

The results of this study show that the average tree density can be established from an increment core taken at breast height. The equations of Table 9 were based on the assumption that the density of the increment core

Table 11. Regression of the average tree density on the density at 25 per cent height. [1])

Species	Regression equation	R^2	Sy.x
Pine	$Y = 63.4+0.845X_2$	.8619	12.2
	$= 81.1+0.813X_2-20.9X_9$	.8658	12.0
	$= 81.7+0.799X_2-15.0X_9+0.059X_4$	.8681	11.9
Spruce	$Y = 48.2+0.877X_2$	.9014	9.4
	$= 67.2+0.839X_2-22.4X_9$	.9052	9.2
	$= 67.8+0.842X_2-16.2X_9-0.217X_{10}$	.9061	9.2
Common birch	$Y = 77.4+0.846X_2$	.8250	13.1
	$= 102.7+0.809X_2-352X_7$	.8306	12.9
	$= 153.1+0.809X_a-841X_7-10.3X_6$	.8314	12.9
White birch	$Y = 83.8+0.826X_6$	.8484	11.4
	$= 78.1+0.823X_2+0.535X_{10}$	.8529	11.2
	$= 84.7+0.811X_2+0.803X_{10}-18.7X_9$	.8553	11.2
Birches, combined	$Y = 75.9+0.946X_2$	.8438	12.3
	$= 74.9+0.833X_2+0.482X_{10}$	.8484	12.1
	$= 82.1+0.819X_2+0.747X_{10}-17.2X_9$	.8506	12.0

[1]) Density at 25 per cent height (X_2) = the arithmetic mean of the densities of cores taken at 20 per cent and 30 per cent heights.

taken at breast height has been correctly measured. The serviceability of the equations is thus not necessarily tied with a sample of certain shape or size. They can be used whether the sample is an increment core taken at breast height or in disc form. Also, the increment core diameter does not have to be the 5.5 mm used here. What is most important is that the systematic error of each method is eliminated before the equations are applied.

As the core to tree density relationship within a species does not vary significantly with geographic location (M i t c h e l l 1964), it seems that the problems set in the study can be solved by taking the increment core at breast height from a standing tree. The average tree density is obtained by using the relevant equation from Table 9.

2. DENSITY VARIATION BETWEEN THE STEMS

21. The external tree characteristics as density indicators

211. Regression of tree density on tree age

For pine, common birch and white birch, age was the most important of the variables tested for effect on the average tree density. The age range of the trees in the samples was 25-150 years for softwoods and 25-100 years for birhes. The density of pine and white birch within these age ranges was illustrated best by a regression equation in which both age and the square of age were independent variables. For spruce, however, the square term proved insignificant, and it was possible to illustrate the correlation between average tree density and age by a straight line. The density of common birch was explained best by the reciprocal of age (Table 12).

Table 12. Coefficients of determination illustrating the correlation between tree density and age.

Species	Independent variable				
	Age	Age^2	$Age+Age^2$	Logarithm of age	1/age
	Coefficient of determination				
Pine	.2409	.1707	.3185	.2975	.3157
Spruce	.1506	.1443	.1506	.1411	.1161
Common birch	.1984	.1677	.2218	.2243	.2388
White birch	.1208	.0990	.1383	.1320	.1284

Pine reaches its maximum density, according to the present material, only after it is more than 100 years old, white birch a little earlier. The density of spruce and common birch stems did not reach the maximum value in this material (Figure 9). However, these tree species obviously show the same development later on, for a decrease in wood density has been reported for the narrow rings of over-mature specimens of practically all the major species studied (L a r s o n 1957).

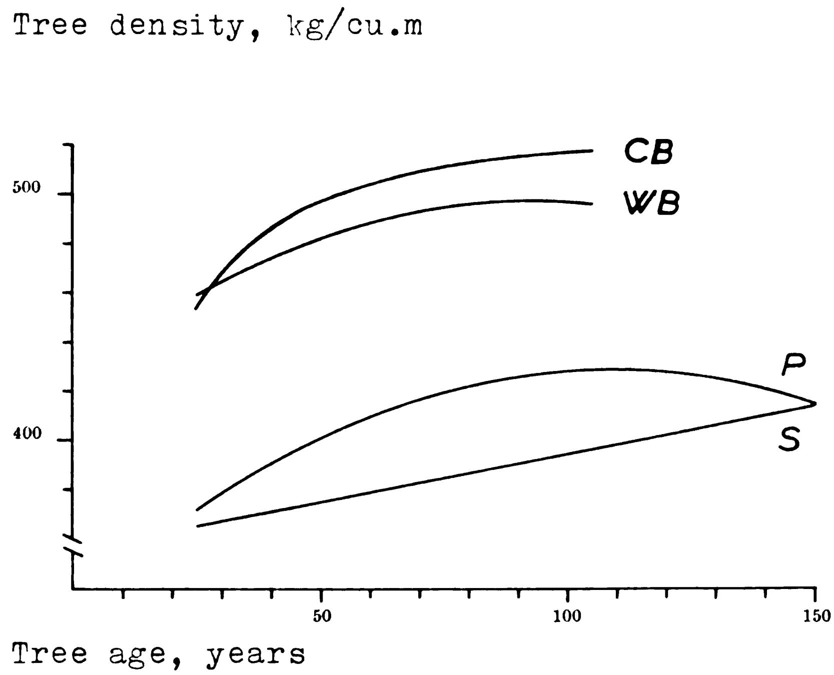


Figure 9. Correlation between tree density and tree age.

Table 13. Regression of tree density on age.

Species	The best regression equation	R^2	Sy.x
Pine	$Y = 333.8+1.759X_4-0.00806X_5$	.3185	27.1
Spruce	$Y = 356.5+0.390X_4$	.1506	27.6
Common birch	$Y = 538.0-2\ 036X_7$	.2388	27.3
White birch	$Y = 425.3+1.565X_4-0.00850X_5$	.1383	27.2

The low density of wood produced by an old tree results from the decreasing vigour of the tree.

The equations which illustrate best the regression between tree density and age are given in Table 13 for each tree species. The correlation is closest for pine, but it is significant for the other tree species as well. The correlation between tree density and age has been correspondingly greater for pine than for other tree species in foreign investigations, too. Wheeler and Mitchell (1962) found that by far the most important single variable tested to predict core density was the reciprocal of age. The coefficient of determination was 0.17 for *Pinus longifolia* and 0.36 for *Pinus taeda*. In the western wood density survey (U.S. Forest Service 1965 b), the significance of age was distinctly smaller for e.g. *Pseudotsuga* and *Abies*. In K l e m's study (1965) only 2 per cent of the density variation of spruce could be attributed to age.

However, the part of the variation in tree density which in the present work was seen to be related to tree age is not caused in its entirety by age (cf. K n i g g e and S c h u l z 1966). Other factors, such as the growth rate, are also involved. The youngest trees in the material are from the best sites, as trees on poor forest site types do not in 25 years reach the minimum stem size used in this study. In spite of this, it is obvious that tree age is of such great significance for tree density that attention should be paid to the following points.

- An endeavour is made in Finland to shorten the rotation time of the growing stock. In consequence, the average density of the wood produced by the forests of southern Finland will decrease.
- The future tree plantations will produce usable timber at a fairly early age. The density of the timber to be harvested from plantation stands will be exceptionally low in the first thinnings owing to the young age of the growing stock. Such timber should be directed to the groundwood pulp, particle board or other industry for which low-density wood is most suitable.
- The growing stock of northern Finland is of considerably older age than that of southern Finland, but for a great part over-mature. This may be responsible for the differences in the pulp and paper industry's raw material consumption which have been found to exist in practice.
- Attention should always be paid to tree age in studies of wood density.

212. Regression of tree density on stem size and form

The correlation between tree density and stem size and form was studied with the aid of the following variables: diameter at breast height above the bark (X_8), stem length (X_{10}), and breast height diameter divided by the stem length (X_{11}). The last-mentioned variable was considered to illustrate the taper of the stem.

The results of regression analysis are shown in Table 14 which gives the coefficient of determination obtained from the equations. The values in brackets were obtained from equations which the F-test did not prove significant at the five per cent level.

Table 14. The interdependence between tree density and stem form and size. Coefficients of determination when the effect of age is not taken into consideration.

Species	Variable		
	X_8	X_{10}	X_{11}
	Coefficient of determination		
Pine	(.0000)	(.0043)	.0093
Spruce	.0886	.0734	.0278
Common birch	.0446	.0523	.0237
White birch	.0073	.0132	(.0022)

The interdependence between average tree density and the variables tested is poor. The correlation is negative for spruce but positive for the other tree species.

It has already been shown that the average tree density increases with age. It might be expected from this that tree density also increases with stem size. This was the finding for southern yellow pines by Wheeler and Mitchell (1962). As different results have been arrived at in the present work, there must be some factor which affects the density of stems of different sizes in a way contrary to the influence of age.

This factor is the growth rate of the tree. Some small-sized trees are young and grow rapidly, while others are old and of slow growth. It is due to the contrary effect of age and the growth rate that stem size does not seem to have a significant effect on the density of the pine and white birch stem. The density of common birch increases slightly with size, for age has a stronger effect than growth rate on this species. The situation is reversed for spruce in which the density decreases with increasing stem size.

If age is taken into consideration as an additional factor in the regression, the influence of stem size and form on density in even-aged trees can be examined. Table 15 shows the coefficients of determination for equations in which the tree density is explained not only by variables illustrating size and form but also by the tree age or its reciprocal.

Table 15 differs considerably from Table 14. Stem size now has a significant influence on the density of softwoods when stem age is constant. For birches, however, the density does not seem to depend on stem size. When age remains constant the correlation between density and these variables is negative in softwoods, as shown by the examples below.

Species	Regression equation	R^2	Sy.x
Pine	$Y = 475.4-2\ 469X_7-1.55X_8$	.3889	26.1
Spruce	$Y = 377.0+0.560X_4-2.34X_8$	.3622	24.0

Table 15. The interdependence between tree density and stem form and size. The coefficients of determination when the effect of age is taken into consideration.(1) For spruce the age has been used instead of the reciprocal of age).

Species	Variable			
	X_7	X_7+X_8	X_7+X_{10}	X_7+X_{11}
	Coefficient of determination			
Pine	.3157	.3889	.3496	.3582
Spruce 1)	.1506	.3622	.3321	.1961
Common birch	.2388	(.2394)	(.2388)	(.2398)
White birch	.1284	(.1340)	(.1290)	.1383

The results are fairly consistent with the following values introduced by N y l i n d e r (1959) in Sweden.

Species	Age, years	Dbh, cm 10	20	30
		Tree density, kg/solid cu.m		
Pine	49	420	405	380
Spruce	45	397	352	338

The stem form also illustrates tree density (Table 15). The more sharply a stem of a certain age tapers, the smaller is the density of pine, spruce and white birch. Taper does not appear to have an effect on common birch. It has a particularly distinct influence on density in the Norway spruce, as has been previously reported by K l e m (1934), K l e m, L ø s c h b r a n d t and B a d e (1945) and P e c h m a n n (1954). In a recent investigation the correlation between density and stem form was negligible, however (K l e m 1965).

213. Regression of tree density on crown size

The relative length of the living crown of all sample trees was measured, but the crown width, density and vigour were not recorded. The picture of the crown was thus inadequate. It was considered, however, that the effect of the crown quality on tree density can be studied by means of the correlation between tree density and crown proportion.

The tree density was higher in softwoods the greater the proportion of the stem that was self-pruned. No significant correlation was obtained for hardwoods. However, as the proportion of living crown in the total stem length of pine and spruce decreases with the age of the tree, the correlation in question may be only ostensible. Hence, again, age must be a constant in the regression. The equation receives the following form for pine and birches,

$$Y = \beta_0 + \beta_1 X_7 + \beta_2 X_{12}$$

and for spruce the age (X_4) is entered instead of the reciprocal of age (X_7). The estimate, b_2, of β_2 now shows the effect of crown proportion (X_{12}) on tree density (Y) when X_{12} is expressed in per cent.

Species	R^2	b_2	t-value of b_2
Pine	.3235	-0.246	$t_{782} = 3.02^*$
Spruce	.1807	-0.347	$t_{748} = 5.24^*$
Common birch	.2401	-0.094	$t_{246} = 0.68$
White birch	.1329	-0.164	$t_{307} = 1.27$

The effect of the crown proportion is still significant for softwoods, but insignificant for birches. However, the effect seems to be fairly small, for the density of pine decreases 2.5 and of spruce 3.5 kg/solid cu.m when the crown proportion increases by 10 per cent.

Obviously, the influence of the crown on the density of wood that forms in the stem is much more important than it has been possible to prove here. The vigour and earlier development of the crown was disregarded in the present study. On the other hand, it is to be expected that, given the same growth rate, a spruce with few needles which grows on a good site produces wood of similar density to that produced by a spruce with profuse needles growing on a poor site (S c h m i d t 1953).

"The crown of the tree is the regulating center for all wood formation. The external factors of climate and environment exert their influence directly on the growth of the crown and only indirectly on the development of wood" (L a r s o n 1963). It also seems reasonable to relate the amount of juvenile wood to the magnitude of the green crown (P a u l 1960).

Severe and continued reduction of the lower part of the crown of Pinus longifolia results in greatly reduced ring width in the lower part of the trunk, but summerwood is reduced less than springwood (M a r t s 1951). Green pruning an open-grown tree converts it to a simulated stand-grown tree, and the artificial crown recession restricts crown-formed wood to the new crown region (L a r s o n 1962).

22. The influence of environmental factors on tree density

221. The influence of stand structure on tree density

In order to study the correlation between stand density and wood density, the density of every stand was determined by using a scale where the density of an open space is denoted by 0 and the density of a fully closed stand by 1. These figures denoting stand density were tested in regression analyses as variables influencing wood density. As tree age was another explaining variable, the value of stand density thus determined was insignificant in the analysis for all tree species.

The result cannot be regarded as surprising. The density in the stand at the time of investigation may often be entirely different from what it has been during the earlier development of the stand. Nor does the classification used take into account the site quality, and consequently it does not illustrate the biological density of the stand.

The size and vigour of the crown of an individual tree and the tree growth rate are dependent on the stand density. As these factors influence wood density, it follows that stand density must also affect wood density. However, the material in the present study was such that it cannot provide a direct answer.

The general trend in conifers is that trees growing at close spacings produce heavy wood and open-grown trees with large crowns produce wood of relatively low density (Wijkander 1897, Cieslar and Janka 1902, Paul 1930, Klem 1944, Hildebrandt 1954, Larson 1957, Ericson 1962 b). Braathe (1953) calculated that the wood density of Norway spruce on fairly dense plots was 5–6 per cent above that on more open plots. There is also a positive correlation between wood density and the stand basal area of southern yellow pines, but the correlation it not a strong one (Wheeler and Mitchell 1962). However, it has been shown that the wood density of Scotch pine (Jalava 1934 a) and Norway spruce (Sirén

1952) seed trees increases in the butt end of the stem immediately after thinning. A thorough study of the effect of thinning on the density and percentage summerwood in Scotch pine and Norway spruce was recently completed in Sweden by E r i c s o n (1966 b).

The methods for producing dense wood in second-growth Pseudotsuga taxifolia forests are similar to those necessary for the natural elimination of side branches in closely stocked stands (P a u l 1932). The regulation of growing space throughout the life of a stand is the silvicultural tool most readily available to the forester in controlling wood density (P a u l 1963).

The effect of stand structure on wood density can be examined also by studying the differences between the tree classes. Four tree classes were distinguished in the present study in the manner described on p. 17, with the tallest trees of the stand ascribed to class 1. The correlation between wood density and tree age and tree class can now be written

$$Y = \beta_0 + \beta_1 X_7 + \beta_2 X_{13}$$

when X_7 is the reciprocal of age and X_{13} represents the tree class. Better results are again obtained for spruce when age (X_4) is entered instead of the reciprocal of age. When the estimate of β_2 is denoted by b_2, the following results are obtained.

Species	R^2	b_2	t-value of b_2
Pine	.3526	5.85	$t_{783} = 6.68^*$
Spruce	.2987	10.61	$t_{749} = 12.57^*$
Common birch	.2392	0.63	$t_{247} = 0.37$
White birch	.1431	2.29	$t_{308} = 2.30^*$

The wood density of trees in the lower tree classes is higher than that of dominant trees. The differences are especially distinct for spruce, but the effect of tree class is not significant for common birch. The coefficients of determination cannot be improved by adding the square of the tree class. Table 16 gives an example of the density of trees of different tree classes in a stand aged 50 years.

Table 16. Wood density of trees of different tree classes in a 50-year-old stand.

Species	Tree class 1	2	3	4
	Density, kg/cu.m			
Pine	397	403	408	414
Spruce	359	369	380	391
Common birch	496	497	498	498
White birch	478	481	484	487

It has been proved that wood density increases from dominant to suppressed trees in pine (B u r g e r 1948, P i l l o w 1954, L a r s o n 1957) and Norway spruce (C i e s l a r and J a n k a 1902, K l e m 1934, V o l k e r t 1941, B u r g e r 1952) stands. In several cases, however, the intermediate tree classes have been shown to have heavier wood than either the dominant or suppressed trees (J a l a v a 1946, N y - l i n d e r 1953 b, H i l d e b r a n d t 1954).

222. The influence of site quality on tree density

As the quality of the site affects the volume growth of trees, it may be assumed also to influence wood density. W i l d e, P a u l and M i k o l a (1951) reported that site conditions exert a marked influence on wood density. Most research workers are of the opinion that the wood density of softwoods is higher on poor than on good sites. This applies to both Scotch pine (L a s - s i l a 1929, S i i m e s 1938, J a l a v a 1946, T a m m i n e n 1962) and Norway spruce (W i j k a n - d e r 1897, K l e m 1934, W e g e l i u s 1946, K l e m 1965). Several studies have reported that the percentage summerwood and density of softwoods depend on the soil moisture supply during the growing season, especially towards the end of the summer (P a u l and M a r t s 1931, C h a l k 1951, L a r s o n 1957, K r a u s and S p u r r 1961).

Investigation results concerning the correlation between the wood density of diffuse-porous hardwoods and site quality are contradictory. Populus tremuloides and Populus grandidentata have generally a higher wood density on the fertile than on the infertile sites, but this relationship does not hold true in all instances (W i l d e and P a u l 1951). Wood density of Liriodendron tulipifera is inversely related to site index (B a r e f o o t 1963).

In studying the correlation between wood density and site quality in the present study, use was made of the forest site types which have such an important role in Finland. The mineral soil forest site types covered by the study are Oxalis-Myrtillus type (OMT), Myrtillus type (MT) and Vaccinium type (VT), the moistest and most fertile type given first. The fourth group consists of undrained swamps (see p. 15).

These four different sites have been fitted into the regression equations by assigning the forest site types the value 1 or 0 as shown on p. 26. The independent variables explaining tree density were the forest site type, tree age, the reciprocal of tree age and the interaction between age or its reciprocal and the forest site type. When only the forest site type was considered, the following correlations were obtained for the different tree species:

Species	R^2	F-value of the equation
Pine	.1313	$F_{4;780} = 29.45^{*}$
Spruce	.1104	$F_{4;746} = 23.14^{*}$
Common birch	.1039	$F_{4;244} = 7.08^{*}$
White birch	.0191	$F_{4;305} = 1.49$

However, the question is not only of the direct effect of site quality, for the tree age also exerts its influence. The age of the growing stock on poor forest site types, especially on undrained swamps, is higher on an average than on good forest site types. Age must therefore be taken into consideration in the regression equations. The wood density of the different tree species can the be predicted best from the following equations.

Pine and birches

$$Y = \beta_0 + \beta_1 X_{16} + \beta_2 X_{17} + \beta_3 X_{18} + \beta_4 X_{19} + \beta_5 X_{20} + \beta_6 X_{21} + \beta_7 X_{22} + \beta_8 X_{23}$$

Table 17. Density of pine, spruce and birch wood on different forest site types.

Species	Forest site type	Age, years				
		25	50	75	100	125
		Density, kg/cu.m				
Pine	OMT	350	395	410	417	..
	MT	356	396	410	416	420
	VT	383	416	426	432	435
	Swamp	381	406	415	419	422
Spruce	OMT	356	364	372	380	..
	MT	368	376	384	392	400
	VT	376	383	391	399	407
	Swamp	379	387	395	403	410
Common birch	OMT	459	497	510	516	..
	MT	463	497	508	513	..
	Swamp	453	480	489	493	..
White birch	OMT	456	488	499	504	..
	MT	458	483	492	496	..
	Swamp	453	481	490	495	..

Spruce

$$Y = \beta_0 + \beta_1 X_{16} + \beta_2 X_{17} + \beta_3 X_{18} + \beta_4 X_{19} + \beta_5 X_4$$

It is possible on the basis of the equations to account for 37 per cent of the total tree density variation in pine, but only 15 per cent in white birch, as shown by the coefficients of determination obtained from the equations.

The equations can be used to predict the average tree density when tree age and forest site type are known (Table 17). However, great accuracy cannot be achieved in

Species	R^2	Sy.x
Pine	.3671	26.2
Spruce	.2098	26.7
Common birch	.2778	27.0
White birch	.1505	27.2

predicting the density of an individual tree. Young stands on good forest site types yield considerably lighter-weight timber than the old stands on poor forest site types. For instance, the weight in solid cu.m in 100-year-old VT stands is 24 per cent higher for pine and 12 per cent higher for spruce than in 25-year-old OMT stands.

The table warrants the following conclusions:

- When the fertility of mineral soil improves, the wood density decreases. As far as undrained swamps are concerned, spruce produces the heaviest wood just in swamps, whereas the situation is the opposite for birch species. The density of pine wood on undrained swamps is higher than on MT sites, but lower than on VT sites.
- The density of pine wood is higher than that of spruce wood, as is commonly known. An exception, however, consists of young stands. The main reason for this is juvenile wood formation in pinewood.
- The wood density of common birch is higher than that of white birch except on undrained swamps where both species have the same wood density.

As low-density wood forms on a good site, it can be expected that improving the fertility of forest soil by fertilization will lead to a decrease in the density of the wood produced by the stand. L a r s o n (1962) points out that the anticipated response to fertilization would be increased crown development. The increased crown activity, in turn, would be expected to promote spring-wood formation.

It was not possible in the present work to study the effect of fertilization on wood density. The problem is, nevertheless, highly topical as Finland's forests will probably be fertilized on a large scale in the near future.

For this reason, some investigation results which give indications of the type of change to be anticipated in the density of wood in consequence of fertilization are presented here.

Application of N, P_2O_5, K_2O, and lime caused a decrease of 8 per cent in the wood density of young *Pseudotsuga taxifolia* (Erickson and Lambert 1958). Application of N, P_2O_5, and K_2O significantly reduced the wood density of *Pinus taeda*, and the wood density averaged 10 per cent less than in trees in the control plots (Zobel, Goggans, Maki and Henson 1961). Williams and Hamilton (1961) applied fertilizer treatments of ammonium nitrate, superphosphate, and these two together for *Pinus Elliottii*. The addition of fertilizers had a definite effect on wood properties, and wood density was lowered on an average from 513 kg/cu.m to 479 kg/cu.m or 6.7 per cent. In Ericson's (1962 a) study nitrogen treatment caused a 4.9 and a 6.2 per cent decrease in wood density of Scotch pine.

Kerr (1931) pointed out that fertilizing has less influence on development of summerwood than on springwood of southern yellow pines. In the study by Klem (1964), the amount of summerwood in Norway spruce did not increase at all, but the quantity of springwood grew by 45 per cent as a result of fertilization. The result was a 7 per cent decrease in wood density. It was established by Pechmann and Wutz (1960) that repeated applications of nitrogen appeared to increase the percentage springwood of Norway spruce. Wood density was reduced correspondingly, but the wood structure and density were similar to those of faster-grown spruce on good sites. Ericson (1962 a) stated that with fertilization, pine and spruce density generally decreases but the density of "hunger wood" which has grown on a very poor soil may even grow through the fertilization.

If forest fertilization becomes widespread in Finland, it can be assumed that the average density of the timber produced by the coniferous forests will decrease to some extent and the raw material consumption of the pulp industry will grow correspondingly per production unit. However, fertilization can be used to increase wood production without any fear that the change in the quality of the raw material of the pulp and paper industry will be greater than the present-day variation between fast-grown and slowgrown wood (J e n s e n, V i r k o l a, H u i k a r i and P a a r l a h t i 1964).

The studies performed so far on the effect of fertilization on wood density have been concerned, however, with young stands. It may therefore be premature to advance hypotheses about the effects of fertilization of old forests on the quality of timber, expecially saw logs. But on the basis of Table 17 alone, it seems possible that the lowering effect of fertilization on wood density is greatest in young stands and it will decrease when the age of the stand to be fertilized increases. Nor does it appear probable that fertilization would result in a reduction in wood density of birches.

23. Stem-to-stem density variation explained by external tree characteristics and environmental factors

Several studies indicate that the stem-to-stem density variation in a stand or locality is very high, but that much of this variation has not been explained by environmental factors (van B u i j t e n e n, Z o b e l and J o r a n s o n 1961). The majority of recent writers agree that it is very difficult to relate wood density to environment (cf. Z o b e l and M c E l w e e 1958).

The variation of tree density has been attempted to explain with the aid of different variables. It is easy to observe that two of them, tree age and growth rate, explain the variation in the tree density better than other factors. The explanatory value of stem size, site quality and other variables is largely based on the correlation between the variable in question and the tree age or growth rate.

The combined effect of environmental factors can be seen in the growth rate of the tree. A measure that illustrates growth rate, on the other hand, is the average ring width. In this study the quotient (X_9) obtained by dividing the diameter in centimetres at breast height above the bark by the age of the tree was used instead. This is not as accurate an indicator of growth rate as ring width, but it does make it possible to observe how the rate of growth influences the wood density. By taking as a second independent variable the reciprocal of age for pine and birches, and the age for spruce, the following regression equations are obtained.

Pine and birches $Y = \beta_0 + \beta_1 X_7 + \beta_2 X_9$
Spruce $Y = \beta_0 + \beta_1 X_4 + \beta_2 X_9$

These equations take into consideration the influence of both age and growth rate. The influence of the latter variable on wood density can be seen from the following, where the estimate of β_2 is denoted as b_2.

Species	R^2	b_2	t-value of b_2
Pine	.3936	- 91.7	t_{782} = 10.03*
Spruce	.3429	- 154.0	t_{748} = 14.79*
Common birch	.2393	- 6.5	t_{246} = 0.41
White birch	.1341	- 25.0	t_{307} = 1.43

Again, it can be seen that the density of softwoods is significantly dependent upon the rate of growth. This negative correlation is especially pronounced for Norway spruce. For birches, on the other hand, the influence of growth rate is not important.

In many recent investigations it has been concluded that the relationship between growth rate and wood density is of little or no importance (Spurr and Hsiung 1954, Larson 1957, Rendle 1958 and 1959, Zobel and McElwee 1958, Goggans 1961 and 1962). It is obvious, however, that this depends to a great extent upon the tree species. Especially the density of Norway spruce seems to depend on the growth rate, but a similar correlation can also be observed in Scotch pine. This is the almost unanimous conclusion arrived at in investigations in Europe concerning these tree species.

Table 18 shows what percentage of the variance of tree density was explained by different variables. For pine and birches the most important independent variable is the age of the tree, in one way or another, but for spruce the growth rate is even more important than age.

Table 19 shows the percentage of the total variance of tree density explained by tree characteristics when the number of independent variables increases from one to six. It is not possible to improve the result for softwoods by

Table 18. Per cent of the total tree density variation explained by tree and stand characteristics. (Values insignificant at the five per cent level are given in brackets).

Variable	Symbol	Pine	Spruce	Common birch	White birch
		Explained variance, per cent			
Age	X_4	24	15	20	12
Logarithm of age	X_6	30	14	22	13
1/age	X_7	32	12	24	13
Dbh	X_8	(0)	9	4	(1)
Dbh/age	X_9	25	33	3	3
Tree length	X_{10}	(0)	7	5	1
Dbh/length	X_{11}	1	3	2	(0)
Crown proportion	X_{12}	10	8	(0)	(0)
Tree class	X_{13}	2	12	(1)	(1)
Stand density	X_{15}	1	1	6	(0)
Forest site type	X_{16}-X_{19}	13	11	10	2
Site type x 1/age	X_{20}-X_{23}	37	..	26	14
Site type x age	X_{20}-X_{23}	..	20	..	..

inclusion of the fourth tree characteristic, and for birches the second or third variable even is insignificant. If, however, the forest site type is included, the proportion of the explained variation can be increased for spruce and birches. The best equations then explain 41 per cent of the total density variation of Scotch pine, 40 per cent of Norway spruce, 28 per cent of common birch and

16 per cent of white birch. K l e m (1965) similarly succeeded in explaining 43 per cent of the tree density variation of Norway spruce with an equation that had 12 independent variables. In the western wood density survey in the United States (U.S. Forest Service 1965 b) the percentage of the explained variation fluctuated from 6 - 31 in different tree species.

Compared with existing forests, fast-growing timber will be harvested in Finland in the future. The first thinnings will take place when the growing stock is still quite young. The rotation age of stands will also be shorter.

Table 19. Per cent of the total tree density variation explained by an increasing number of external tree characteristics as independent variables. (The thickened number refers to the last significant increase in the explained variance for each species).

Independent variable								Explained variance, per cent
X_4	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	
			Pine					
-	-	X	-	-	-	-	-	32
-	-	X	-	X	-	-	-	39
-	-	X	-	X	-	X	-	41
-	-	X	-	X	-	X	X	41
-	-	X	-	X	X	X	X	41
-	-	X	X	X	X	X	X	41
			Spruce					
-	-	-	-	X	-	-	-	33
X	-	-	X	-	-	-	-	36
X	-	-	-	-	X	X	-	37
X	-	-	-	-	X	X	X	37
X	-	-	X	-	X	X	X	37
X	-	-	X	X	X	X	X	37
			Common birch					
-	-	X	-	-	-	-	-	24
-	-	X	-	-	-	-	X	24
-	-	X	X	-	X	-	-	24
-	-	X	X	-	X	X	-	24
-	-	X	X	-	X	X	X	24
-	-	X	X	X	X	X	X	24
			White birch					
-	X	-	-	-	-	-	-	13
-	X	-	-	-	-	X	-	14
-	X	-	X	-	X	-	-	14
-	X	-	X	X	X	-	-	14
-	X	-	X	X	X	-	X	15
-	X	-	X	X	X	X	X	15

Conclusions from the wood density of the future forests can be drawn on the basis of the combined effect of environmental factors or growth rate of the trees. Attention has been paid previously to the possibility that the anticipated extensive forest fertilization may in the future forests result in a decrease in wood density. The same effect may be caused by the more general use of planting and seeding as methods of forest regeneration.

Klem (1944), Olson, Poletika and Hicock (1947), Giordano (1951), Hildebrandt (1954) and Sirén (1959) have proved that the forest-grown wood of Scotch pine and of Norway spruce is higher in wood density than plantation-grown material. With more planting space, wood density decreases and the knot percentage increases. The production of one ton of spruce sulphite pulp required 4.7 solid cubic metres of wood from young plots with planting spaces of 1.25 x 1.25 metres, but 6.2 solid cubic metres from plots of the same age with planting spaces of 3.5 x 3.5 metres (Klem 1944). When the stand gradually grew denser, the differences began to decrease (Klem 1952).

24. Density as an inheritable property

The sample was collected from a geographically restricted area to exclude this factor liable to cause variation, In spite of this, the tree density varied widely. The standard deviation of the tree density was 8 per cent for softwood stems and 6 per cent for birches (Table 20).

Table 20. Standard deviation and range of tree density.

Species	Density, kg/cu.m	
	$\bar{X} \pm S$	Range
Pine	409 ± 32.8	311 - 521
Spruce	387 ± 30.0	308 - 482
Common birch	497 ± 31.2	407 - 571
White birch	482 ± 29.2	397 - 561

Attempts were made to explain the variation in tree density by using several tree and stand characteristics, but even in the most favourable cases the unexplained standard deviation for softwoods has been 6 per cent and for birches 5 per cent. To some extent this is due to measuring errors, the possible omission of some environmental factors and the fact that the tested linear equation patterns have not always been the best possible. In spite of this, it is apparent that the main reason for the unexplained variation is heritability, because wood density is the result of the interaction of environment and genotype.

Heritability is the relationship of the heritable portion of the variability of wood density to the total variability of wood density (Z o b e l 1961). "When the material is propagated by sexual means, the non-additive effects of the individual genotype cannot be passed on to their progenies, so the term heritability must be employed in the narrow sense. When vegetative propagation is used, the effects of dominance and epistasis of individuals are transferred unchanged. In this case the term heritability may be employed in its broad sense" (T o d a 1958).

When investigating the possibilities of forest tree breeding, the first point to clarify is the extent to which the desirable wood properties are transmitted from parent to progeny. For the present, there is not sufficient information available on the heritability of wood density in Scotch pine, Norway spruce, common birch and white birch, but some foreign investigations provide references and hints.

A close relationship exists between core wood density and the density of the total tree bole (Z o b e l, W e b b, and H e n s o n 1959, T h o r b j o r n s e n 1961). This speeds up the process of breeding, since it is possible to predict from quite young trees, at least roughly, the density of the wood that will form later. Data on one-year and five-year old wood from grafts of Pinus taeda showed significant differences in the wood density of the clones (van B u i j t e n e n 1962). In another investigation the inheritance of wood density was moderately strong for two-year old seedlings of the same species (C e c h, S t o n e c y p h e r and Z o b e l 1962). A positive correlation has also been found between the original tree and the graft trees for Scotch pine and Norway spruce (E r i c s o n 1960). Genetic variations and heritabilities, however, will probably change as the trees grow older. This is because the wood of the core is more sensitive to environmental influences than adult wood (G o g g a n s 1962).

It has also been proved that there are differences in wood density due to heritability between the geographical races of Scotch pine (E c h o l s 1958) and Norway spruce (K l e m 1957, D i e t r i c h s o n 1964). Still an unsolved problem, however, is the extent to which the variation in the wood density of these species can be attributed to heritability.

Almost one-third of the tree density variation in southern yellow pines may be due to genetic factors (W h e e l e r and M i t c h e l l 1962). F i e l d i n g and B r o w n (1960) obtained broad-sense heritabilities up to 0.7 and narrow-sense heritability 0.2 for Pinus radiata. In another investigation broad-sense heritability of this same species was found to be 0.74 in the juvenile wood produced during the first eight years of the trees (D a d s w e l l, F i e l d i n g, N i c h o l l s and B r o w n 1961). As to the conifers in general, narrow sense heritabilities as high as 0.60 - 0.70 and broad--sense heritabilities of up to 0.85 have been reported, whereas the values for poplars are much lower (Z o b e l 1963).

One of the most important properties of wood, and one which should be taken into consideration in forest tree breeding, is wood density. This indeed is already being done in many countries. "A good part of the initial work of the U.S. Forest Products Laboratory in the field of wood density surveys, was concerned with screening for wood quality trees that had been selected and rated as plustrees on the basis of form, vigour, growth rate and the like. The purpose was to make certain that trees destined for further study and use in tree improvement programs were average or above, with respect to wood quality" (M i t c h e l l 1958).

The problem of significant small-scale tests on wood in living trees has occupied an important place in the breeding programme of the U.S. Forest Service at the Southern Institute of Forest Genetics. When the average tree density, the diameter and the age are known, "the wood quality index" can be determined (E c h o l s 1959). In England, cores are extracted at breast height from plustrees of Picea sitchensis to obtain evidence that the timber is satisfactory as to its wood density and other wood properties (P h i l l i p s 1963).

"The external appearance of a tree can be deceptive and occasionally borings from promising-looking trees have shown them to possess unsuitable timber qualities" (H o l - l o w a y 1965). One is not free to select for only volume, or for density alone. There is a negative genetic correlation between growth rate and wood density. This means that one must evaluate the total wood production, including both volume and wood density, for effective breeding procedure (van B u i j t e n e n 1963). A strict selection for wood density alone would result in a decrease in the average diameter, while a selection for diameter alone would result in a decrease in wood density (S t o - n e c y p h e r, C e c h and Z o b e l 1964).

Thus, it seems apparent that wood density is a factor worth major attention also in Finland when practising forest tree breeding. The first step would be to screen the plustrees and to remove from among them individual trees that are not up to a minimum standard. Care should also be taken in the new seed tree orchards now being established not to include tree individuals that give a sub-average wood density. By taking wood density into consideration in the forest tree breeding program one can to some extent avoid the threat of decreasing wood density inherent in future silvicultural methods.

3. DENSITY OF THE MOST IMPORTANT TIMBER ASSORTMENTS

31. Density of saw and veneer timber

It is possible to make use of certain stand characteristics when seeking to acquire logs, poles or piles with good strength properties. High-density logs are obtained from slow-grown and old stands. Over-aged stands must be avoided, however. The site quality permits certain conclusions about the wood density of logs (Table 21).

Table 21. Density of saw and veneer logs from different forest site types.

Forest site type	Pine	Spruce	Birch
	Density, kg/cu.m		
	$\bar{X} \pm S$	$\bar{X} \pm S$	$\bar{X} \pm S$
OMT, MT	420 ± 30	370 ± 23	502 ± 30
VT	433 ± 37	382 ± 22	523 ± 34
Swamp	393 ± 18	385 ± 34	474 ± 23
Average	427 ± 36	373 ± 26	501 ± 32

Poor sites generally yield high-density logs, but the differences between various forest site types are small. The pine and birch logs of peat lands are an exception. The former often come from over-mature trees and may therefore be of exceptionally low density. For birch logs the main issue is the composition of the tree species. The proportion of white birch compared with common birch increases with the moisture of the site (cf.p.16). The following figures show the difference in the wood density of common birch and white birch logs.

Species	Wood density of veneer logs, kg/cu.m
	$\bar{X} \pm S$
Common birch	510 ± 31
White birch	478 ± 27

One of the most important criteria for saw and veneer timber pricing is the top diameter of the log. The way in which the wood density varies with the log size is thus of interest. Table 22 shows the density of logs of different sizes. The table includes both butt and top logs.

Table 22. The effect of top diameter on the density of saw and veneer logs.

Top diameter, inches	Pine	Spruce	Birch
	Density, kg/cu.m		
	$\bar{X} \pm S$	$\bar{X} \pm S$	$\bar{X} \pm S$
5, 5 1/2	413 ± 33	375 ± 22	..
6, 6 1/2	424 ± 32	379 ± 28	472 ± 25
7, 7 1/2	427 ± 33	372 ± 25	498 ± 33
8, 8 1/2	424 ± 32	372 ± 23	502 ± 30
9, 9 1/2	426 ± 29	367 ± 25	505 ± 31
10 +	457 ± 31	369 ± 23	515 ± 30

The density of birch logs increases distinctly with the log diameter. This is obviously true of pine as well, but for spruce the differences are fairly small. In birch logs, the proportion of common birch is highest in the thickest logs.

Especially in pine the part of the stem from which the logs derive affects the density of the logs. This can be seen from the following.

Position of the log	Pine	Spruce	Birch
	Density, kg/cu.m		
	$\bar{X} \pm S$	$\bar{X} \pm S$	$\bar{X} \pm S$
Butt logs	438 ± 34	376 ± 26	502 ± 33
Other logs	402 ± 22	368 ± 23	501 ± 22

The wood densities of logs of various grades were also compared for pine. Although grading is based solely on external log characteristics (cf. H e i s k a n e n and S i i m e s 1960), it is also an excellent guide to the density of the logs. Wood density decreases as the grade falls, being 10 per cent higher in the first than in the third grade. The wood density of first grade pine saw logs obtained from a VT site is as high as 454 kg/solid cu.m.

Log grade	Density of pine saw logs, kg/cu.m $\bar{X} \pm S$
1	450 ± 34
2	433 ± 32
3	408 ± 28

Waste which originates when lumber is produced is converted into chips for the pulp industry. These chips are obtained chiefly from the outside portions of the logs, where the wood density is highest. The wood density of chips obtained from pine and spruce slabs was determined as described in Chapter II. The method is not entirely suitable theoretically, but the following estimates give an idea of the wood density of sawmill chips from slabs.

Species	Density of sawmill chips from slabs, kg/cu.m
Pine	441
Spruce	379

The wood density of sawmill chips obtained from pine slabs is higher than given by any other timber assortment in Finland utilized as raw material for pine sulphate pulp. In addition, "the chips coming for the most part from slabs or the outside of the logs contain fibers appreciably longer than the average of those in a whole log" (G r e e n 1963).

On the other hand, the point that the wood density of pine chips from slabs is 15 per cent higher than that of spruce chips must also be borne in mind. This notwithstanding, they are both sometimes used in a mixture for the manufacture of sulphate pulp without regard for the effect of this difference on the pricing of the raw material or the production process.

32. Density of cordwood

The wood density of normal pine pulpwood is 7 per cent higher than the wood density of pulpwood made from tops. In addition, timber from tops is known to contain a greater proportion of knot wood. According to N y l i n d e r (1959), the percentage of knot wood is greatest at 80-90 per cent stem heights. Knot wood interferes in many ways with the preparation of chemical and groundwood pulp (cf. W e g e l i u s 1939). Moreover, when the smaller solid content of a stack of timber from tops is taken into consideration, it is obvious that top timber is distinctly poorer than normal pulpwood as raw material for pine pulp. The differences in the wood density of spruce and birch pulpwood are similar but smaller.

The minimum top diameter of pulpwood was in this investigation 8 cm under the bark. This was the practice when the study was started. Since then the minimum top diameter of pine and spruce pulpwood has been lowered to 7 cm, however.

In addition pulpwood of 5-8 cm diameter, so-called small-diameter pulpwood, was made of pine and spruce. Two types can also be distinguished in this small-diameter pulpwood: pulpwood made from small-sized trees or from the tops of taller trees. In pine, both are of lower density than the corresponding normal-sized pulpwood, the difference being 2 per cent. The same applies to spruce as regards top timber, but the difference is only 1 per cent. The density of pulpwood made from small-sized spruces, on the other hand, is 4 per cent higher than that of normal spruce pulpwood, because this kind of timber primarily consists of slow-grown undergrowth spruces.

However, in practice the above-mentioned types of small-diameter pulpwood are not kept separate. The relative proportion of both timber assortments varies with the stand from which the timber is harvested. It is even common that pine and spruce are not kept separate. In addition, it appears to be characteristic that the wood density of small-diameter pulpwood varies sharply between stands.

Table 23. Density of pulpwood obtained from different forest site types.

Forest site type	Pine	Spruce	Birch
	Density, kg/cu.m		
	Normal pulpwood [1]		
OMT, MT	403	378	495
VT	427	394	520
Swamp	414	393	483
Average	417	382	495
	Pulpwood from tops		
OMT, MT	386	377	489
VT	388	381	499
Swamp	360	382	451
Average	386	378	486
	Small-diameter pulpwood [2]		
OMT, MT	382	389	..
VT	426	403	..
Swamp	440	426	..
Average	410	394	..
	Small-diameter pulpwood from tops		
OMT, MT	376	370	..
VT	380	389	..
Swamp	380	387	..
Average	378	374	..

1) Does not include pulpwood made from the tops of saw log trees.

2) Does not include small-diameter pulpwood made from the tops of saw log and pulpwood trees.

For these reasons, no endeavour was made to give a figure of general acceptability concerning the density of small-diameter pulpwood. But it is possible from the data presented to calculate the wood density in different cases when the proportion of pine and spruce, on the one hand, and that of small-sized stems and tops on the other hand are known.

It is possible to some degree to draw conclusions about the density of pulpwood obtained from a stand on the basis of the external stand characteristics. Table 23 shows the effect of the forest site type on the density of pulpwood.

Poor sites yield dense pulpwood. Of especially high density is small-diameter pulpwood obtained from the small-sized stems of undrained swamps. Exceptionally low-density pulpwood, again, is obtained from the first thinnings of young, fast-growing forests.

Birch wood of poor quality is still utilized as fuelwood on a large scale in Finland. The average wood density of birch fuelwood is 492 kg/solid cu.m, according to the present study. However, if both birch pulpwood and birch fuelwood are prepared concurrently, the latter comes chiefly from the tops of the trees. The wood density of such fuelwood is 480 kg/solid cu.m.

It is possible that at least a part of the top now left in the forest as logging residues will in the future be used for the production of pulp. Because of this, the density of this kind of wood was also determined. The figures below show that the wood density of the tops left behind in the forest as logging residues is low for pine and birch but high for spruce compared with the means for the tree species in question. A point worthy of consideration is that the density of spruce logging residues is higher than that of pine logging residues.

Species	Density of logging residues from tops, kg/cu.m
Pine	368
Spruce	381
Birch	470

In Table 24 are assembled the average densities of different timber assortments. It is proposed that these figures be used in southern Finland until the effect of geographical variation can be assessed. It should be emphasized, furthermore, that the figures denote the density of clear, defect-free wood.

Table 24. Density of different timber assortments.
(1) and 2): see Table 23)

Timber assortment	Pine	Spruce	Birch
	Density, kg/cu.m		
Saw and veneer logs	427	373	501
Normal pulpwood [1])	417	382	495
Pulpwood from tops	386	378	486
Small-diameter pulpwood [2])	410	394	..
Small-diameter pulpwood from tops	378	374	..
Normal fuelwood	..	..	492
Fuelwood from tops	..	..	480
Saw mill chips from slabs	441	379	..
Logging residues from tops	368	381	470

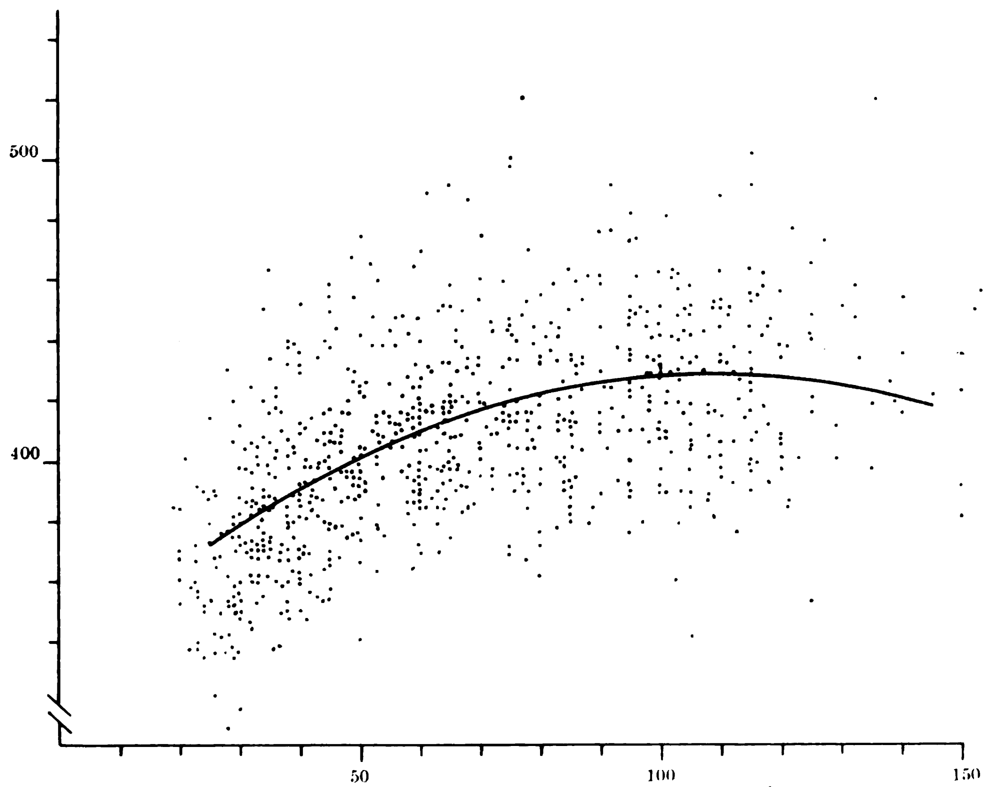
The dry weight of timber is also affected by defects in wood. The most important is knottiness, for knot wood has an above-average density. The density of knot wood may in Norway spruce be three times that of normal stem wood (W e g e l i u s 1939). B o u t e l j e (1966) reported that the density of knot wood of Scotch pine is on the average 2 times and that of Norway spruce 2.5 times as high as the density of clear stem wood. The presence of reaction wood in timber has the same effect, whereas decay has a contrary effect. The combined effect of defects is such that the true dry weight of timber is probably slightly higher than the density of clear wood indicates. H a r d y and W e i l a n d (1964) noted that knots increased the dry weight of pulpwood made of spruce species of Maine by 1.73 per cent.

The density of normal pulpwood in southern Finland is 417 kg/solid cu.m for pine, 385 for spruce and 495 for birch according to the present study. J a l a v a (1959) calculated the true dry weight of pulpwood to be 430, 390 and 500 kg/solid cu.m, respectively. As the latter numerical series includes the effect of knots, it can be concluded that the figures reported earlier by Jalava for pulpwood and those obtained here by another method are in accordance. By way of comparison, mention may be made of the study made by B r a a t h e and O k s t a d (1964) in Norway in which the average wood density of birch pulpwood is about 502 kg/solid cu.m.

IV. The reliability of the results

The statistical procedure used in the investigation is based primarily on regression analysis. The sample data are then supposed to meet certain requirements. First of all, it is assumed that the values of the independent variables are measured with essentially no error.

Tree density, kg/cu.m



Age, years

Figure 10. Tree density of pine against age.

The measurements were done as carefully as possible. The magnitude of the error involved in the wood density measurements and the correction of the error were established in Chapter II.

Second, the sample must be drawn from a population for which the variance is homogeneous. This means that the variance of the wood density values about the regression surface must be the same at all points of a certain combination of the independent variables. Graphic presentation can be used to show that the sample meets this requirement. Figure 10 serves as a pattern of that.

The third requirement id that the deviation of the wood density values from the regression surface must not be dependent on each other. The independence of errors can usually be assumed if the Y values are randomly selected, as is the case in this investigation. Purposive selection of X values on the other hand is usually permissible.

Fitting a simple or multiple linear regression does not necessarily assume the normality of the distribution of the wood density values. But because t- and F-tests were used in the tests of significance, the Y values should be normally distributed. The distributions of the average tree density values of pine, spruce, common birch and white birch are shown in Figures 11-14.

Two main types of departure from the normal may occur. In one the distribution of the data is asymmetrical or skewed, the mean and median being different. The other, kurtosis, occurs in symmetrical sets, characterized by

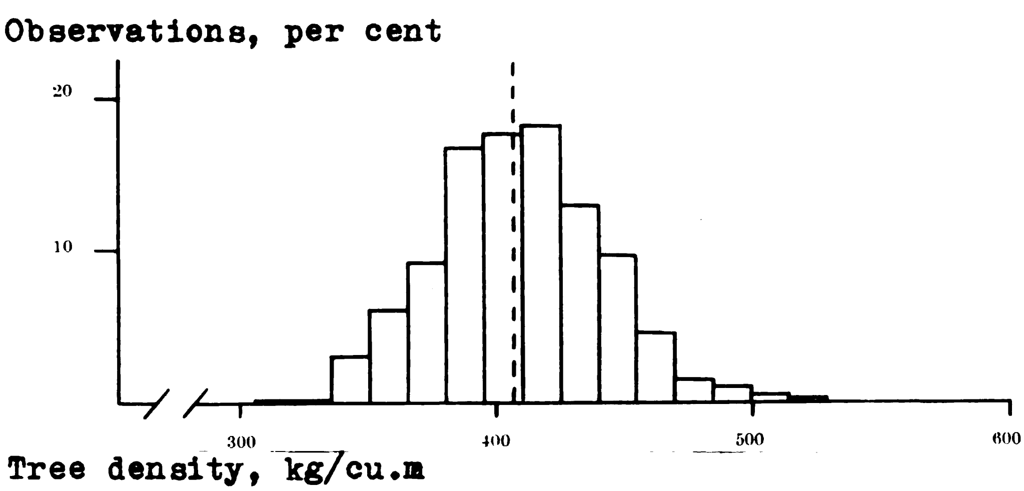


Figure 11. Distribution of tree density of pine.

either an excess or a deficit of observations concentrated near the center of the range. When g_1 is the measure of skewness and g_2 the measure of kurtosis (S n e d e c o r 1957), the following test results are obtained.

If g_2 is zero, there is no departure from normality so far as this measure is concerned. In this investigation the values of g_2 seem to be positive for pine, spruce, and birches. "A positive value of g_2 indicates an excess of

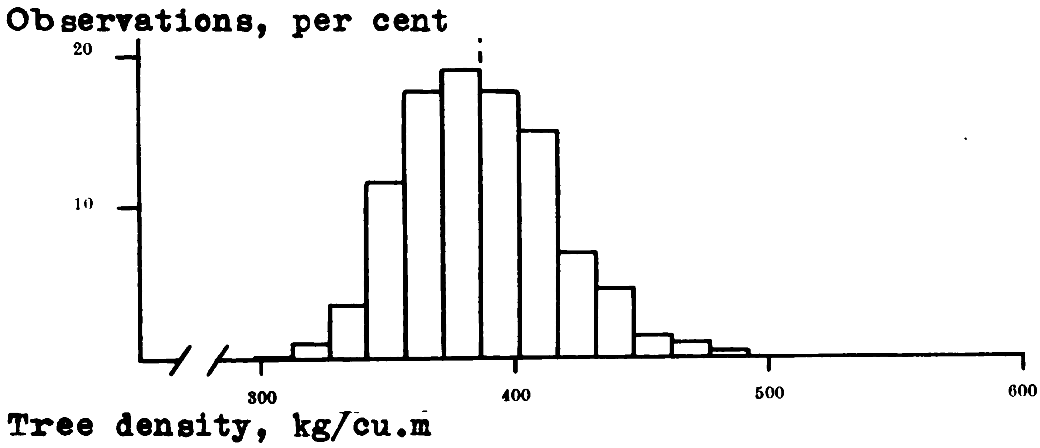


Figure 12. Distribution of tree density of spruce.

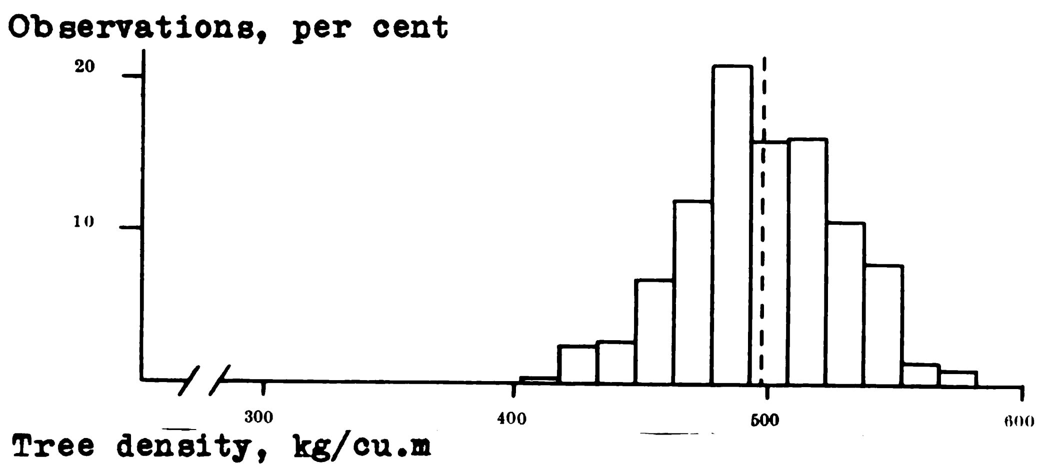


Figure 13. Distribution of tree density of common birch.

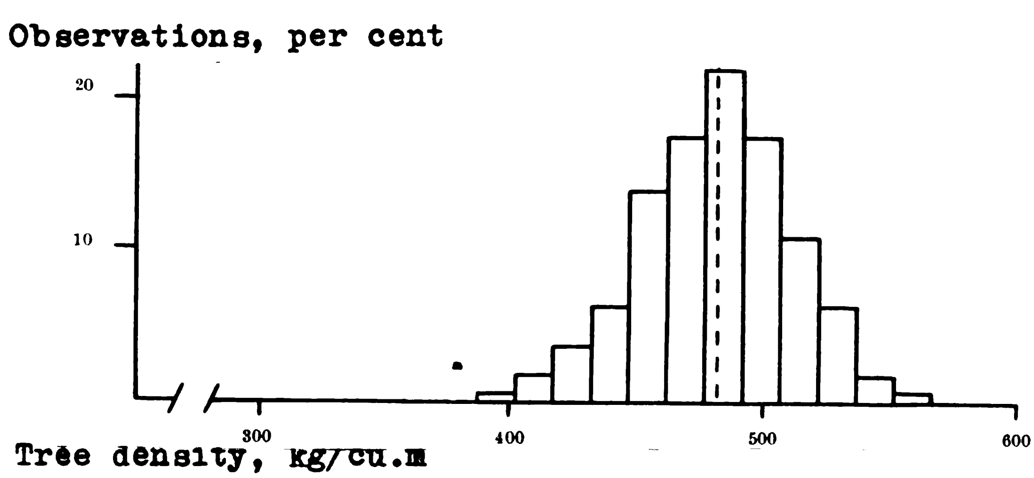


Figure 14. Distribution of tree density of white birch.

Species	t-value of g_1	t-value of g_2
Pine	+ 2.49*	+ 1.60
Spruce	+ 4.61*	+ 0.40
Common birch	- 0.79	+ 0.56
White birch	- 1.45	+ 0.32

items near the mean and far from it with a corresponding depletion of the flanks of the distribution. This is the manner in which the distribution of t departs from normal" (S n e d e c o r 1957). The values of g_2 are insignificant for every species, however.

If g_1 is zero, the distribution of the sample is symmetric. A positive value of g_1 indicates an excess in the number of observations smaller than the mean, whereas a negative value indicates an opposite situation. For birches, which have a relatively high wood density, the value of g_1 is negative but insignificant. For pine and spruce, which are lower in wood density, g_1 is positive and significantly different from zero (cf. K o l l m a n n 1951).

As to the birches, no significant departure from normality can be demonstrated. The excess of low tree density values of pine and spruce, on the other hand, indicates that the population from which they have been drawn is asymmetric.

As pine and spruce material is not perfectly normal, the results of the t-test and the F-test must be treated with a certain reserve. The tests were performed at the 5 per cent level of significance. If the difference was then significant, this was denoted by an asterisk after the test value.

It is advisable for the practical applications of the results to know what the sample represents and how it does so. As already mentioned, the study was confined to a limited geographical area. Collection of material was possible in this region only in State forests for the most part, although some private forests were also available for the purpose. These forests must be regarded as better than the average for the area.

The forest areas made available for the study also included many stands in which it was not possible for one reason or another to fell sample trees. Another limiting factor was that artifically regenerated forests and drained swamps were omitted from the material. An endeavour was then made to collect a random sample from the remaining stands of the study area, but in the final phase of the field work the material was supplemented nevertheless in some extreme cases such as OMT pines and VT birches.

For wood density, i.e. the Y values of the regression equations, the material was selected at random as presupposed in regression analysis. On the other hand, purposive selection was applied to certain stand characteristics employed as X values. Although selection of X values is permissible in regression analysis, it influences certain applications of the results, such as calculation of the average wood density of timber assortments.

The values reported for the wood density of timber assortments are means weighted by bolt volume. These means were further adjusted separately for each tree species with the aid of the areas and the yield values of different forest site types in order to provide better conformity with average conditions in southern Finland. The values thus corrected can be considered to represent the average wood density in present-day conditions of timber assortments harvested from the study area. These figures may change if silvicultural treatments are intensified.

The pilot survey of the study material revealed that the geographical variation did not seem to affect wood density within the sample. Hence latitude, longitude and altitude were ignored in selecting independent variables of the regression equations.

The geographical variation of wood density is, however, a matter of importance. Mayr put forward the optimum theory according to which each tree species forms the highest density wood within the optimum of its range (G a y e r and F a b r i c i u s 1921). J a l a v a (1946) holds this optimum range for Scotch pine to be central Finland, and for Norway spruce south of Finland. According to T r e n d e l e n b u r g (1939) the optimum range of Scotch pine reaches from southern Finland to Germany, as to the wood density. The differences in the pulp yield per unit volume of timber between the pine sulphate pulp mills of southern and northern Finland, and the differences in pulp properties, also indicate differences in wood density of the raw material (cf. K a l l a 1966). In a recent study the difference in wood density of pine and spruce pulpwood between southern and northern Finland was not significant, however (U i t - t o t e h o - - - 1966).

The values reported for the density of timber assortments are most reliable in their application to the study area. It is suggested however, that these figures be used for the whole of southern Finland until the geographical variation in wood density has been clarified in later studies.

V. Practical viewpoints

It is necessary in the forest industries and in the management of forests to pay increasing attention not only to the volume but also to the quality of wood. As wood quality is a concept bound with the purpose of use of the wood, it is not possible to speak in general terms of good wood or poor wood. In lieu of quality, wood quality indicators which anable indirect determination of the suitability of wood for various purposes must be used. One of the most important wood quality indicators is wood density.

High-density wood is advantageous for many uses, but in some cases low-density wood gives a better end product. For the wood user to obtain the most suitable timber for his purposes and to be able to price if fairly, it is important to know where to obtain timber of certain wood density. This information is also needed in industrial planning, sorting of raw material, and quality control of the end product. On the other hand, the forest grower should know which factors affect the density of the wood produced by the forest in order to be able to influence the situation when he so desires.

It is obvious that wood density is greatly dependent on the inheritable properties of tree. The significance of heritability lies in the possibility that forest tree breeding may influence the wood density of the future forests. It has appeared from some studies that hereditarily fast-growing trees tend to produce wood that is lighter than the average. Hence, if wood density is disregarded, when choosing plustrees, the density of the wood produced by the future forests may be lower than it is at present. In selecting plustrees, their growth rate should be determined as dry matter yield, rather than as volume yield.

Another factor affecting wood density is the age of the tree. The wood density of Scotch pine, Norway spruce and birches increases with tree age. Since the rotation time of Finnish forests is to be reduced, the average wood density will decrease at least in southern Finland. Exceptionally low-density timber is obtained from young stands in connection with the first thinnings.

The third important factor affecting wood density is the growth rate of the tree. Density decreases in both Scotch pine and Norway spruce with acceleration of the growth rate, whereas the role of this factor appears to be insignificant in birches. It is to be expected that the wood of the fastgrowing plantation forests of the future will be of expecially low density. The fertilization of forests has a similar influence. It must be noted, however, that when the age of the stand increases the effect of the growth rate on wood density decreases.

It may be assumed that wood density varies with both race and climatic factors in different parts of Finland. This is suggested by the differences known to exist in the raw material consumption and the properties of the end product of the pulp industries in southern and northern Finland. To establish these differences, a study of the variation in wood density in different parts of Finland must be undertaken, for instance with the method evolved in the present work.

It has also been shown in the present study that there are considerable differences in wood density between timber assortments. It is thus possible for industry in some cases to take consideration wood density in its pricing procedure without incurring special costs. It is also possible in some degree to screen raw material, for instance by keeping the low-density pine pulpwood from the tops of saw timber trees separate in the timber yard. Most of this pulpwood is gathered into separate stacks in the harvesting stage already (cf. M u r t o 1949).

Let us take as an example a mill producing kraft paper from pine. Its pulp yield per solid cubic metre of wood is directly proportional to the density of pulpwood. The quality of the product, too, improves with the increase in wood density. Hence, it is possible to place the various timber assortments utilized by the mill in an order of avdantage on the basis of the dry matter content per solid cubic metre of wood. If the value 100 is assigned to the density of normal pine pulpwood, the following values will be obtained for other assortments. For the sake of comparison, the corresponding values for spruce are also presented.

Timber assortment	Pine	Spruce
	Ratio	
Saw mill chips from slabs	106	91
Saw logs (butt, middle and top logs)	102	89
Normal pulpwood	100	91
Small-diameter pulpwood	98	95
Top saw logs	96	88
Pulpwood from tops	93	90
Small-diameter pulpwood from tops	91	90
Logging residues from tops	88	91

A list of this type naturally does not give a final of the real value ratios within a tree species. It is necessary to consider also the variation of knottiness, heartwood content and other factors in the different timber assortments. Wood density, however, constitutes the basis of the calculations.

Wood density varies in many cases more than the solid cubic content of a stack. In practice, however, it is the latter that is considered and wood density that is disregarded.

VI. Summary

Knowledge of wood density may be of great significance in determining the quality of timber used for a certain purpose. The continuous enquiries addressed to the Forest Research Institute, especially by industry, have shown that data on wood density are needed for many purposes in practice. Therefore, in spring 1962, the Forest Technolygy Department of the Forest Research Institute started a study to ascertain the influence of different factors on the variation of wood density in Scotch pine (*Pinus silvestris* L.), Norway spruce (*Picea abies* (L.) Karst.), common birch (*Betula verrucosa* Ehrh.) and white birch (*Betula pubescens* Ehrh.).

The object was to find out the wood density variation within the stem and between stems, and the wood density of the most important timber assortments. The investigation was confined to a limited geographical area in southern Finland. In addition, a method was to be evolved for a wood density inventory using standing trees.

The sample consisted of 2 095 felled trees from which a total of 20 220 increment cores were taken. The wood density of the cores was determined by the mercury immersion method (E r i c s o n 1959) as basic density. The unit of measurement employed for density was kilogramme per solid cubic metre. The statistical procedure was based chiefly on regression analysis.

Some of the most important results of the study are reported in the following.

The density of pine increases from pith to cambium especially sharply in the region of juvenile wood. The same tendency continues outside the juvenile wood zone. The density of the wood that forms depends above all on the percentage summerwood (Figure 4) and the tree age at the respective stem height (Figure 5). Ring width (Figure 6) is of significance, too, even outside the juvenile wood zone.

The density of spruce wood decreases within the first annual rings towards the cambium, but begins to increase

again in a few years. The percentage summerwood and the ring width appear to be the most important factors.

The density of birches also increases from pith to cambium. The importance of the age of the annual ring is also great, but the ring width does not influence wood density of birches.

Density decreases in the longitudinal direction of the stem from butt to top especially sharply in Scotch pine (Figures 7 and 8). The change is similar in common birch and white birch, though smaller in the latter. The density of Norway spruce decreases from the butt to the middle of the stem, but then begins to increase again towards the top. Density variations in the longitudinal direction of the stem are decisive for the density of the different timber assortments obtained from the stem.

The density variation between stems has been explained with the help of various independent variables and their combinations (p. 25). The best multiple linear regression equations explain 41 per cent of the tree density for Scotch pine, 40 per cent for Norway spruce, 28 per cent for common birch and 16 per cent for white birch (p. 62). Regarding the individual independent variables, the tree density variation in the pine and the birches is explained best by the reciprocal of age (Tables 12 and 13), in the spruce by the quotient of breast height diameter and age, which illustrates the rate of growth (p. 61). The site quality, i.e. the forest site type, also affects wood density (Table 17). It has been concluded on the basis of the magnitude of the unexplained density variation that hereditary factors have a great influence on wood density and its variation.

It can be assumed on the basis of the results that the density of the softwood timber produced by the future forests of Finland will decrease a little under the influence of the intensification of silviculture. To offset this, forest tree improvement activity should take into account, in addition to volume growth, also wood density and other wood properties.

By way of application of the investigation results, the density values of different timber assortments have been calculated. The differences between the timber assortments are considerable, especially in Scotch pine. The weight of a solid cubic metre of pine wood is highest in saw mill chips from slabs, then in saw logs, normal pulpwood, small-diameter pulpwood, pulpwood from tops, small-diameter pulpwood from tops and lowest in logging residues from tops. The differences between the timber assortments are smaller in spruce and birch wood. Comparison of corresponding assortments shows that spruce is of lower density than pine except for the logging residues from tops.

It has been noted in many connections that an inventory should be made, as soon as possible, of the wood density variation in different parts of Finland. This can be done from increment cores collected from standing trees on the basis of the method evolved in the present study (Table 9). Samples taken at breast height can be used to predict the average tree density with sufficient accuracy so that the method can be applied also to determining the wood density of plustrees.

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