Wood and pulp characteristics of juvenile Norway spruce: A comparison between a forest and an agricultural stand

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ABSTRACT: The authors compare two 30-year-old Norway spruce stands for basic density fiber characteristics and properties of kraft and thermomechanical pulp. One stand was on agricultural land and the other on forest land. The agricultural stand had a higher wood volume production per hectare but lower potential for pulp production. Stems from the agricultural stand had the shortest and the widest fibers, the thinnest fiber cell walls, and the lowest basic density at a given annual ring width.

KEYWORDS: Agriculture, bibliographies, fiber structure, forests, juvenile wood, kraft pulps, picea abeis, properties, refiner mechanical pulps, sites, Sweden, thermomechanical pulps, tree dimensions.

Because of the recent grain surplus in northern Europe, the rate of establishing forest plantations on agricultural land has increased during the last few decades. Most planting has been with Norway spruce (*Picea abies* (L.) Karst.). During an 80-year rotation, the total yield is 50–100 m^3/hectare (ha). There is a higher yield from Norway spruce on agricultural land than on forest land with an equivalent site index *(1)*.

Wood characteristics such as basic density correlate with annual ring width *(2, 3)*. Small-dimension stems with narrow rings should have a higher basic density and different fiber characteristics compared to similarly aged large-dimension stems. Due to its high growth rate, the basic density of Norway spruce grown on agricultural land should be low. This leads to differences in wood and pulp characteristics.

Persson *et al. (4)* reported that discs from agricultural land at 4-m height had a basic density of 335 kg/m^3. By comparison, the basic density of Norway spruce pulpwood in Sweden averages 390–420 kg/m^3 depending on the particular region *(5)*. Wide rings and a high content of juvenile wood in Norway spruce grown on agricultural land are two factors supposed to affect adversely the quality of wood and pulp from such stands.

At a given ring width, intermediate stems have a higher basic density than suppressed and dominant stems *(6)*. In another study, tall stems had higher basic densities than expected based on their ring widths *(7)*. The thinning regime may therefore influence the wood and pulp properties of the stand.

The characteristics of unbleached kraft pulps from 30-year-old Norway spruce wood samples from different silvicultural regimes at a basic density ranging from 350–390 kg/m^3 were similar *(8)*. Pulp from very fast grown wood with a very low basic density (323 kg/m^3) differed in strength and other properties.

Juvenile wood forms close to the pith and exhibits the characteristic of gradual changes in fiber dimensions and other wood properties *(9, 10)*. It also contains more early wood than mature wood does *(11)*. Early wood is wood with fibers where the double cell wall thickness is thinner

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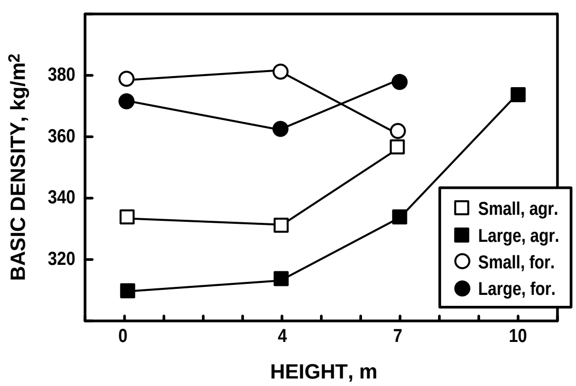
I. Characteristics of the forest and agricultural stands before thinning

	Forest stand	*Agricultural stand*
Site quality class, m	27	29
Total age, years	28	29
Initial spacing, m	2.3	2.1
Stems/ha	2077	1917
Diameter at breast height, basal area weighted, cm	11.7	12.4
Height, m	9.0	10.0
Height to first living branch, m	0.7	1.8
Ring width at breast height, mm	3.3	4.0
Basal area, m^2/ha	24.4	24.8
Volume, m^3/ha	99.1	116.6

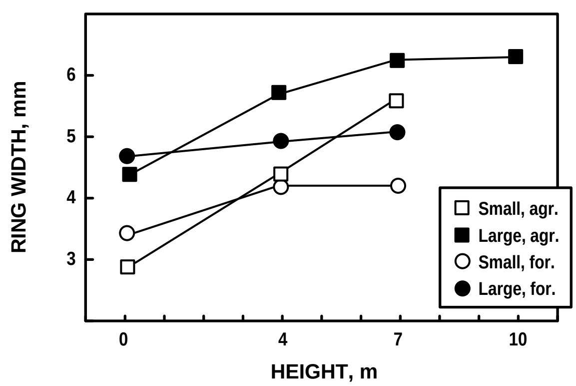
II. Basic density of discs from the pulpwood samples

	Basic density, kg/m³
Forest, small	383
Forest, large	353
Agricultural, small	315
Agricultural, large	299
Reference	415

1. Vertical variation of mean basic density in morphology sample discs at stem heights of 0, 4, 7, and 10 m



2. Vertical variation of mean ring width in morphology sample discs at stem heights of 0, 4, 7 and 10 m



than the lumen *(12)*. The fibers of early wood are shorter and wider, and they have a thinner cell wall compared with late-wood fibers. Differences in the content of juvenile wood can explain more of the variation in wood characteristics than dissimilarities in growth can explain *(9)*.

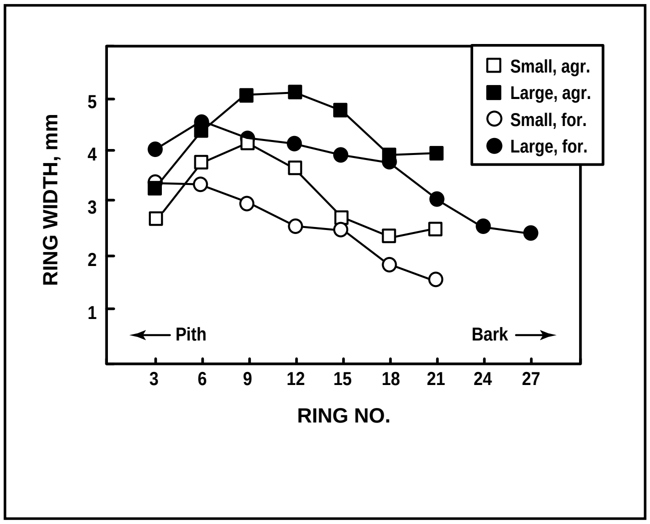
The intent of this project was to compare a forest and an agricultural Norway spruce stand with stems of small and large dimensions for wood characteristics. These included basic density and fiber morphology. The comparison also included kraft and thermomechanical pulp (TMP) characteristics.

Experimental

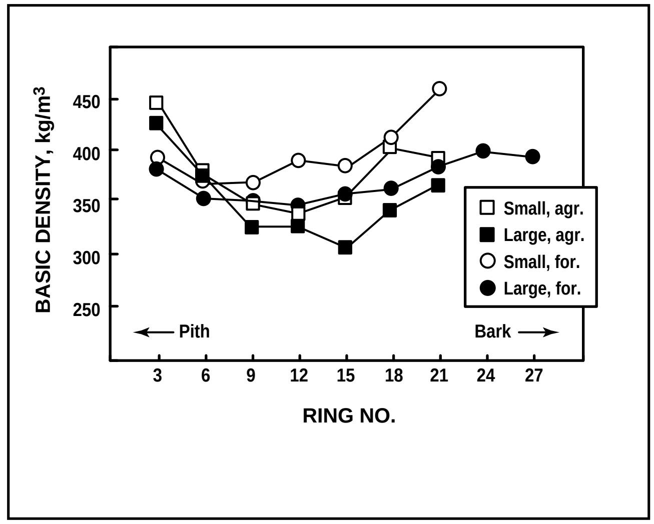
Materials

The examination involved two Norway spruce stands in central Sweden. One stand comprised spruces planted on agricultural land belonging to Siljanfors Experimental Forest, section 356, in Mora. The specific location is 60° 53' N and 14° 20' E at an altitude of 248 m. The designation of this stand is "the agricultural stand." The other stand was on very fertile forest land situated at Källslätten, section 66–55, in Falun. Its location is 60° 38' N and 15° 28' E at an altitude of 235 m. Here the designation is "the forest stand." The selection of these stands considered their similarity in age, spacing, plant material, diameter, etc. The difference in geographic location was necessary to obtain stands with comparable age and site characteristics. **Table I** describes the characteristics of the two stands before

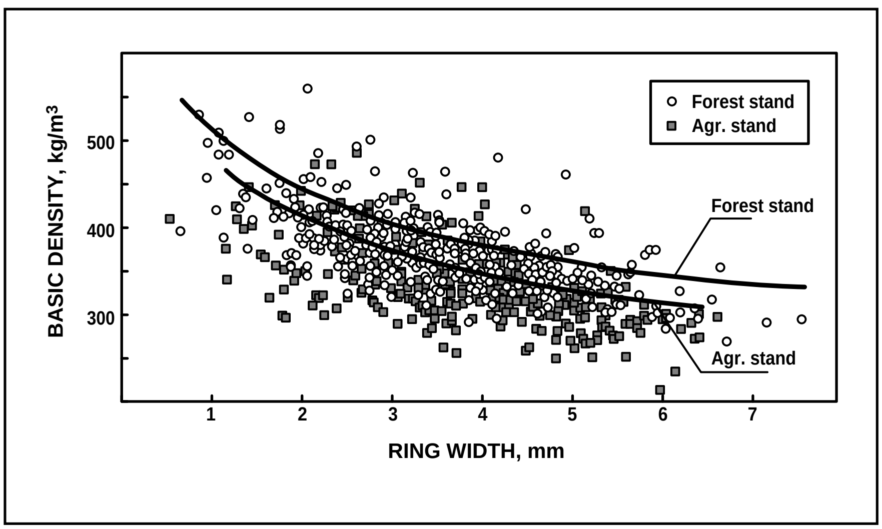
3. Radial variation in the ring width for morphology sample cores at breast height



4. Radial variation in basic density for morphology sample cores at breast height



5. Relation between basic density and ring width in morphology sample cores from breast height for the whole cores with the basic density level curves for the forest and agricultural stands



thinning. In this table, the site quality class is the dominant height at 100 years of age *(13)* and the volume calculation derives from the volume functions for individual trees *(14)*.

Considering their field and ground layer vegetation, both sites classify as moss-rich with low herbs. The soil type is an iron podzol of sandy till on the forest site and a cultivated podzol of sandy-loamy till on the agricultural site. The plantings on both sites used seedlings of local provenances.

A random sample in each stand included a total of 400 stems. Since the main analysis was for pulp properties, further reference will be to pulpwood samples. Stems in the stands fell into two classes—small and large dimensions. Each dimension class stand had 200 sample stems. The small-dimensioned stems had a diameter at breast height of less than 12.5 cm in the forest stand and less than 14.5 cm in the agricultural stand.

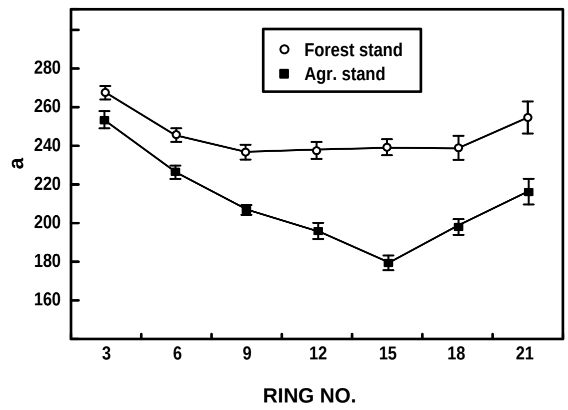
There was a random choice from the pulpwood stems of 65 sample stems from each stand for further analyses of field properties, basic density, and fiber morphology. Because the main use of these stems was for morphology measurements, their reference is as morphology samples. A large reference collection of Norway spruce obtained in other studies (unpublished) was the basis for comparison of kraft and TMP properties.

Methods

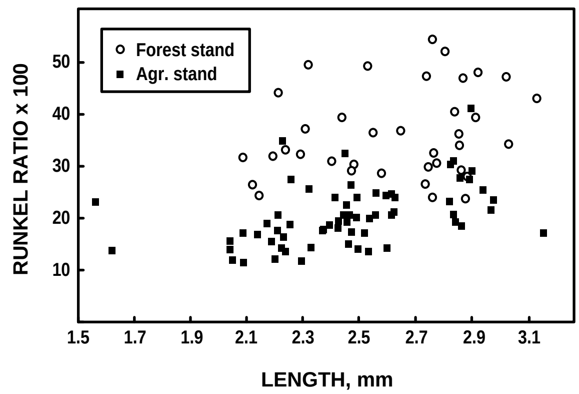
Field examination and wood handling. After felling the pulpwood sample trees, two knot-free discs of 3-cm thickness and one of 20-cm thickness were cut from the pulpwood sample trees for determining basic density and pulp properties. After debarking of the discs, one underwent testing for basic density and the other was for kraft pulping and chemical analyses. Laboratory chips of approximately 3-mm thickness were cut by hand. Combination of the chip samples formed one sample per stand and diameter class. The quartering-cone technique divided these into aliquots. The 20-cm disc was for thermomechanical pulping. For practical reasons, there were no pulp assessments on the material from the forest stand.

The assay of the morphology sample stems used the following technique. At 1.3-m height, two horizon-

6. Basic density level (a) in the morphology sample cores at breast height calculated at different ring numbers from the pith showing standard deviations



7. Relation between the Runkel ratio of Eq. 2 and fiber length for the fibers of the 10th ring from the pith at 4-m height from the morphology samples



tal increment cores were taken from the cambium to the pith from the south- and west-facing sides of the trees. After felling, the heights from the stump to the stem top and to the first living branch were measured. The stems were cross-cut at 0 (stump height), 4, 7, and 10-m height. At each cross-cut, a knot-free disc with thickness of 5–10 cm was cut out for determination of basic density. Using the discs taken at 4-m height, a vertical core from the 10th ring from the pith was cut out for fiber morphology assessments. The discs were debarked.

III. Arithmetic mean length, width, and cell wall thickness of early-wood fibers from the 10th ring from the pith at 4-m height in the morphology samples

	Length, mm	*Width, µm*	*Thickness, µm*
Forest, small	2.70	36.3	5.0
Forest, large	2.59	39.1	4.9
Agricultural, small	2.52	45.6	3.8
Agricultural, large	2.51	46.1	3.7

Basic density. The discs of the morphology sample stems were cross-calipered, and the number of annual rings was counted. The discs were for determining the basic density by water immersion (TAPPI T 258 om-94). Basic density measurements on the pulpwood discs also used water immersion (SCAN CM 43:89). The horizontal increment cores (morphology sample) were cut into sections. Each section contained three annual rings. A micrometer measured the length of each core section. Water displacement subsequently determined the basic density of the sections *(15)*.

Fiber morphology. Thin slices of the early wood from the vertical cores (morphology samples) were placed in test tubes and treated with equal volumes of concentrated acetic acid and 30% hydrogen peroxide for 24 h at 60°C. The samples were washed with distilled water and shaken to separate the fibers. The fibers were stained with fuchsine and preserved by addition of formaldehyde. The fiber length was measured on 25 undamaged fibers in each core. The radial fiber width and the lumen and cell wall thicknesses were measured on 10 fibers in each core.

Fiber length and width were also determined on specially prepared kraft pulp (pulpwood sample). An aliquot of hand-cut chips from each of the different stands and dimension classes was further subdivided into pin-formed chips. These underwent pulping in a mini-digester (130 cm^3). Pulping was performed at a liquor to wood ratio of 5:1 for 2 h. The white liquor charged had an effective alkali of 133 g/L and a sulfidity of 34%. A method based on TAPPI T 234 cm-84 using Congo red for staining determined the fiber coarseness on these kraft pulps. Fiber dimensions in vertical cores and in pulp were measured with MOP Videoplan equipment (Carl Zeiss GmbH).

Chemical composition of wood. An aliquot of chips from each stand and

IV. Chemical analyses of woods in percentages

	Ethanol extractives	*Cellulose*	*Lignin*	*Glucomannan acetate*	*Glucorono-xylan*	*Galactan*	*Arabinan*
Forest, small	1.4	40.8	27.5	17.6	9.3	2.1	1.3
Forest, large	1.5	40.3	27.6	18.1	9.0	2.2	1.3
Agricultural, small	1.1	40.3	28.6	17.1	9.7	1.8	1.4
Agricultural, large	1.3	40.3	28.9	16.3	9.6	2.2	1.4
Reference	1.7	41.3	27.2	17.8	8.9	1.8	1.3

dimension class was ground in a Retsch-mill for the subsequent determination of ethanol extractives, carbohydrate composition, and lignin content using standard procedures.

Kraft pulping and bleaching. The pulpwood samples from the agricultural stand and the references underwent kraft pulping in a M/K Systems Mini-mill digester with forced liquor circulation. The liquor to wood ratio was 4:1. Cooking time was 2 h at 170°C. Operating temperature was reached after 2.5 h. The effective alkali charge varied to reach kappa no. 32. The sulfidity was 38%. The chips were washed at elevated temperature overnight. The washed chips were disintegrated and screened on a Wennberg screen with a 0.3-mm slot width. Oxygen delignification was carried out at high consistency (HC) in autoclaves at conditions according to a routine procedure. Bleaching was performed in the laboratory sequence (D50 + C50)(E + P) D E D according to standard procedures. The reason for this sequence on the pulpwood sample was to permit comparison with the earlier treated reference.

Thermomechanical pulping. The Norwegian Pulp and Paper Institute performed the thermomechanical pulping. The pulpwood samples for the TMP-trials were chipped in a Nicholson Drum Chipper. The chips were screened on a vibration screen equipped with an upper screen deck with 32-mm square openings and a fines deck with 6-mm square openings.

The refining was carried out in an atmospheric 36-in. Sunds Defibrator double-disc refiner. The chips underwent presteaming for 10 min and soaking in cold water for 2 min. Preheating was at 120°C for 3 min before a two-stage refining process over the CSF range of 80–300 mL.

Pulp testing. The bleached kraft pulps were beaten in a PFI refiner and tested according to relevant SCAN methods. The TMP was also tested according to appropriate SCAN standards.

Calculations. Mean values for all measured traits for each stand were weighted by diameter class. Calculation of tree volumes used volume functions for individual stems *(14)*. The relation between density and annual ring width was calculated using the equation developed by Olesen *(3, 16)*:

$$R = a + [700/(RW + 2)] \qquad (1)$$

where

R = basic density

RW = ring width

a = a positive constant.

Equation 2 *(17)* provides calculation of the Runkel ratio:

$$\text{Runkel ratio} = 2T/D \qquad (2)$$

where

T = cell wall thickness

D = lumen diameter.

A t-test evaluated differences between the two stands and the two dimension classes within the stands. The square roots of all values were calculated and arc sine transformed to meet the requirements of the test. An F-test disclosed differences between the constants obtained in the regression analysis. Differences were regarded significant when $p \leq 0.05$. Statistical analysis used the SAS statistical program package for personal computers *(18)*.

Results and discussion

Basic density

Figure 1 shows that the mean basic density of the morphology sample of the four different tree classes in this study ranged from 314 to 382 kg/m^3 measured on discs from 4-m height. Large-dimensioned stems from the agricultural stand had the lowest basic density. Small-dimensioned stems from the forest stand had the highest basic density. There were significant differences in basic density between the two stands at both 0- and 4-m height and between small- and large-dimensioned stems. An exception was at 0-m height in the forest stand. **Figure 2** shows the difference in ring width between the two stands. It was significant only at 4-m height.

Table II shows the basic density for the pulpwood samples. The values of the reference pulpwood was similar to a sample of pulpwood logs from the same province, i.e. 414 kg/m^3, at 0.86-mm ring width *(19)*. In contrast, the basic density of a sample of pulpwood logs from central Norway was 350 kg/m^3 at a ring width of 4.4 mm *(20)*. This is in the same range as the values reported in this study.

The difference in geographic location between the two stands was probably not large enough to affect the basic density. According to Ericson *(21)*, the anticipated difference in basic density between the two stands owing to different latitude would be 2.5 kg/m^3 at a ring width of 4 mm. Differences in the microclimate between the stands might also influence the basic density. Genotype has a substantial influence on basic density *(22)*. Since both stands originate from local provenances, however, the difference in basic density due to genetic variation in the material is probably not an explanation.

There was no significant difference in basic density between sample stems at initial spacings of 2.1 and 2.5 m in a 30-year-old spacing trial in southern Sweden. The stems had a basic density of 360–375 kg/m^3 and 4–5-mm ring width at 4-m height *(6)*. Molteson *et al. (23)* found no significant difference in basic density between these two spacings in another trial. It therefore seems that the differences in initial spacing between the forest and agricultural

V. Delignification and bleaching results

	Kraft pulping to kappa no. 32		*Oxygen delignification*			*Prebleaching and final bleaching chemicals consumption*[1]						
	Alkali demand[2]	*Total yield, %*	*NaOH consumption*[3]	*Kappa no. after O stage*	*Pulp yield O stage, %*	*D50+C50*	*E+P*	*D1*	*D2*	*Kappa no. after E+P stage*	*Brightness, ISO, %*	*Pulp yield, bleaching, %*
Agricultural, small	156	48.7	17.7	21.0	97.5	37.4	1.8	9.5	3.4	-	88.2	-
Agricultural, large	161	47.7	14.7	17.0	95.8	29.9	1.8	10.5	2.9	2.3	88.8	97.3
Reference	153	49.9	17.6	18.0	97.0	27.4	1.8	12.6	3.5	2.6	88.7	96.2

[1]kg/moisture free metric ton of pulp
[2]kg effective alkali/ton of wood pulp
[3]kg/ton pulp

VI. Fiber length, width, and coarseness of kraft pulp from the pulpwood samples of whole discs

	Fiber length, mm		*Fiber width, µm*		
	Arithm. mean	*Length weighted mean*	*Arithm. mean*	*Width weighted mean*	*Coarseness, µm/m*
Forest, small	1.72	2.12	39.4	42.7	172
Forest, large	1.86	2.31	44.1	47.3	175
Agricultural, small	1.72	2.07	43.1	46.0	180
Agricultural, large	1.61	2.01	48.2	51.7	162
Reference	2.06	2.61	38.9	42.3	195

stands in the present study may account for only a small part of the difference in basic density.

These findings indicated that the differences between the stands in basic density were due to different site conditions or their dissimilar management histories or both. It is, however, not possible to distinguish between these two factors in this study.

Vertical variation. Figure 1 shows basic density of samples at different heights. Differences in basic density between samples from 0- and 4-m height only occurred in the large-dimensioned stems in the forest stand. At 4-m height, all discs had fewer than 15 rings. Presumably these contain juvenile wood of low density. Only the tallest stems reached 7- and 10-m height. At heights above 4 m, the basic density tended to increase with height. At 7 m, all discs contained fewer than 10 rings. These form the inner part of juvenile wood having a relatively high basic density.

Contradictory results exist regarding the development of basic density with height *(21, 24, 25)*. According to Elliot *(2)*, the vertical variation in basic density in a given ring from the pith is low in the juvenile wood. In mature wood, however, the basic density decreases with height. When examining whole discs, the number of rings varies depending on the vertical position in the stem. The relative amount of juvenile wood therefore varies in the disc. This will affect the basic density.

Radial variation. The radial variation in ring width at breast height shown in **Fig. 3** was larger in the agricultural stand. The maximum occurred at a higher ring number from the pith compared with the forest stand. The basic density data of **Fig. 4** reveals the highest value near the pith. It decreased outward with a minimum coinciding with the maximum ring width. Other studies show similar patterns *(22, 26)*. The ring number at which the basic density reached its minimum was therefore higher for the agricultural stand than for the forest stand. The difference in basic density between stands was significant for almost all ring numbers, although the difference in ring width was not.

Basic density level. Several investigators have reported a negative relationship between basic density and ring width *(2, 3)*. **Figure 5** shows the basic density level according to Eq. 1. For the data in this figure, the value of constant *a* was 239.2 ± 1.7 for the forest stand and 210.5 ± 1.9 for the agricultural stand. The basic density level significantly differed by 15-40 kg/m^3 between two stands. This means that variables other than ring width explain the difference in basic density between the two stands. At a given growth rate, the site quality class also influences the basic density *(16, 27)*.

Figure 6 show the constant a and it's dependence on ring number with the standard deviations for a. The basic density level reached a minimum between the 10th and 15th ring from the pith and then increased toward the bark. The minimum occurred at lower ring numbers and at a lower absolute level in the agricultural stand than in the forest stand. The increment in basic density level had not leveled off at the bark indicating that the stems had not yet started to produce mature wood. According to Olesen *(26)*, Norway spruce starts to produce mature wood between the 15th and 20th annual rings.

In this study, there was no significant difference in basic density level between the small and large dimension classes. The variation in basic density due to differences in initial spacing occurs mainly in variations in ring width *(6)*. It is therefore possible to assume that the variations in the ring width better reflect the within-stand variation in basic density than the between-stand variation.

Fiber morphology

The arithmetic average of fiber length from the morphology sample ranged from 2.5 to 2.7 mm. **Table III** shows a mean fiber width variation from 36 to 46 µm. Note particularly that these measurements refer to early-wood fibers only. There was

VII. Production and consumption values for the forest and agricultural stands

	Wood volume production[1]	*Dry matter production[2]*	*Specific wood consumption[3]*	*Pulp production[4]*
Forest stand	99.1	37.3	5.6[5]	17.7
Agricultural stand	116.6	38.3	6.9	16.9

[1]m^3/ha
[2]Moisture free metric ton of wood/ha
[3]m^3/a.d. metric ton of bleached kraft pulp
[4]a.d. metric ton of bleached kraft pulp/ha
[5]Based on an estimated pulp yield

a significant difference between the two stands for all measured fiber dimensions. Stems from the agricultural stand had shorter and wider fibers with thinner cell walls compared with stems from the forest stand. The only significant difference in fiber dimensions within the stands was the lumen width in the forest stand. The small-dimensioned stems had narrower lumen than large-dimensioned stems. Results from other studies support this finding. For instance, Stairs *et al.* *(28)* reported the fiber width at breast height of early wood of Norway spruce to be 38.0 µm for slow-grown trees and 42.3 µm for fast-grown trees. Corresponding values for the fiber length were 3.2 mm and 3.5 mm, respectively. Fibers from predominant trees are approximately 3% longer than those of dominant trees at a given ring width *(29)*.

According to Nylinder and Hägglund *(25)*, the fiber length at 4-m height in Norway spruce with an identical ring width and age as the two stands in the present investigation from the same altitude and latitude would be about 2.5–2.8 mm. The fiber width in such trees would be in the range of 37–39 µm *(25)*. The fiber length and width from the forest stand were therefore near the expected values. Fibers from the agricultural stand were wider than expected, however, but had a fiber length comparable to that earlier reported *(30)*. Another author reported much lower fiber widths of 23–30 µm from the 10th ring from the pith at 1.3–1.8-m height *(26)*.

Wide rings contain a large amount of early wood *(11)*. The early-wood content of a cross section of a stem from the agricultural stand from the same height and with the same number of rings as an identical sample from the forest stand would therefore be higher for the former. The differences in fiber dimensions between the forest and agricultural stands were larger than between the classes of small and large dimension within each stand.

Using the fiber cross dimensions, it is possible to divide the forest and agricultural stands into the two distinct classes of **Fig. 7**. At the same fiber length, the Runkel ratio from Eq. 2 for the forest stand was larger i.e. the relative amount of fiber wall per unit of cross-sectional fiber area is larger than that for the agricultural stand.

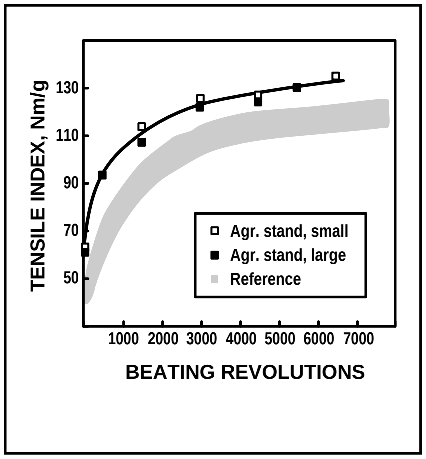
This study indicates that site or management history or both affect fiber properties more than growth rate does.

Chemical composition of wood

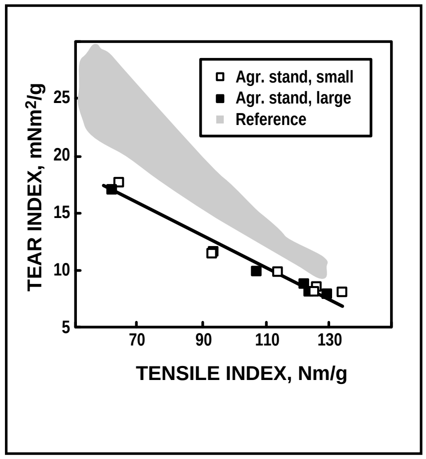
Table IV provides the results of the chemical analyses. Neither the cellulose nor the hemicellulose content of the pulpwood samples differed in dimension classes or stands. The glucomannan content of wood from the agricultural stand was lower, however, than from the forest stand. It was approximately the same as that of the pulpwood reference. Other results *(31)* support this finding. In that work, the mannose content increased with the ring number at a given height in the stem especially for rapidly grown Norway spruces. Wood of Norway spruce has a higher content of galactan in the late wood, and it has a higher content of xylan in the early wood *(32)*. Recent work showed that at a given sample height the xylose content of juvenile Norway spruce wood decreased with increasing ring number from the pith *(31)*. The glucose content increased and the galactose content remained almost the same. The glucose content varied depending on the growth rate. Slow-grown trees had a higher glucose content than faster-grown trees at a given sample position. This difference corresponds to approximately 2% higher cellulose content in slow-grown trees.

The lignin content of the wood samples from the agricultural stand was approximately 1.1–1.3% higher than from the forest stand. It did not differ from the pulpwood reference. The differences between the stands were larger, and the differences between the dimension classes

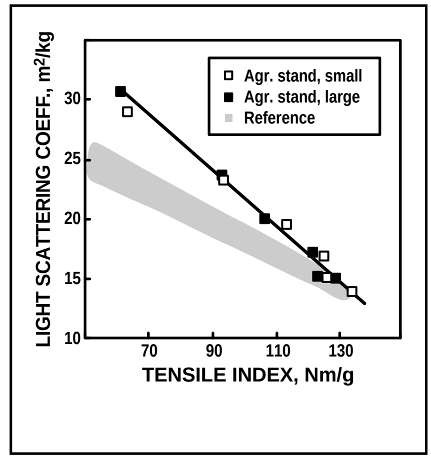
8. Tensile index development during beating of bleached kraft pulp



9. Tear index vs. tensile index for bleached kraft pulp



10. Light scattering coefficient vs. tensile index for bleached kraft pulp



were smaller than expected *(25)*. The lignin content in coniferous early wood is higher than that in late wood *(33, 34)*. A recent investigation reported that lignin content decreases with increasing ring number *(31)*. In addition, the lignin content of juvenile Norway spruce for a given position in the stem was approximately 2% higher for fast-grown trees than for slow-grown ones.

The extractives content was higher in larger- than in smaller-dimensioned stems. It was also higher in the wood from the forest stand than from the agricultural stand. Nylinder and Hägglund *(25)* found that the extractives content increases with latitude and relative height position in the stem but decreases with increasing altitude and late-wood content. It correlated positively with growth rate.

Kraft pulp

Table V shows that the kraft pulp yield at kappa no. 32 was approximately 1.7% lower for wood from the agricultural stand than for the reference. This was mainly due to the former having a higher lignin content and a lower cellulose content. This translates to a higher alkali demand during cooking. The large-dimensioned stems from the agricultural stand had 1% lower pulp yield than the small-dimensioned ones. This was due to the higher lignin, extractives, and galactan contents of these stems and their high alkali demand. The wood from the forest stand was not pulped. Using data on the chemical composition of the wood from this stand and previous measurements on samples from similar stands, the total pulp yield would probably be 49.0–49.3% at kappa no. 32. The kraft pulp yield from fast-grown juvenile Norway spruce from southern Sweden at a constant kappa number was approximately 1.5–2% lower than that from slow-grown wood *(31)*. Differences in yield between juvenile wood and normal pulpwood of other conifers are of the same order of magnitude or even larger *(35–37)*.

Table V also indicates that there were no differences between pulp from the agricultural stand and that from the reference in bleachability.

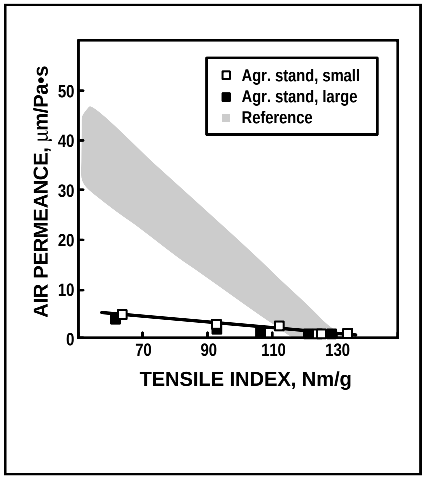
Properties of bleached kraft pulp. Comparing kraft pulps of juvenile wood of conifers to those of mature wood, the literature characterizes them by their low beating demand, high sheet density, high relative bonded area (with related properties such as tensile index, burst index, etc.), low surface roughness, good light scattering ability at moderate levels of beating, and low tear index *(35, 38, 39)*.

Figure 8 shows that the tensile index of the unbeaten pulp from the agricultural stand was approximately 10–15 Nm/g higher than that of the reference pulp. This is a result of the higher fiber flexibility and larger number of fibers per gram of pulp. This leads to a higher sheet density and increased opportunities for creating inter-fiber bonds. No differences between the two dimension classes in this stand were discernible. At a constant tensile strength of 80 Nm/g, the beating demand was considerably lower for the pulp from the agricultural stand compared to the reference pulp. The sheet density was approximately 5–10% higher for the pulp from the agricultural stand at constant tensile index over a range from 70 to 100 Nm/g compared with that of the reference.

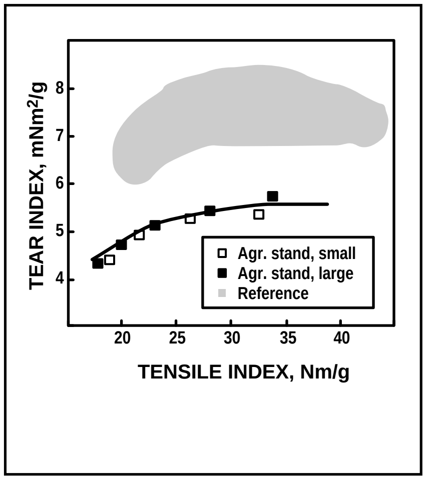
Figure 9 shows the low tear index for the pulp from the agricultural stand. This was mainly due to the short fiber length indicated in **Table VI**. At a constant tensile strength of 80 Nm/g, the tear strength was 15–35% lower compared with that of the reference pulp.

At moderate levels of beating, the light-scattering coefficient of the pulp from the agricultural stand was higher than that of the reference pulp as **Fig. 10** indicates. Pulp from the agricultural stand contains approximately 50% more fibers per gram of pulp. This provides more light-scattering surfaces than the fewer fibers in the reference pulp.

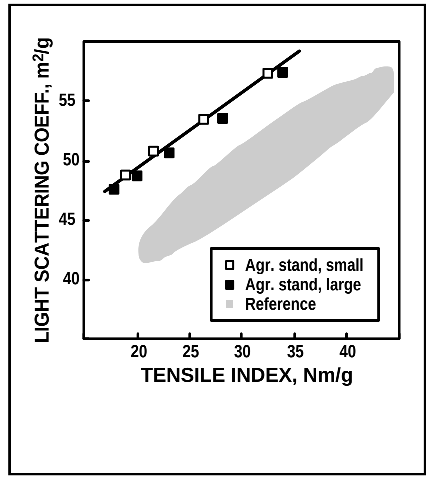
11. Air permeance vs. tensile index for bleached kraft pulp



12. Tear index vs. tensile index of TMP



13. Light-scattering coefficient vs. tensile index of TMP



The low Runkel ratio from Fig. 7 for the fibers from the agricultural stand in combination with a low late-wood content indicates, however, that the fibers easily collapse. This is also experienced as very rapid densification of the sheet during beating. It causes the light-scattering coefficient of the pulp from the agricultural stand to decrease more rapidly in response to a given increase in tensile index compared to the reference pulp. At a tensile index of 80 Nm/g, the bleached kraft pulp from the agricultural stand had a 15–35% higher light-scattering coefficient than the reference pulp.

The larger number of fibers per gram of pulp from the agricultural stand compared with the reference suggests there is a larger specific fiber surface. This would cause a larger dewatering resistance.

Figure 11 provides the porosity of the sheet as Gurley air permeance. The data clearly demonstrates the difference between pulps from juvenile wood and pulps containing a high amount of mature wood. The pulp from the agricultural stand has a very low air permeance even before beating. This further corroborates that these fibers are extremely flexible and collapsed in the dry sheet. The pulp from the reference has a considerably higher porosity at intermediate levels of beating. A low surface roughness also reflects the high fiber flexibility of the juvenile-wood fibers from the agricultural stand.

Implications for kraft pulping. Table II showed that the basic density of the pulpwood sample varied considerably. These large differences inevitably cause the specific wood consumption to vary drastically between the different types of wood. Using reference pulpwood, the specific wood consumption was approximately 4.9 whereas it was 5.6 m^3/a.d. metric ton bleached kraft pulp for the forest stand and 6.9 m^3/a.d. metric ton bleached kraft pulp for the agricultural stand. The wood basic density is an important factor affecting the raw material costs when purchasing pulpwood by volume, product quality, and processability.

In a kraft pulp mill, the chip volume fed to the digester usually determines the actual alkali charge assuming the bulk density is constant. Variations in bulk density may therefore lead to excessive or insufficient charging of alkali. This can consequently influence the quality of the final product and enhance quality variation imposed by the density variation itself. In addition, large variations in wood basic density can disturb the chip flow in a continuous digester.

Table VII shows a higher volumetric wood production per ha for the agricultural stand but a lower density compared with the forest stand. These two factors canceled each other almost completely leaving a difference in dry matter production per ha between the stands of only 1 metric ton of dry solids/ha. At this age, the productivity of the two stands for potential production of kraft pulp is higher for the forest stand than for the agricultural one, however. It is unknown how this relationship changes during the rotation period.

Thermomechanical pulp

In this investigation, we did not find any significant difference between wood from the agricultural stand and the reference wood in energy required to reach a certain freeness level. Considering the energy required to reach a certain tensile index such as 30 Nm/g, we found that the reference required approximately 15% less energy.

Previous work stated that wood of high basic density requires more energy to produce TMP at a given freeness level compared to lower density wood. The use of Norway spruce grown on agricultural land consequently would lead to considerable energy savings *(40)*. There are, however, contradictory opinions regarding the relationship between wood basic density and specific energy consumption in mechanical pulping *(41)*. Hatton and Johal *(42)* reported approximately 8% increase in energy demand at 100-mL CSF for refiner mechanical pulping of juvenile compared to mature wood of second-growth Douglas fir and Jack pine. Corson *(43)* stated that corewood (juvenile wood) of Radiata pine (*Pinus radiata*) required at least as much energy as the slabwood (mature wood) did to develop freeness. Recent data for Norway spruce *(44)* support this statement. The energy savings were approximately 500 kWh/a.d. metric ton pulp at 100-mL CSF for wood from final fellings on agricultural land compared to wood from forest land. At constant tensile index, however, the wood from the agricultural land had a similar or even higher energy requirement than the wood from the forest land. There was also a similar difference in energy consumption at a constant tensile index for juvenile and mature wood of Radiata pine *(45)*. It is evident from these statements and our findings that, if the specific energy consumption depends on the basic density, it also depends on the wood age.

Kärenlampi *(46)* stated that a greater energy demand of juvenile wood can be expected since the relation between intertracheid bonding area and coarseness is larger than for mature wood. Freeness is inversely related to the specific surface of the whole pulp *(47, 48)*. Juvenile wood initially has more fibers or specific surface per gram of wood or pulp. These statements imply that juvenile wood fibers also develop sheet properties differently. It can therefore be confusing to compare properties of pulps from fibers with extremely different characteristics such as juvenile wood and mature wood at a constant CSF only. Pulp quality prediction and refiner operation often use freeness measurements assuming a given relationship between CSF and a set of sheet properties. The implication is that variations in the juvenile wood content of the wood furnished to a TMP line operating at constant CSF would increase the variation in pulp quality and the production level.

Figure 12 shows that the tear index of the TMP from the agricultural stand was considerably lower than that of pulp prepared from the reference. This is due to the approximately 20% shorter fiber length of the pulp from the agricultural stand compared with that from the reference. At a tensile index of 30 Nm/g, the tear strength of pulp from the agricultural stand was 20–35% lower than the reference. This relative difference is in the same range as that derived from Sundblad's *(44)* data at a tensile index of 40 Nm/g. It is larger than anticipated, however, using the difference in fiber length at a constant CSF *(49)*. When compared at the same tensile strength, the fiber length differences directly translate into differences in tear index.

As already indicated for bleached kraft pulp, the light-scattering coefficient at a given tensile strength is higher for juvenile wood than for mature wood. As **Fig. 13** indicates, this is also true for TMP. At a tensile index of 30 Nm/g, the light-scattering coefficient was 10–20% higher for the TMP from the agricultural stand than for reference pulps. Corson *(45)* reported corresponding relative differences at constant tensile index between the TMP of juvenile and mature wood of Radiata pine. Figure 13 shows that the rate at which the light scattering increased with tensile index was approximately the same for the agricultural stand and the reference. This implies that the extensive fiber collapse of the kraft pulp fibers from the agricultural stand that led to the faster decrease in light scattering per unit gain in tensile index for this pulp compared with the reference was less for mechanical pulps *(41, 48)*.

Conclusions

The agricultural stand had a higher wood volume production per ha but lower basic density compared with the forest stand. In addition, the specific wood consumption during kraft pulping was higher for the agricultural stand than for the forest stand. Consequently, the forest stand had a higher potential for kraft pulp production per ha. How this potential changes over an entire rotation period is unknown, however.

Fibers in wood produced by the agricultural stand were shorter and wider and had thinner cell walls compared with those produced by the forest stand. This investigation indicates that at a constant growth rate differences in basic density and fiber properties exist between stands. This suggests that the site or past management or both factors affects these properties independently of the ring width.

Wood from the agricultural stand produced a kraft pulp that had entirely different properties compared with kraft pulp from the reference Norway spruce. The tear index, porosity, and surface roughness were lower, but the light scattering ability was higher.

TMP from the agricultural stand compared to the reference had inferior strength properties but a higher light-scattering ability and a higher specific energy consumption to reach a certain tensile index.

Part of these discrepancies in both chemical and mechanical pulp are probably from the differences in wood age. In both types of pulping, the digester size or the refiner capacity often limits the production rate. A drastic decrease in the basic density of the raw material may therefore lead to production deficits.

This study is an example of how wood and pulp properties might vary between and within two stands. The results indicate differences between the stands. Verification by further investigation is necessary, however.

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