A HYPOTHESIS RELATING CURRENT ANNUAL HEIGHT INCREMENT TO JUVENILE WOOD FORMATION IN NORWAY SPRUCE

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ABSTRACT

The relationship between current annual height increment and anatomical and physical wood properties was studied on material from two spacing experiments in Norway spruce [*Picea abies* (L.) Karst.] on good sites in southeastern Norway. The two experimental plots were clearfelled for wood analysis at 52 and 79 years of age, respectively.

The first experiment comprised three spacings (1.25 × 1.25, 1.75 × 1.75, and 2.25 × 2.25 m), but differences in stand density had been evened out by thinnings at an early stage. No significant relationship between basic wood density and initial spacing was found here. The second experiment comprised one spacing (5.5 × 3.0 m).

Current annual height increment culminated at the age of 18–19 years in the first experiment and at 28–29 years in the second experiment. In both experiments, a transition phase between formation of the juvenile wood and the mature wood at the stump height level (root-neck) clearly coincided with culmination of the current annual height increment.

This supports a synchronous growth hypothesis, which states that the formation of mature wood in the stump height area (root-neck) commences when the current annual height increment has culminated.

Keywords: Juvenile wood, height increment, anatomical and physical properties, synchronous growth hypothesis.

INTRODUCTION

It is well known that living organisms experience various phases of development during their life cycle. These phases have their foundation in the dynamics of life, which mirror certain energetic or physiological conditions that either stimulate or slow down growth.

The difference in quality between wood produced in each life phase can easily be studied by analyzing each anatomical, physical, and mechanical property from growth ring to growth ring, from pith to bark. Each property creates a defined characteristic polynomial development, which shows the variations in the properties from the pith to the bark with time as the decisive factor.

The quality of the wood is a result of a long and comprehensive production process. It stems, among other things, from a complicated interplay between the genetic dispositions of the trees, their natural requirements (growth conditions, site quality, and age), and silvicultural measures practiced during the period of maturation.

In plantations of Norway spruce [*Picea abies* (L.) Karst], use of fast-growing provenances in large spacings with relatively short rotation is a contributory reason why a large part of the volume of the tree consists of juvenile wood.

As the name implies, juvenile wood is produced by cambium in the juvenile stage. In other words, it is always nearest the pith. Seen from a technological point of view, one can say that juvenile wood, compared with mature wood, has, among other things, lower strength properties, shorter and narrower tracheids, lower percentage of late wood, thinner cell walls, larger lignin and hemicellulose content, and less cellulose content. The larger fibril angle in the S_2 tracheid wall layer results in the juvenile wood shrinking and swelling considerably more in the longitudinal direction than mature wood (Bendtsen 1978; Thörnqvist 1990).

It has been the normal practice so far to determine the juvenile wood zone by a certain number of growth rings from the pith, but sometimes this is also determined as a zone within a certain distance from the pith. This determination is made on the basis of changes in the wood and fiber properties in the cross section of the trunk.

This paper endeavors to define the boundary line between juvenile and mature wood by the cross section of the trunk at the stump height area (root-neck) with the aid of a synchronous growth hypothesis. This hypothesis is based on the following:

The transition from juvenile wood formation to mature wood formation in the stump height area (root-neck) in homogeneous monocultures of spruce (conifers) takes place at the culmination of the current annual height increment.

The hypothesis has its logical background in the growth theory. The trees undergo considerable stress after planting. This applies especially to tree species adjusted to semi-shade or shade at the initial phase. The juvenile growth period is characterized by exponential height increment and the rapid establishment of the vegetative organs (crown). This period ends when the current annual height increment culminates. The better the site quality, the earlier the current annual height increment culminates, and the larger the height increment will be at culmination time. After the culmination of the current annual height increment (juvenile phase), the formation of mature wood commences (vital production phase).

The hypothesis for determination of the boundary line between juvenile wood and mature wood on the basis of height increment

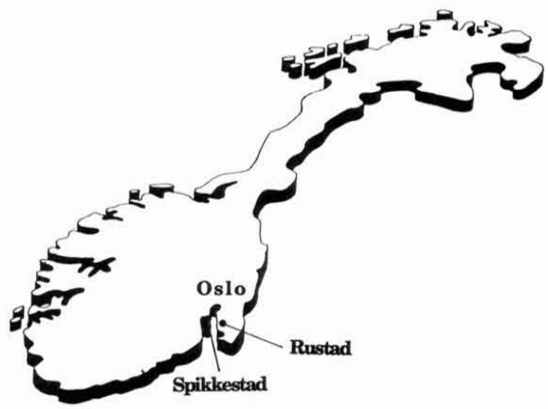

FIG. 1. Location of sample plots.

culmination has been tested in two separate assessments. The boundary line between juvenile wood and mature wood was determined by analyzing the various anatomical and physical properties, and the results were compared with the height increment observations.

MATERIAL AND METHODS

Description of sample plots

The material for this investigation originates from two experimental plots—Spikkestad and Rustad, both in southeastern Norway (Fig. 1).

Spikkestad

The sample plot is a spacing experiment with six subplots, established by the Norwegian Forest Research Institute in 1936 in Rud Forest, Spikkestad in Røyken. The experiment was laid out on arable land with 2/1 transplants of Norway spruce. The initial spacing was 1.25 × 1.25, 1.75 × 1.75, and 2.25 × 2.25 m, with two replications for each block. The spacing plots were treated in different ways. The silvicultural program is described by Braastad (1970). From the age of 25, the number of trees was practically the same for subplots 1, 2, 3, and 4.

After thinning in the autumn of 1966 and snow damage in 1966/67, there was little difference in stand density between all six subplots. The number of trees then varied from 734 to 1,057 per ha. The spacing experiment

TABLE 1. *Stand data of the spacing experiments of Spikkestad and Rustad at the time of final cutting, age 52 and 79 years, respectively.*

	Sample plot						
	Spikkestad						Rustad
	Original designation of samples						
	626 I–III			627 I–III			
	225 a	175 a	125 a	225 b	175 b	125 b	597/I
	Sample designation in laboratory						
Stand data[a]	1	2	3	4	5	6	7
Initial spacing, cm	225	175	125	225	175	125	300 × 550
Number of trees per ha	573	529	529	471	597	553	482
Mean height (H_L), m	25.8	24.7	24.2	25.3	24.0	24.4	27.1
Mean DBH overbark, cm	30.5	29.7	28.8	30.4	27.6	27.6	34.3
Site index (H_{40})	25.3	26.7	25.7	26.0	25.5	25.1	22.5
Basal area overbark (G), m^2/ha	41.8	36.5	34.5	34.3	35.8	33.0	44.6
Volume overbark (V), m^3/ha	522	430	404	416	418	394	566
Total yield (V_T), m^3/ha	736	690	715	683	691	750	596
Mean annual increment (MAI), m^3/ha	14.15	13.27	13.76	13.13	13.28	14.42	7.55

[a] The data were registered at the Spikkestad experiment in 1985 and at the Rustad experiment in 1987 by the Norwegian Institute of Forestry Research.

was terminated and clearcut in 1985 at age 52. Stand data before clearcutting are given in Table 1.

Rustad

The Rustad experimental plot was established in 1953 by the Norwegian Forest Research Institute in a spruce plantation from 1913 on former arable land. The plants had been taken up from natural regeneration in ditches nearby and planted with a spacing of 5.5 × 3.0 m, (600 plants per ha). In 1953 there were 508 trees/ha left, and 65 of the 600 trees planted per ha had resulted in small trees. The height of 29 sample trees was determined in 1932, 1938, 1944, and 1950. Development of the basal area increment from 1938 to 1953 was determined on the basis of 40 core tests. Since 1953 the increment of the sample plot has been calculated on the basis of surveying every third year (Braastad 1968). The experiment has no subplots and no replications. The calculated stand data are given in Table 1.

Selection of sample trees

The material for this assessment was collected in the autumn of 1985 from Spikkestad and in the spring of 1988 from Rustad when the sample plots were clearfelled. All the trees selected were normally developed and free from rot or other serious flaws. In each test plot, all the trees complying with these criteria were divided into five equally large groups according to mean diameter at breast height (Table 2).

From each diameter class, a tree was randomly chosen for testing. In this way, all the healthy trees had the same chance of being tested. Thirty trees in all were tested from Spikkestad and 5 from Rustad. Information on the trees from the seven plots is given in Table 3.

Selection of sections from the sample trees

The sample trees were cut up in sections (Fig. 2a). From each sample tree, 5 pieces of

TABLE 2. *Mean diameter classes.*

	Mean diameter classes ($D_{1.3\,m}$) in mm overbark				
Plantation	1	2	3	4	5
Spikkestad	183–254	255–281	282–306	307–331	332–389
Rustad	231–276	277–320	321–354	355–384	385–457

TABLE 3. *Tree data from 7 plots.*

Plantation	Sample designation in laboratory	Number of sampled trees	Mean tree length, m	Mean DBH overbark, cm	Mean crown length, m	Mean crown length, %
Spikkestad	1	5	25.7	30.7	8.3	32.4
	2	5	25.4	29.7	8.0	31.7
	3	5	25.5	28.4	8.4	33.0
	4	5	26.2	30.5	8.5	32.6
	5	5	25.0	27.2	8.9	35.7
	6	5	25.1	28.2	9.1	36.5
Mean of trees from Spikkestad			25.5	29.1	8.5	33.6
Rustad	7	5	26.5	32.7	15.9	60.1

3-cm-thick trunk discs were taken out—the first at the stump height and the others at the same distances up the trunk in length sections equal to 20% of the length of the tree (Fig. 2b). Then two section samples were taken from each trunk disc. These cover a 6-mm-wide strip along a diameter in the trunk in a north-south direction (Fig. 2c and 2d). Section sample 2c was later divided into individual growth ring sections from the pith and out towards the bark. These sections were used to analyze the basic density, absorption capacity, and dry matter content (Fig. 2e). After maceration, these growth ring blocks were used to assess the tracheid length (Fig. 2f). The section sample 2d was used for analysis of the growth rings (growth ring width, early- and latewood share in growth rings) (Fig. 2g), and then for analysis of the anatomical structure (tracheid diameter measured in a radial direction) (Fig. 2h).

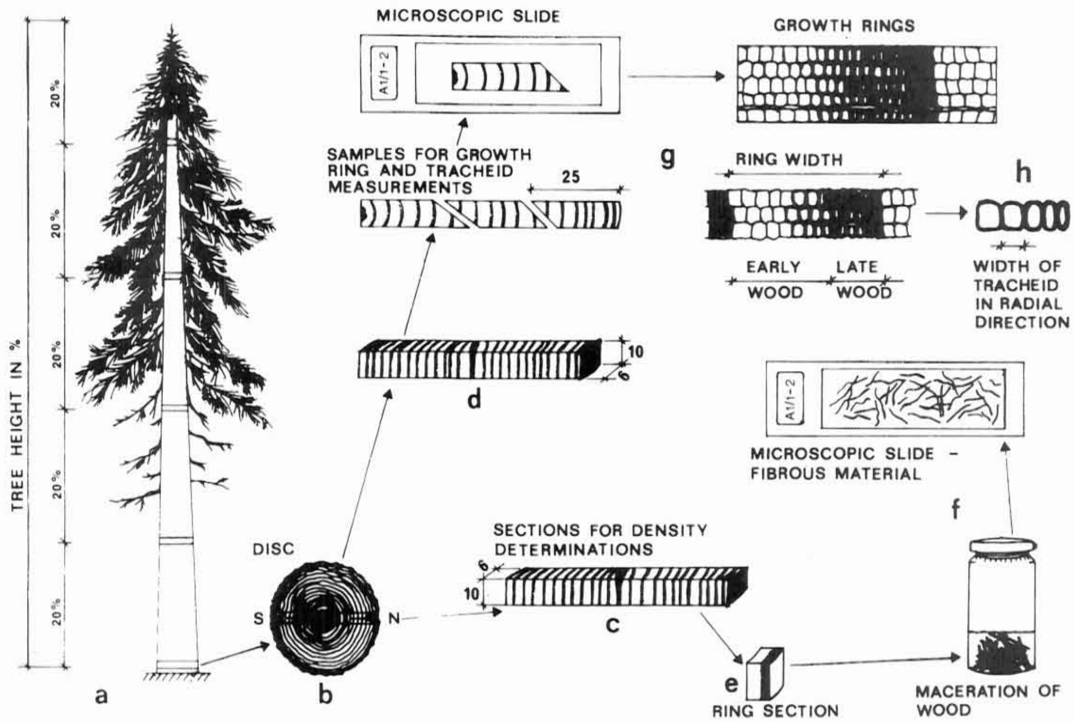

FIG. 2. Division of trunk discs and selection of test pieces.

Assessed anatomical and physical properties

The physical properties of all five trunk sections (01, 20, 40, 60, and 80% of tree height) were assessed. These assessments were made on individual growth rings (cleaved growth ring blocks from the pith and out towards the bark in a north-south direction). The following physical properties were assessed:

Basic density ρ_{y}.—The basic density is the wood mass in an absolutely dry condition in g, divided by the volume of the wood in the green condition in cm^3—expressed in g/cm^3. When measuring the basic density, distilled water is used as the buoyancy element with the determination of the volume of the samples (Olesen 1971).

Absorption capacity W_{m}.—The maximum moisture mass in the wood in g after 24 hours immersion in distilled water, expressed in percentage of the wood mass in an absolutely dry condition in g.

Dry matter content D_{mc}.—The dry matter content is the wood mass in absolute dry condition in g expressed in percentage of the wood mass in green condition in g.

The growth ring structure was systematically measured from the pith and out towards the bark, in both directions (towards north and south) in all five trunk sections on all the trees selected in the Spikkestad sample plot. The following anatomical properties were assessed:

Growth ring width G_{rw}.—The annual secondary thickness growth of the tree, measured with the aid of an automatic growth ring surveying machine with an accuracy of 0.01 mm.

Latewood percentage L_{p}.—The latewood part in the growth ring is calculated in percentage of the full growth ring width. For latewood, we calculated the part of the growth ring where the common wall between two tracheids multiplied by 2 is equal to or larger than the cell lumen, all measured in a radial direction. The latewood percentage is measured with an accuracy of 0.1%.

Only the growth ring width was assessed on the material from the Rustad sample plot.

The tracheid structure was assessed only on the material from the first six plots (Spikkestad). These analyses are very demanding, and it was therefore decided to assess only two selected trees from each subplot (12 trees in all). One tree was taken from the middle diameter class from each square, plus one random tree. The analyses were carried out on all five trunk sections. The following anatomical properties were assessed:

Tracheid length T_{l}.—Tracheid length is measured in μm with an accuracy of 10 μm. Thirty-five tracheids were measured per growth ring.

Tracheid width T_{w}.—Tracheid width is measured in a radial direction in μm with an accuracy of 1 μm.

Use of anatomical and physical properties for the determination of the boundary line between juvenile wood and mature wood

All the assessed properties clearly show variations in the cross section of the trunks. The juvenile wood zone was determined on the basis of changes in the wood and tracheid properties in the stump height area (root-neck). The boundary line between juvenile wood and mature wood is decided by the age, where there is a transition between the two characteristically different parts of the curve, which describes the correlation between individual properties and age, determined at the stump height.

In addition to this, the boundary line between juvenile wood and mature wood was determined in the same way and also in the five trunk values; but instead of age, the growth ring numbers from pith to bark were chosen as the variable. This was done to avoid dislocation (displacement) due to the different ages of the individual trunk levels.

Growth properties (height growth functions)

Biologically, height growth is a decisive growth factor, which determines the sociological differentiation in the stand, the course of natural selections, the development of the crown and the trunk, and thereby also the choice of silvicultural measures (Korpel' 1971). Height growth is dependent on several factors such as tree species, age, genetic disposition, climate and soil conditions, to name the most important.

Theoretical basis for cumulative height growth and height increment functions

Growth acceleration can best be studied with the help of cumulative height growth and height increment functions. The cumulative height growth functions are similar to each other, i.e., they have an S-shaped form, something that is characteristic for organic growth generally (Korf 1939). Each forest mensuration factor (y) which increases with age, can be described as a function of age

$$y = f(t) \tag{1}$$

An S-shaped cumulative height growth curve is convex seen from below, during the first age phase up to a determined age t_1. At this time, the cumulative height growth curve reaches an inflection point and then becomes concave. At a high age, when the current annual height increment is small and the growth only increases slightly, we can make the following conclusion regarding the cumulative height growth function: at age $t \rightarrow \infty$ the cumulative height growth function (y) will approach a determined asymptotic value (A), which can be expressed in the following way:

$$\lim_{t \rightarrow \infty} y = \lim_{t \rightarrow \infty} f(t) = A \tag{2}$$

This equation (2), which actually describes the growth capacity with determined growth conditions, is very important and also real (Korf 1939). If the cumulative height growth functions are defined as (1), one can mathematically define the current annual height increment as the first derivative of this function, namely

$$y' = \frac{dy}{dt} = f'(t) \tag{3}$$

The mean annual height increment is then:

$$\eta = \frac{f(t)}{t} \tag{4}$$

The inflection point on the cumulative height growth curve, $y = f(t)$, is found at age $(t) = t_1$. At this time the first derivative is a maximum, namely

$$f'(t_1) = \max \tag{5}$$

The maximum for the mean annual height increment is at age $(t) = t_2$. At this age, the mean annual height increment is equal to the current annual height increment. This is a very important forest mensuration moment (Korf 1971). The following is applicable:

$$\frac{f(t_2)}{t_2} = f'(t_2) \tag{6}$$

From a mathematical point of view, proof that this is correct is very simple. The mean annual height increment according to Eq. (4) is:

$$\eta = \frac{f(t)}{t}$$

The maximum for this function occurs when its first derivative is equal to 0. The first derivative is:

$$\eta' = \frac{f'(t)t - f(t)}{t^2} \tag{7}$$

For $t = t_2$ the first derivative must be equal to 0, namely

$$\frac{f'(t_2)t_2 - f(t_2)}{t_2^2} = 0 \tag{8}$$

and of that

$$f'(t_2) = \frac{f(t_2)}{t_2} \tag{9}$$

It is therefore evident that both annual height increments (current and mean) are the same at the time when the mean annual height increment culminated (Korf 1971). In a geometrical interpretation, it can be assumed that the function curves for both annual height increments intersect each other at one point, where $t = t_2$ (Figs. 7, 8 and 9). Each cumulative height growth curve has, in principle, three different growth phases. With different conditions of growth, the growth phases have different durations. The first phase of the cumulative height growth curve ranges from the formation of the growth conditions (planting of the tree) to the age (t_1). This phase is completed at the inflection point on the cumulative height growth curve, i.e., at the time when the current annual height increment culminates. We call this development stage the formation phase or the juvenile stage. This phase has an approximate exponential progress.

The next phase is from the age of t_1 to age t_2. At age t_2 the mean annual height increment culminates and at this point is equal to the current annual height increment. We can call this phase the vital production phase or an approximate linear phase.

The third and final phase is from age t_2, and is theoretically unlimited and, in practice, is completed at felling time. We can call this phase the old age phase. Under normal circumstances, height increment decreases and becomes very little.

In this paper, these height growth phases are studied in relation to the tested anatomical and physical properties.

Selected cumulative height growth and height increment functions for the tested material

From the time of planting to the time of felling of the trees, the Norwegian Forest Research Institute regularly measured the height of the individual trees, and these data have been used for calculation of the cumulative height growth and annual height increment functions.

In order to find an S-shaped height growth age function that thoroughly covers all development phases, an analytical equation must be arrived at which allows one to carry out the necessary mathematical operations (interpolation, extrapolation, derivation, and integration) which are important for the study of the growth process.

It was discovered, when testing several functions, that the best one for these fast-growing spruce trees was a three parameter height growth function after Michajlov (1952), which is identical to Korf's function from 1939 (Poleno 1977). This function is defined in the following way:

$$y = a \cdot e^{-\left(\frac{k}{t^c}\right)} \tag{10}$$

where t = age and a, k, c = constants.

The function thoroughly covers the height growth development and at the same time reveals great flexibility. It is also easy to calculate the other height growth properties, such as the current annual height increment y' and the mean annual height increment y/t, and also those "maxima" where the current and mean annual height increment culminates.

The first derivative is as follows:

$$y' = akc\frac{e^{-\left(\frac{k}{t^c}\right)}}{t^{c+1}}. \tag{11}$$

The second derivative is as follows:

$$y'' = akc\frac{e^{-\left(\frac{k}{t^c}\right)}}{t^{c+2}}\left[\frac{kc}{t^c} - (c + 1)\right] \tag{12}$$

The third derivative is as follows:

$$y''' = akc\frac{e^{-\left(\frac{k}{t^c}\right)}}{t^{3c+3}} \cdot \cdot[t^{2c}(c^2 + 3c + 2) - - t^c(3kc^2 + 3kc) + k^2c^2]. \tag{13}$$

The relationship between the height increment function and the boundary of juvenile wood/mature wood based on anatomical and physical properties

The manner in which the boundary line between juvenile and mature wood is determined in the cross section of the trunk, based on analyses of the anatomical and physical properties, is described in a previous section. This boundary line is compared with the height increment functions that are found, and this is the basis for determination of the relations between height growth and juvenile/mature wood, which again results in a synchronous growth hypothesis.

RESULTS

Height growth data

Fast-growing provenances of Norway spruce at good sites, such as the tested material from Spikkestad and Rustad, show relatively large current annual height increments at culmination time—72 cm annually for the Spikkestad experiment and 58 cm annually for the Rustad experiment.

From the combined Figs. 7, 8, and 9, it is obvious that the current annual height increments culminate at an age of 18 years (t_1) at the Spikkestad experiment and at an age of 28 years (t_1) at the Rustad experiment. The mean annual height increment culminates at an age of 36 years (t_2) at the Spikkestad experiment and at an age of 54 years (t_2) at the Rustad experiment. This is quite a typical picture of today's forest culture with Norway spruce as monoculture, at good sites. It has a relatively rapid height development, large diameter growth, with all the negative consequences for the quality (properties) of the wood as a result.

The relationship between the tested anatomical and physical properties and the growth ring numbers from the pith, at five different trunk heights (01, 20, 40, 60, and 80% of the tree height)

In order to illustrate the progress at the five trunk levels in a visually satisfactory manner, it was necessary in this case to choose growth ring numbers from the pith instead of age as variables.

Growth ring numbers from the pith should be understood here as the location of the growth rings in the cross section of the trunk. Registrations commence at the pith—(growth ring No. 1) and end at the bark—(growth ring No. n). The development of the individual tested properties shows, in principle, the same course in all five trunk sections (Figs. 3 and 4).

We have compared the diameter of the juvenile zone (absolute value) versus the total

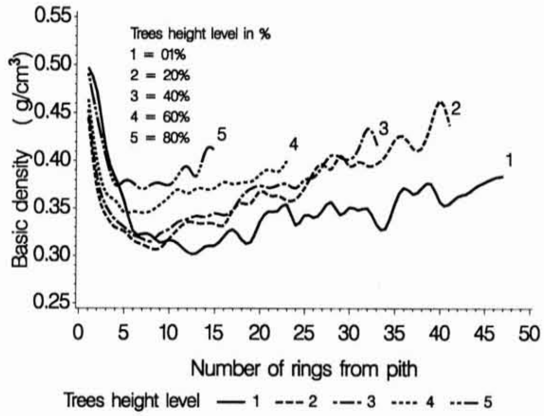

FIG. 3. Relationship between basic density and growth ring number in five trunk sections—Spikkestad experiment.

diameter at a given height. The results show that the juvenile tree zone is narrower farther up the tree, whilst the part of the juvenile wood in the cross section, generally increases with the height of the tree (Fig. 5).

Relationship between the age and the tested physical and anatomical properties of the first trunk section (01% of the tree height) in relation to culmination time for the current annual height increment

Basic density (ρ_y) – age (t).—Most of the tested properties have a close relationship to

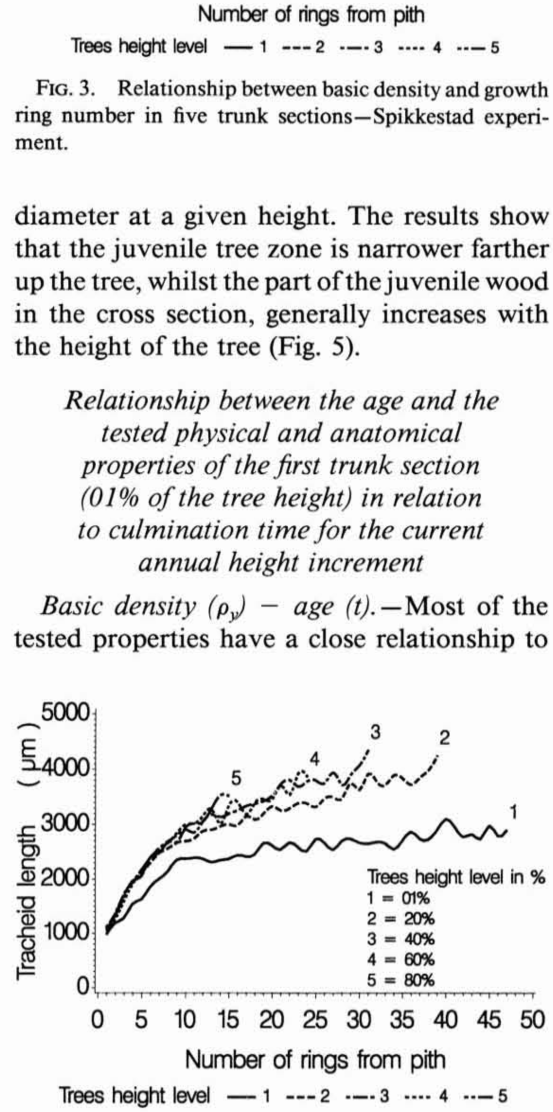

FIG. 4. Relationship between tracheid length and growth ring number in five trunk sections—Spikkestad experiment.

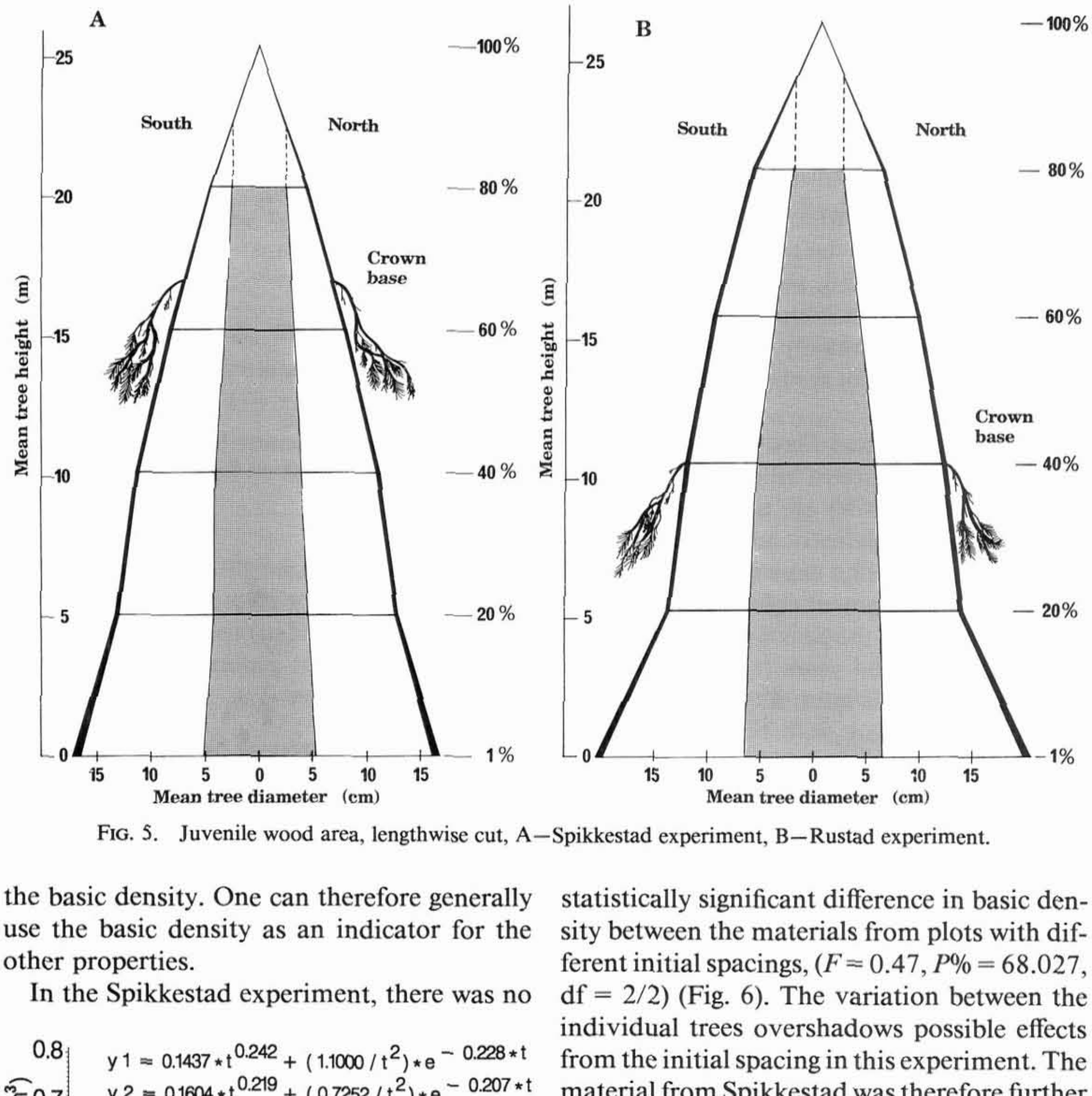

FIG. 5. Juvenile wood area, lengthwise cut, A—Spikkestad experiment, B—Rustad experiment.

the basic density. One can therefore generally use the basic density as an indicator for the other properties.

In the Spikkestad experiment, there was no statistically significant difference in basic density between the materials from plots with different initial spacings, ($F = 0.47$, $P\% = 68.027$, df = 2/2) (Fig. 6). The variation between the individual trees overshadows possible effects from the initial spacing in this experiment. The material from Spikkestad was therefore further treated and analyzed in one operation.

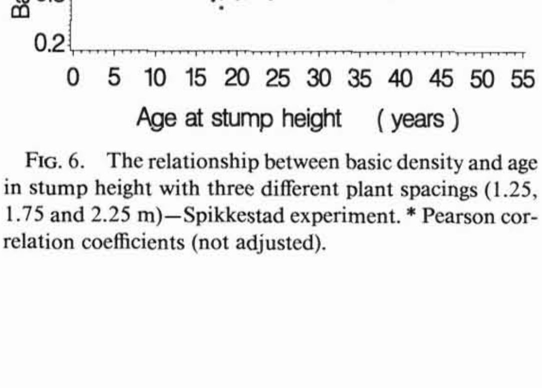

FIG. 6. The relationship between basic density and age in stump height with three different plant spacings (1.25, 1.75 and 2.25 m)—Spikkestad experiment. * Pearson correlation coefficients (not adjusted).

The poor relationship found here between initial spacing and basic density can have several explanations. From a relatively early period in the rotation, there was practically no difference in the number of stems per hectare between the individual spacing plots (Table 1). This can partially explain that the initial spacing in the experiment had no significant influence on the basic density. The duration of the influence from different spacings has been too short.

Another explanation could be that the small difference in initial spacing from 1.25×1.25

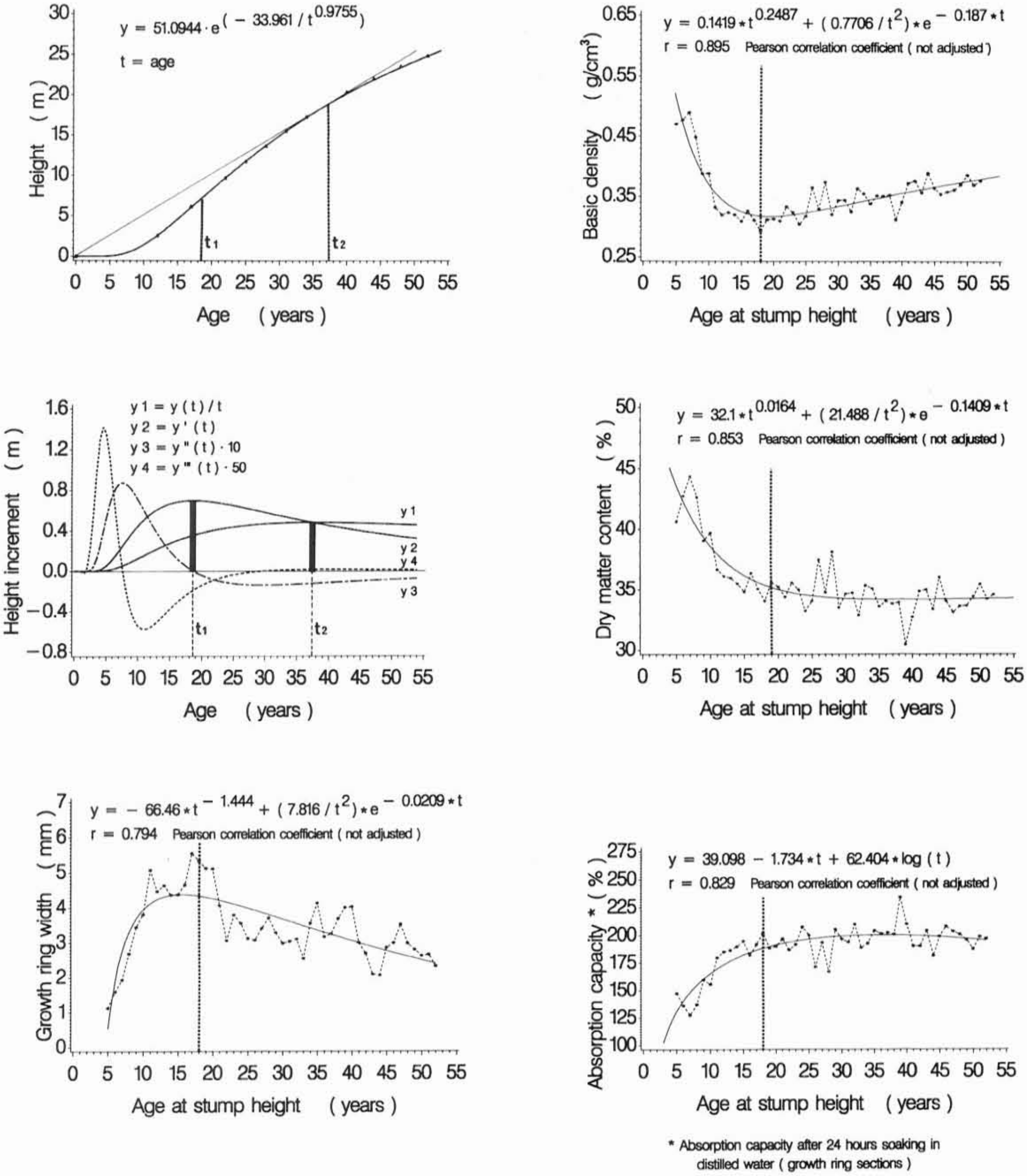

FIG. 7. Relationship between the age and the tested physical and anatomical properties in the first trunk section (01% of height of tree) in relation to culmination time for the current annual height increment. Material from the Spikkestad experiment.

to 2.25 × 2.25 m does not have very much influence on the development of juvenile wood. In my opinion the height growth development (site index) is of much greater importance for the development of juvenile wood than a moderate difference in plant spacing (1 m). A slight difference in spacing has also had minimal influence on the variation in the size of the crown (31.7–36.5% of the length of the tree) (Table 2). There is a completely different situation in

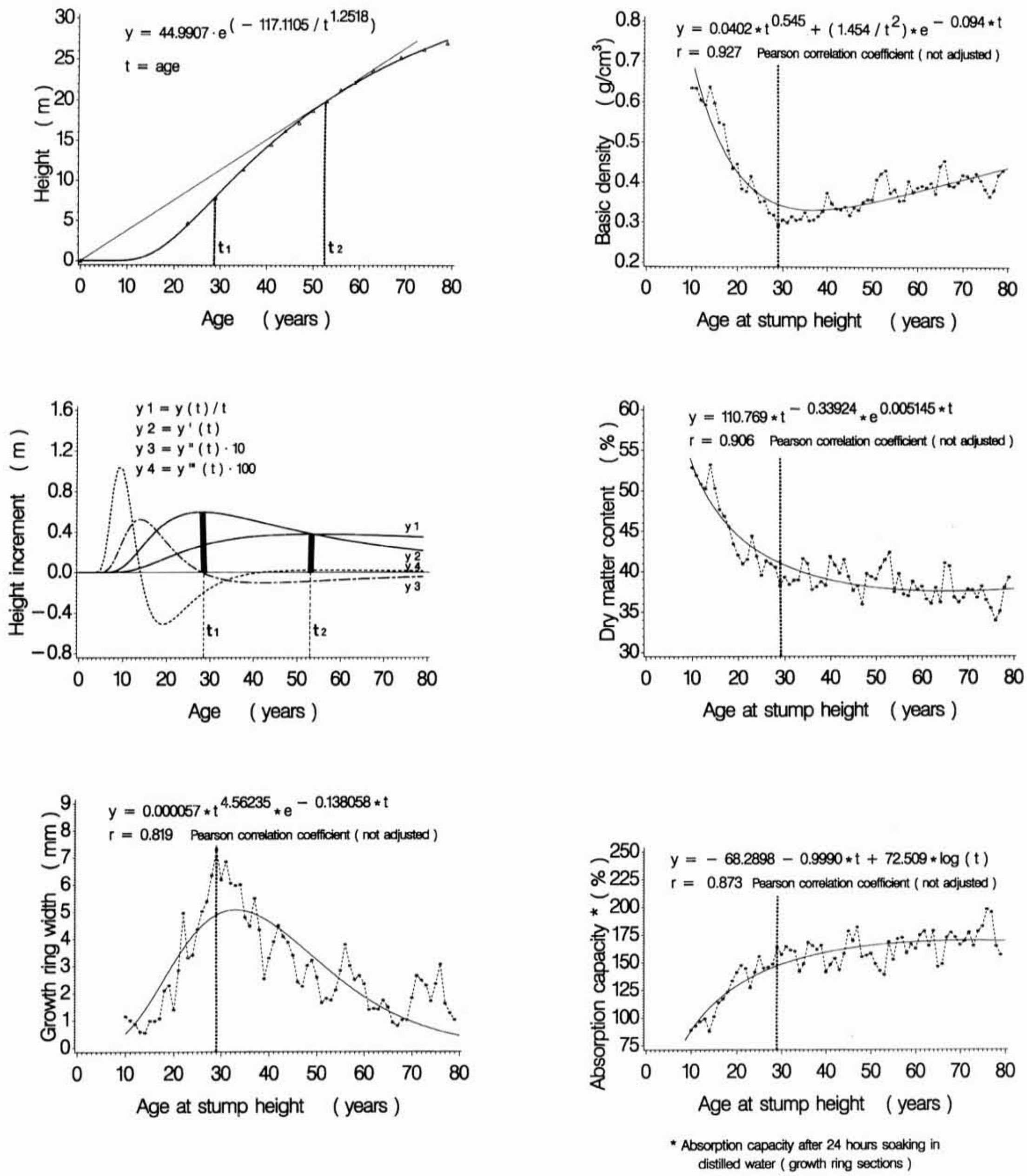

FIG. 8. Relationship between the age and the tested physical and anatomical properties in the first trunk section (01% of height of tree) in relation to culmination time for the current annual height increment. Material from the Rustad experiment.

the Rustad experiment, with very large plant spacing (3 × 5.5 m), relatively high site index (H40 = 22.5) and crown size as much as 60.1% of the length of the tree (Tables 1 and 2).

The results from the Spikkestad experiment show that there is a very good relationship between basic density and age (Fig. 7). The basic density decreases very strongly initially and then less strongly, until it begins to rise again for wood produced after the age of 18–

20 years. The variations in a radial direction are quite considerable, from practically 0.500 g/cm^3 nearest the pith to a minimum up to 0.300 g/cm^3 for wood produced at 18–20 years of age.

At the Rustad experiment the trees completed production of juvenile wood at the age of 28–29 years measured at the stump height (Fig. 8). In other respects, the curves have the same characteristic progress as that of the Spikkestad material. The variations in a radial direction are also very great, from 0.650 g/cm^3 nearest the pith to a minimum of up to 0.300 g/cm^3 for wood produced at 28–29 years of age.

Absorption capacity (W_m) – *age* (t).—The tests show that the absorption capacity as an age function, in principle, has the same progress for both the tested materials (Figs. 7 and 8). The curve for the material from Spikkestad shows first a strong increase from approximately 130 to approximately 200% at an age of 18–19 years, and then practically flattens out. The curve for the material from the Rustad sample plot shows almost the same increase as for the material from Spikkestad. The increase goes from approximately 90 to approximately 170% at an age of 28–30 years, and then the curve shows continued increase with the rise in age.

Dry matter percent (D_{mc}) – *age* (t).—The dry matter percentage is, to a large degree, correlated with the density of the wood. It decreases strongly in the first part of the growing period and then gradually stabilizes. The development processes are, in principle, the same for both test areas, but changes take place more rapidly in the material from Spikkestad. Here, after 18–20 years the curves flatten out, whereas the material from Rustad only begins to stabilize after 28–30 years (Figs. 7 and 8).

Growth ring width (G_{rw}) – *age* (t).—The variations here are partly of a genetic nature, caused to a certain extent by the age situation, and are largely the result of the crown size and growth conditions (soil, climate). The annual variations are large, but the progress of the curves is, in principle, the same for both test areas. The development is more rapid at Spikkestad, but Rustad achieves the largest maximum value. The Spikkestad material shows an increase in the growth ring width from 1.49 mm at the pith up to 5.39 at the age of 17 years, and then decreases with the rise in age towards the bark (Fig. 7). The curves for the material from Rustad show similar progress. The growth ring width increases here from 0.83 mm at the pith up to 7.39 mm at the age of 28–29 years, and then decreases with increasing age towards the bark (Fig. 8).

Latewood part of the growth ring (L_p) – *age* (t).—The latewood part shows large annual variations, which to a large degree follow the variations in the growth ring width. The minimum value (3.5%) is found at a growth ring width of 5.5 mm, whilst the maximum value (15%) is found at the age of 50 years, with a growth ring width of 2.5 mm. The common factor is a comparatively weak declining process in the first growth period, and a gradual strengthening in the progress from 18–20 years of age (Fig. 9).

Tracheid length (T_l) – *age* (t).—The function of the tracheid length in relationship to the age shows the same characteristic progress for all the five trunk sections from the Spikkestad sample plot (Fig. 4). At the stump height the tracheid length increases considerably from 980 μm at the pith to 2,390 μm at the age of 17–20 years and achieves a maximum value of approximately 3,000 μm after 45–50 years (Fig. 9).

Tracheid width in a radial direction (T_w) – *age* (t).—The function of tracheid width in the growth ring in relationship to the age shows the same progress at all five trunk heights. In the stump height the tracheid diameter increases from 17.2 μm at the pith to 33.5 μm at the age of 19 years. After culmination time (18–19 years), the average tracheid width is, in point of fact, practically unchanged with increasing age (Fig. 9).

DISCUSSION AND CONCLUSIONS

The two experiments, Spikkestad and Rustad, represent, according to Norwegian stan-

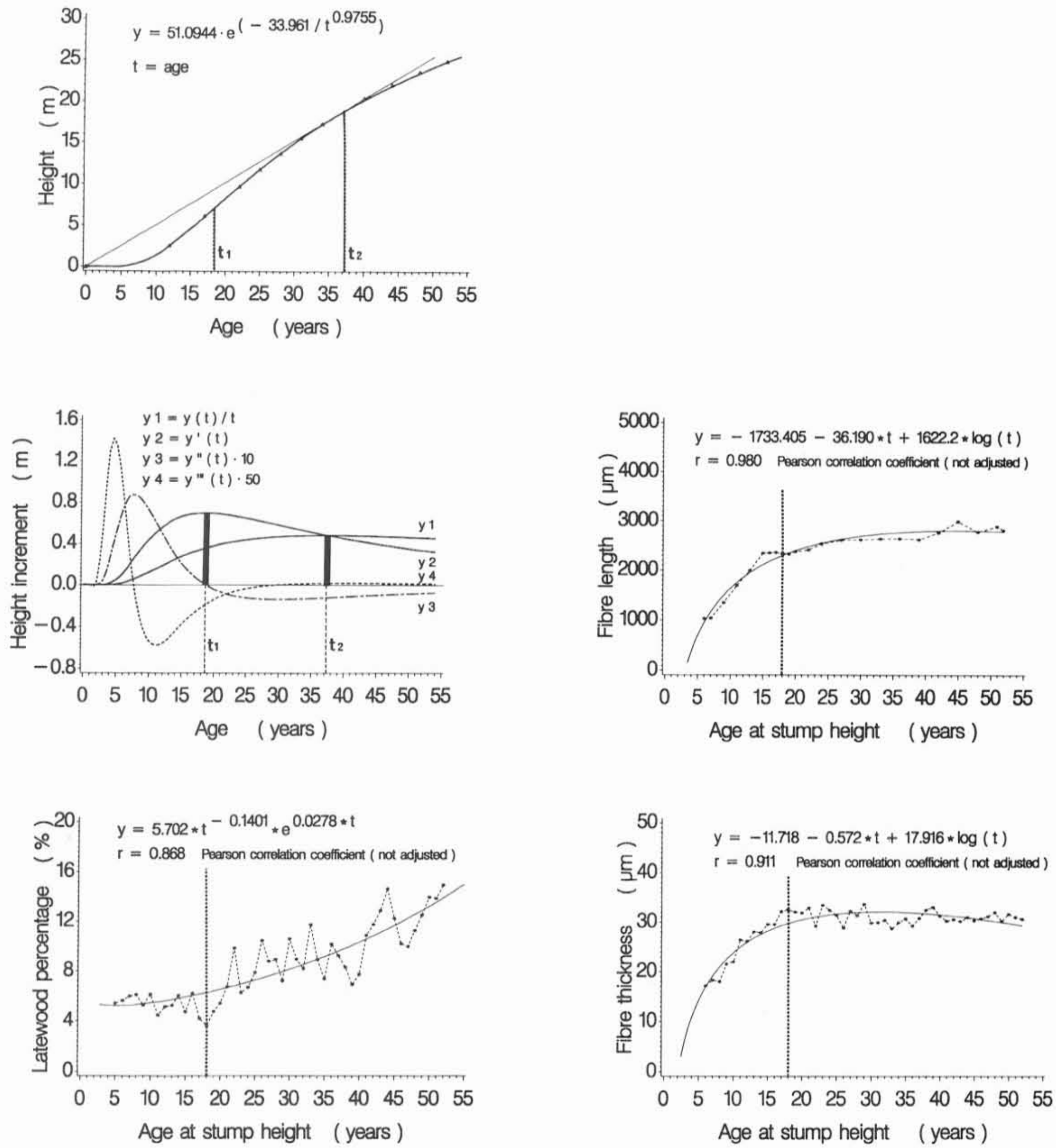

FIG. 9. Relationship between the age and the tested anatomical properties in the first trunk section (01% of the height of the tree) in relation to culmination time for the current annual height increment. Material from the Spikkestad experiment.

dards, very high and high site index, respectively. Plant spacing is substantially larger on the Rustad experiment, and this has led to considerably larger crown development—60% mean as compared to 30% on the Spikkestad experiment. However, these differences do not fully describe the weaker development that has been established for the trees on the Rustad area. Other factors may have influenced the growth of the trees immediately after planting, for example, competition with weeds (Braastad 1967).

Despite these differences, the development curves show that most of the properties have, to a large degree, had a similar course of development in both experiments.

The current annual height increment culminates at the Spikkestad experiment after 18–19 years, but on the Rustad experiment culminates after 28–29 years. The largest annual height increment measurement was 72 cm on the Spikkestad area and 58 cm on the Rustad area.

The results from these examinations show that there is a relationship between current annual height increment and the anatomical and physical properties examined at stump height.

The curves for the basic density and growth ring width show a clear inflection point after 18–20 years for the material from the Spikkestad area and after 28–30 years for the material from the Rustad area.

The curves for the dry matter content and absorption capacity have another course, and the inflection point is not as distinct. However, there is a definite tendency to flattening out after approximately 18–20 years for the material from the Spikkestad area and after 28–30 years for the material from the Rustad area.

For both sets of materials examined, differences in the development of the physical properties and growth ring width take place at the same time that the current annual height increment reaches its maximum.

The remaining anatomical properties (latewood percentage, tracheid length, and tracheid width) were examined only on the material from Spikkestad.

Because the latewood percentage is closely related to the growth ring width, annual variations are large. However, the development follows an exponential function to a great degree. The problem with this property is to determine a clear inflection point, but it is not unreasonable to place it close to the same point of time as for the other properties.

The development of tracheid length and tracheid width follows a logarithmic curve with a relatively sharp gradient up to 18–20 years, and then a more or less substantial adjustment. This takes place somewhat quicker for tracheid width than for tracheid length.

The transition between the formation of juvenile wood and mature wood coincides with the marked changes in the development of the physical and anatomical properties. For the material from the Spikkestad area, this means that at 18–20 years of age and for the material from the Rustad area between 28–30 years of age.

These transition phases again take place at the culmination of the current annual height increment and indicate a close relationship between height increment and the development rhythm for formation of juvenile wood and mature wood at stump height. This supports the hypothesis presented regarding a synchronized relationship between annual height increment and wood properties in the homogeneous monocultures of Norway spruce.

Under the same growth conditions (site index), the height increment of a homogenous monoculture of a light demanding species, for example, Scotch pine (*Pinus silvestris*), will culminate at an earlier point of time than the height increment of a corresponding monoculture of a semi-shade demanding species as, for example, Norway spruce (*Picea abies*), and considerably earlier than shade-demanding species as, for example, Silver fir (*Abies alba*) (Assmann 1961). This is substantiated by tests made in the USA with the pine species: *Pinus caribaea* (Zobel and Talbert 1984); *Pinus elliottii* (Zobel et al. 1959, 1972; Zobel and Talbert 1984); *Pinus radiata* (Nicholls and Dadswell 1965); and *Pinus taeda* (Zobel et al. 1959; Greene 1966; Zobel 1976; Zobel and Talbert 1984; Bendtsen and Senft 1986).

In these tests the boundary of juvenile wood formation in the cross section of the trunk was registered at a relatively early time, i.e., at the age of 5–13 years. This is theoretically in agreement with earlier statements regarding light-demanding tree species and tallies well with the synchronous growth hypothesis.

With *Pinus ponderosa* (Zobel and Talbert 1984), the boundary line for juvenile wood formation in the cross section of the trunk was registered later, i.e., at the age of 20 years. It is well known that *Pinus ponderosa* has slow growth in the first years and therefore the annual current height increment of this species culminates later (Pokorný 1963).

With other species of wood such as *Pseudotsuga menziesii* (Senft et al. 1986) and *Tsuga heterophylla* (Panshin and deZeeuw 1980), the boundary line for the formation of juvenile wood was registered later, 15–16 years for *Pseudotsuga menziesii* (semi-shade demanding tree), and 20 years for *Tsuga heterophylla* (shade-demanding tree). It would be very interesting to know whether this theory is in agreement with the American investigations carried out on material from semi-shade and shade-demanding tree species.

One can mention a European test which was carried out on Norway spruce by Boutelje (1968). Boutelje also takes the transition zone into consideration—the wood which is produced some years after the actual transition. In his tests, the boundary for juvenile wood was determined at an age of 20–30 years.

These results are not directly comparable because they are calculated on another basis, but one cannot disregard the fact that these results can also be relevant for our investigations, after reduction of the transition period.

None of these publications have direct information about annual height increment for the material examined. Therefore one cannot draw any definite conclusions regarding the correlation between height increment and the transition phase in juvenile wood/mature wood in these instances. On the other hand, taking into account what is already known about the height increment for the various species, broadly speaking one could say that the relation between the species with regard to age at the transition phase, juvenile wood/mature wood indicates a connection as presented in the results of this work. If the synchronous growth theory as presented here can be verified with several similar tests, it will be possible to use the height increment as an indicator of the juvenile wood part of the trunk and thereby enable a more rapid quality assessment in each individual case.

One can conclude by saying that with a monoculture of Norway spruce (and other conifers) of the same age and species, the formation of juvenile wood is in direct relationship to the annual height increment of the tree. When the current annual height increment culminates, the formation of the juvenile wood in the root-neck of the tree (stump height level) is defined by the synchronous growth hypothesis. From this time the tree produces mature wood at the bottom of the trunk and juvenile wood higher up the trunk in the same growth ring. Juvenile wood will, in the course of time, press steadily farther up the trunk in favor of the mature wood.

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