# Quality and Yield of Pulpwood in Drained Peatland Forests: Pulpwood Properties of Scots Pine in Stands of First Commercial Thinnings

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The inherent structural dynamics of drained peatland forests may result in a great variation in various wood and fiber properties. We examined variation in fiber and pulp properties i) among stands, ii) among trees within stands, and iii) within trees in young stands dominated by Scots pine (*Pinus sylvestris* L.). The stands, selected to cover a maximal range of the potential variation, were all at a stage of development where the first commercial thinnings would be feasible. Differences in the processability of the thinning removals were small. In similar kraft cooking conditions, a 5-unit variation in the kappa number of unbleached pulp was observed among the stands. Stand origin had no effect on pulp bleaching. The wood formed prior to drainage had a higher density, shorter fibers, was slightly slower delignified by cooking, and its yield was slightly lower than that of post-drainage wood. These properties, except for high density, are typical for juvenile wood in general, and at stand level they did not correlate with the proportion of pre-drainage wood. When the variation in fiber and pulp properties was broken down into its components, most of it was derived from tree-level in all the cases. On average, the fiber and pulp properties did not differ from those observed for first-thinning pulpwood from upland sites. Consequently, peatland-grown pulpwood may be mixed with other pulpwood in industrial processes. It would probably be best suited as the raw material for pulps with high bonding requirements, e.g. in the top ply of multi-ply board grades or in some specialty grades.

**Keywords** fiber, peatland, *Pinus sylvestris*, pulping, pulpwood, silviculture, thinning
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# 1 Introduction

More than 10 million ha of peatlands have been drained for forestry in Northern Europe (Paavilainen and Päivänen 1995). Almost half of the total drained area, about 4.6 million ha, is found in Finland, where peatland forests currently account for about a quarter of the annual increment of the total growing stock (Hökkä et al. 2002). Even in Finland, the total annual drain from cuttings in peatland forests is presently less than 10 million $m^3$. However, according to recent scenarios based on data provided by the 8th national forest inventory, the cuttings may increase up to 15–20 million $m^3$ in the course of the next 20 years (Nuutinen et al. 2000). Much of this increase is expected to come from thinnings carried out in young stands dominated by Scots pine (*Pinus sylvestris* L.).

Pristine peatland forests are characteristically uneven-structured (Groot and Horton 1994, Norokorpi et al. 1997, Macdonald and Yin 1999). This structural feature may persist or become even more evident due to natural in-growth over several decades following drainage (Hökkä and Laine 1988). After drainage, the growth rates of individual trees often increase dramatically (Hökkä et al. 1997). Smaller trees generally show faster and greater responses in both diameter and height increment. Growth rates directly affect wood density (Hakkila 1968) and, consequently, the usability of the wood material. The inherent structural dynamics of forests on drained peatlands may thus result in great variation in wood density, both within and among individual trees as well as stands. Due to large variations in the age and growth rate of trees, variability in wood and fiber properties can also be expected.

The quality properties and suitability for various purposes of use of wood produced in peatland stands are still insufficiently known. Furthermore, we lack knowledge on how these properties may be affected by silvicultural treatments. Pulpwood from first commercial thinnings is generally considered less attractive than pulpwood from more mature stands because of the high wood cost and low quality (e.g. Hakkila 1998). If first thinnings on peatland sites are neglected because the pulping properties of the wood material are insufficiently known, i.e. assumed to be potentially unacceptably poor, the future development of the stands, and the return on drainage investments, are at risk.

The objectives of this study were: 1) to quantify the variation in fiber and pulp properties and 2) to identify the foremost ecological factors affecting the variation in these properties in pine-dominated stands on drained peatland. The study was confined to sites that were at a stage where the first commercial thinning would be feasible according to the current management guidelines.

# 2 Material and Methods

## 2.1 Study Sites

The study sites (Fig. 1, Table 1) were selected from a set of stands initially meant to be treated by commercial thinnings by the forest owners (i.e. Finnish Forest Research Institute [Metla], Finnish Forest Service, Stora Enso, and non-industrial private owners) and where Metla had earlier set up thinning experiments. Thus, the management histories (time and manner of stand establishment, timing of first and complementary ditchings, precommercial thinnings, fertilizations, etc.) of the selected sites were well documented. All stands were at a stage where first commercial thinning would be feasible according to the current management guidelines.

When selecting the sites, we aimed at capturing a maximal range of the potential variability in pulpwood properties. Stand properties that we assumed would cause variability were site productivity, climate and the time elapsed since the first ditching. All of these properties varied relatively widely in our material (Table 1). Further, one southern and one northern stand comprised merely of trees that had emerged after the first ditching while the others had a varying proportion of trees containing stemwood formed before drainage.

The selected sites represented all peatland forest site types (sensu Laine 1989) generally managed for pine: *Vaccinium myrtillus* type 2 (MT2; Mtkg(II) in the Finnish nomenclature), *Vaccinium vitis-idaea* types 1 and 2 (VT1, VT2; Ptkg(I) and Ptkg(II), respectively) and Dwarf-shrub type (DsT; Vatkg). MT2 type is character-

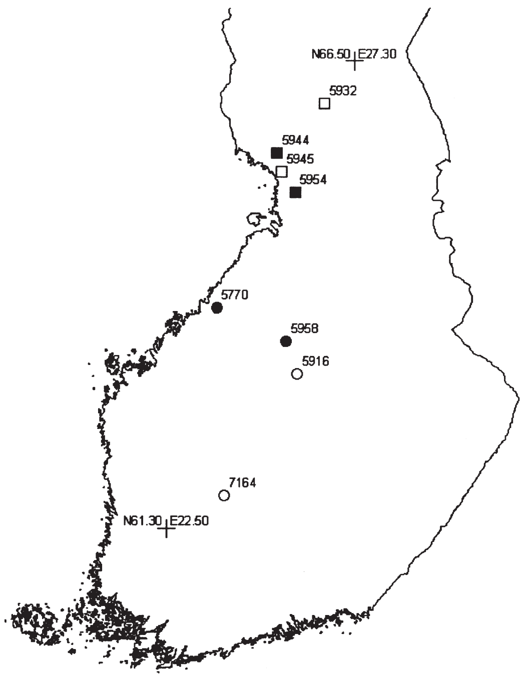


**Fig. 1.** Location of the sample sites. Symbols refer to site groupings for ANOVA, circles = southern sites, rectangles = northern sites, open symbols = estimated total yield < 400 m$^3$ ha$^{-1}$, filled symbols = estimated total yield > 400 m$^3$ ha$^{-1}$.

ized by the dominance of *Vaccinium myrtillus* L. and *V. vitis-idaea* L. in the field layer. Herbs typical of mesic upland sites (e.g. *Trientalis europaea* L.) are also indicator species. MT2 develops from mesotrophic treeless sites or composite pine mire sites, having the properties of both treeless and forested sites, typically with *Carex* peat. VT types have dwarf-shrubs typical of pine mires (*Ledum palustre* L. and *Vaccinium uliginosum* L. on VT1, mainly *Betula nana* L. on VT2) scattered amongst the *V. vitis-idaea*- and *V. myrtillus*-dominated field layer community. VT1 develops from the least fertile spruce mires and minerotrophic pine mires, having *Sphagnum* spp. residue-dominated peat. VT2 develops from treeless sites or composite oligotrophic tall-sedge mires and has peat made up mainly of *Carex* spp. residues. Forests classified as DsT develop from ombrotrophic pine mire sites. Pine mire dwarf-shrubs are dominant in the field layer. The peat consists of *Sphagnum* spp. and *Eriophorum vaginatum* L. remains.

These site types form a post-drainage production potential gradient, MT2 being the most productive and DsT the least productive of the pine sites (Laine 1989). No clear differences in potential productivity have been assumed between types 1 and 2 of MT and VT. These types have been divided largely because of nutrient imbalances and other silvicultural problems related to tree stand composition being more common in type 2 due to their more genuine, and wet, mire origin (Laine

**Table 1.** Study site properties.

| Stand | Temperature sum, dd [a)] | Site type [b)] | Peat depth, m | V, m$^3$ ha$^{-1}$ [c)] | $H_{100}$, m [d)] | First ditched | PDW % [e)] | Total yield [f)] |
|---|---|---|---|---|---|---|---|---|
| 5932 Kumpukivalo | 862 | VT2 | 0.4 | 100 | 12 | 1934 | 0.0 | 329 |
| 5944 Kalliokoski | 962 | MT2 | 0.2 | 145 | 12 | 1961 | 0.1 | 475 |
| 5945 Työlässuo | 982 | VT2 | 0.2–0.5 | 150 | 12 | 1957 | 2.2 | 388 |
| 5958 Rehula | 1039 | VT2 | 0.6–1.0 | 160 | 14 | 1973 | 12.7 | 556 |
| 5770 Mannila | 1068 | VT1 | 0.2 | 205 | 17 | 1954 | 4.4 | 635 |
| 5954 Naurua | 1020 | VT2 | 0.3 | 220 | 17 | 1939 | 2.4 | 476 |
| 5916 Kolima | 1050 | DsT | 0.2–0.8 | 165 | 15 | 1958 | 0.0 | 374 |
| 7164 Ahvenräme | 1127 | DsT | >1 | 130 | 16 | 1967 | 4.6 | 382 |

a) Cumulative annual temperature sum with a +5 °C threshold
b) According to Laine (1989); see text for descriptions
c) Stand volume
d) Stand dominant height
e) Proportion of pre-drainage wood of total stemwood volume
f) Simulated for the whole tree stand rotation (S. Kojola and T. Penttilä, unpublished data)

1989). The pre-drainage differences are reflected in the peat nutrient regime several decades after drainage (Westman and Laiho 2003).

## 2.2 Sampling

### *2.2.1 Stand-Level*

The recently assessed (mapping of individual trees and measurement of tree DBH [diameter at 1.3m]) unthinned control plots of the thinning experiments on the selected sites provided the tree stand framework for applying the experimental thinning operation. The plot-wise basal area sum of the trees to be retained was recorded and adjusted according to the Finnish guidelines for best management practice (Hyvän metsänhoidon suositukset 2001) and the trees to be removed were marked and tallied for DBH (minimum 8 cm) by tree species, separating dead trees from those alive. Standard stand and tree characteristics were then computed for the retained stands and thinning removals using the KPL-software package by the Finnish Forest Research Institute (Heinonen 1994).

A 10-tree sample of Scots pine emulating the DBH distribution of the removal was harvested from the buffer zones of the plots on each site. The minimum DBH for harvesting was 8 cm. Each tree to be felled was tallied for DBH (mm), and measured for length (0.1 m), the last 5-year height-increment (0.1 m) and crown limit (0.1 m) after felling. The stems were pruned avoiding damage to bark, and cut into 2-meter logs.

The sampling had been done in a way ensuring as good a representativeness for the estimated thinning removals as possible. Although our sample of 10 trees covered the DBH distributions of the thinning removals quite well, the number turned out to be too small to be fully representative on a volume or mass basis. Therefore, larger trees were over-represented in the distribution of pulpwood volume by DBH class. Thus, we adjusted the samples by removing parts of sample logs from the largest trees before chipping.

### *2.2.2 Tree-Level*

Two sets of sample discs were taken at each log cut, i.e. at 2 m intervals starting from the stump: a 5 cm thick disc just below the cut for determination of pulp properties and a 2 cm thick disc just above the cut for dendrochronological measurements and stem analysis. The log cuts were made between branch whorls so that the sample discs did not include branch wood.

## 2.3 Preparation of Stand-Level Material

The sample logs were delivered to Teollisuuden Hake Oy located in Kuusankoski. The logs were debarked using a rotor debarker (VK 16 S, Valon Kone Oy) and chipped using a disk chipper (Bruks 1702M). The chips were then screened using a gyratory-hole screen with 45 mm holes on the upper screen and 8 mm holes on the fines screen.

The chip size distributions were normal for a disk chipper and similar for all the chip samples

**Table 2.** Size distribution (SCAN-CM 40:94) for the chip samples from the sample logs.

| Stand | 45 ∅, % | 8 //, % | 13 ∅, % | 7 ∅, % | 3 ∅, % | Fines, % | Sum | Overs | Accepts | Pins + fines |
|---|---|---|---|---|---|---|---|---|---|---|
| 5932 | 0.0 | 6.6 | 66.3 | 24.8 | 2.2 | 0.1 | 100.0 | 6.6 | 91.1 | 2.3 |
| 5944 | 0.0 | 7.4 | 64.9 | 25.0 | 2.6 | 0.1 | 100.0 | 7.4 | 89.9 | 2.7 |
| 5945 | 0.2 | 5.5 | 72.7 | 19.8 | 1.7 | 0.1 | 100.0 | 5.7 | 92.5 | 1.8 |
| 5958 | 0.0 | 3.8 | 66.7 | 26.4 | 3.0 | 0.1 | 100.0 | 3.8 | 93.1 | 3.1 |
| 5770 | 0.0 | 4.9 | 65.6 | 26.5 | 2.9 | 0.1 | 100.0 | 4.9 | 92.1 | 3.0 |
| 5954 | 0.2 | 5.7 | 66.6 | 25.0 | 2.4 | 0.1 | 100.0 | 5.9 | 91.6 | 2.5 |
| 5916 | 0.1 | 5.6 | 65.0 | 25.9 | 3.3 | 0.1 | 100.0 | 5.7 | 90.9 | 3.4 |
| 7164 | 0.0 | 3.6 | 65.5 | 27.5 | 3.3 | 0.1 | 100.0 | 3.6 | 93.0 | 3.4 |

**Table 3.** Bleaching conditions.

| | Stage | | | | | | |
|---|---|---|---|---|---|---|---|
| | O | D0 | E1 | D1 | E2 | D2 | SO2 |
| Consistency, % | 10 | 3 | 10 | 9 | 10 | 9 | 2 |
| Temperature, °C | 95 | 50 | 60 | 70 | 70 | 70 | 25 |
| Time, min | 90 | 60 | 60 | 180 | 60 | 180 | 15 |
| Initial pH | | 3 | | | | 8.5 | 4.5 |
| $O_2$, bar | 8 | | | | | | |
| Act. Cl multiple | | 0.20 | | | | | |

(Table 2). The chips can also be considered to have been bark-free, because all possible bark residues attached to the logs after rotor debarking were removed manually with a knife. The chips were analyzed for dry matter content (SCAN-CM 39:94) and basic density (SCAN-CM 43:95).

Kraft pulps were manufactured from each chip sample. The experiments were conducted in 15-litre electrically-heated rotating digesters. The cooking conditions were as follows:

| | |
|---|---|
| Charge of chips | 2200 g o.d. |
| Liquor-to-wood ratio | 3.5 l $kg^{-1}$ o.d |
| Charge of effective alkali | 4.5 mol $kg^{-1}$ (18% NaOH) |
| Sulphidity | 35% |
| Heating 20 °C to 80 °C | 30 min |
| Heating 80 °C to 170 °C | 90 min |
| H factor | 1250–1450 |

After the cooks, the pulps were washed with deionized water, disintegrated in a rod mill for 20 minutes, and screened on a flat-slotted laboratory screen (slot widths 1.0 mm and 0.3 mm), centrifuged, and then granulated. Total pulp yields, amounts of screen rejects, kappa numbers (ISO 302) and black liquor pH values were determined. The fiber properties of the unbleached pulps were measured using a Kajaani FS 200 analyzer (length, coarseness).

Four of the unbleached pulps were included in the bleaching and pulp testing experiments. The selection was based on the property variation in the unbleached pulps, to include material with varying fiber length and coarseness. Further, we excluded stand 7164, which was closest to 'normal' unbleached pulp. The pulps were bleached applying the ODEDED sequence with a target brightness of 89 ISO. The conditions are listed in Table 3.

Determinations were made of bleaching yields, chemical consumptions, brightness values, viscosity values (SCAN-CM 15:99), and kappa number values (ISO 302). The bleached pulps were tested after beating in a PFI mill (ISO 5264-2). The pulp properties were tested as listed in Appendix 1.

Wood consumption in the production of bleached kraft pulp was calculated as follows:

$$W_{cons} = 0.9 / [(1 - b) \cdot \rho \cdot Y]$$

where

$W_{cons}$ = Wood consumption, $m^3$ stem wood (including bark) per tonne of air-dry pulp

$b$ = Fraction of bark

$\rho$ = Wood density, tonne dry wood per $m^3$ wood

$Y$ = Bleached pulp yield, tonne dry bleached pulp per tonne of dry wood

## 2.4 Preparation of Tree-Level Material

Six stands were included in the analysis of tree-level properties. We used the DBH distribution of the sample trees within the stand as a criterion for the selection of these stands. An approved stand had to have sample trees representing all of the following DBH classes: 9, 12, 14 and 16 cm.

The thicker sample discs were delivered to KCL where the discs were debarked and chipped manually using a hammer and a sharp knife. The chip size was about 50×30×3 mm (length×width×thickness). To obtain an accurate yield determination the chips were dried before the cooks, weighed as oven-dry, and rewetted before the actual cooks. The chip samples were cooked by the kraft method. The experiments were conducted in 0.15 l autoclaves immersed in a polyglycol bath. The bath was pre-heated to 55 °C before immersing the autoclaves. The cooking conditions were as follows:

| | |
|---|---|
| Charge of chips | 20 g o.d. |
| Liquor-to-wood ratio | 4.0 l $kg^{-1}$ o.d |
| Charge of effective alkali | 5.0 mol $kg^{-1}$ (20% NaOH) |
| Sulphidity | 35% |
| Heating 55 °C to 170 °C | 90 min |
| Time at 170 °C | 105 min |

Total pulp yields, amounts of screen rejects, kappa number values (ISO 302) and black liquor pH values were determined. The fiber properties (length, coarseness) of the pulps were measured using a Kajaani FS 200 analyzer.

The second set of sample discs was used for tree-ring analyses and density measurements conducted at the Finnish Forest Research Institute, Rovaniemi Research Station. The disc volumes for the wood's basic density calculations were measured by water displacement (SCAN-CM 43:95). Whenever there was enough pre-drainage wood, the discs were split into parts formed before and after drainage, and density was measured for each part separately. The average density for each tree was calculated by weighing the density of each disc by its area.

The tree-ring data were used for calculating the annual volumes for each tree using the KPL software. The volumes in the year of drainage were used to calculate the proportion of pre-drainage wood of the total volume for each tree. Further, the tree-ring data provided the total age, as well as the number of pre- and post-drainage rings, for each disc. The average ring widths were calculated both for the intact discs, and for the pre- and post-drainage parts separately.

### 2.5 Statistical Analyses

First, the effects of geographic location and site productivity on wood density and fiber properties on the stand level were analyzed using analysis of variance. The stands were grouped into two 'location classes', south and north, and two productivity classes, estimated total yield smaller or greater than 400 $m^3$ $ha^{-1}$ (see Fig. 1). The total yield estimates (S. Kojola and T. Penttilä, unpublished data) were obtained from simulations done using the MOTTI stand simulator developed at the Finnish Forest Research Institute (Salminen and Hynynen 2001).

Next, the stand- and tree-level variation in wood density and fiber properties was analyzed using mixed linear models that accounted for the hierarchical data structure. The models consisted of a fixed part covering the variation explained by independent variables, and a random part covering the remaining variation at the different hierarchical levels: stand, tree, and disc. Parameter estimation was done by using the MLwiN software (Rasbash et al. 2001), which estimates the fixed and random parameters simultaneously. We used the restricted iterative least squares (RIGLS) method recommended for small samples. It is an iterative method producing restricted maximum likelihood (REML) estimates for the parameters.

The contributions of the different hierarchical levels to the total variance of the dependent variables were first analyzed with a model containing only a constant in the fixed part. The models were then constructed by entering independent variables one by one. Comparing the parameters and their standard errors indicated whether the parameters were statistically significant. The independent variables that were tested included stand-level variables temperature sum, geographic location (latitude), peat depth, site type (dummy) and fertilization (dummy), tree-level variables DBH and tree age (number of annual rings at stump level), and disc-level variables height position (dummy), number of pre- and post-drainage rings, age (number of tree rings in the disc), and average tree-ring width both for the intact discs and for pre- and post-drainage wood separately.

# 3 Results

### 3.1 Stand-Level Material

Differences in the processability of the raw material obtained from the thinning removals from various stands were small (Table 4). Kraft cooking of the chip samples representing

**Table 4.** Results from chip analyses and cooking experiments, samples from eight stands.

| Stand | Wood analyses | | Cooking | | | | | | | | Fiber properties | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dry matter content | Basic density | H factor | Effective alkali | Kappa number | Total yield | Screen-ings | Screened yield | Black liquor | Total yield at kappa 30 | Fiber length arithm. | Fiber length by length | Coarse-ness | l/w [a)] |
| | % | kg m$^{-3}$ | | mol kg$^{-1}$ | | % | % | % | pH | % | mm | mm | mg m$^{-1}$ | |
| 5932 | 44.3 | 387 | 1450 | 4.5 | 31.3 | 44.4 | 0.6 | 43.8 | 12.8 | 44.2 | 1.00 | 1.88 | 0.164 | 11.5 |
| 5944 | 40.7 | 385 | 1350 | 4.5 | 33.0 | 47.4 | 0.5 | 46.9 | 12.9 | 46.9 | | | | |
| | | | 1450 | 4.5 | 30.3 | 46.7 | 0.6 | 46.1 | 12.8 | 46.6 | 1.03 | 1.86 | 0.160 | 11.6 |
| 5945 | 44.2 | 396 | 1350 | 4.5 | 31.4 | 47.7 | 0.8 | 46.9 | 12.9 | 47.4 | 1.05 | 1.95 | 0.183 | 10.7 |
| | | | 1450 | 4.5 | 28.7 | 46.9 | 0.6 | 46.4 | 12.8 | 47.2 | | | | |
| 5958 | 46.8 | 424 | 1450 | 4.5 | 30.6 | 46.3 | 0.7 | 45.6 | 12.8 | 46.2 | 1.13 | 2.01 | 0.179 | 11.2 |
| 5770 | 47.3 | 437 | 1350 | 4.5 | 30.4 | 45.8 | 0.6 | 45.2 | 12.9 | 45.7 | 1.15 | 2.13 | 0.185 | 11.5 |
| | | | 1450 | 4.5 | 29.2 | 45.9 | 0.5 | 45.4 | 12.8 | 46.0 | | | | |
| 5954 | 50.7 | 443 | 1350 | 4.5 | 32.7 | 45.8 | 0.7 | 45.1 | 12.8 | 45.3 | 1.04 | 2.01 | 0.167 | 12.0 |
| 5916 | 43.6 | 400 | 1350 | 4.5 | 30.5 | 47.0 | 0.7 | 46.3 | 12.8 | 46.9 | 1.03 | 2.04 | 0.188 | 10.9 |
| | | | 1450 | 4.5 | 28.6 | 46.6 | 0.5 | 46.1 | 12.8 | 46.9 | | | | |
| 7164 | 44.1 | 421 | 1250 | 4.5 | 31.2 | 48.0 | 0.9 | 47.1 | 12.9 | 47.8 | 1.12 | 2.19 | 0.201 | 10.9 |
| | | | 1350 | 4.5 | 27.8 | 47.3 | 0.4 | 46.9 | 12.9 | 47.7 | | | | |

[a)] Reinforcement coefficient

**Table 5.** ANOVA tables summarizing the effects of geographic location and site productivity on wood basic density and selected fiber properties in the removal of pine pulpwood in the first commercial thinnings of eight drained peatland forest sites. Productivity classes: A = estimated total yield greater, and B = smaller, than 400 $m^3$ $ha^{-1}$.

| Dependent variable | Effect: latitude | | | Mean | sd | Effect: site productivity | | | Mean | sd |
|---|---|---|---|---|---|---|---|---|---|---|
| Basic density, kg $m^{-3}$ | F | 1.29 | South | 420.5 | 15.3 | F | 2.04 | A | 401.0 | 14.40 |
| | p | 0.300 | North | 402.8 | 27.3 | p | 0.204 | B | 422.3 | 26.07 |
| | | | All | 411.6 | 22.6 | | | All | 411.6 | 22.56 |
| | | | RMSE | | 22.1 | | | RMSE | | 21.06 |
| Fiber length, mm | F | 9.74 | South | 2.092 | 0.083 | F | 0.02 | A | 2.015 | 0.134 |
| | p | 0.021 | North | 1.925 | 0.069 | p | 0.890 | B | 2.003 | 0.111 |
| | | | All | 2.009 | 0.114 | | | All | 2.009 | 0.114 |
| | | | RMSE | | 0.076 | | | RMSE | | 0.123 |
| Coarseness, mg $m^{-1}$ | F | 8.30 | South | 0.188 | 0.009 | F | 1.39 | A | 0.184 | 0.015 |
| | p | 0.028 | North | 0.168 | 0.010 | p | 0.283 | B | 0.173 | 0.011 |
| | | | All | 0.178 | 0.014 | | | All | 0.178 | 0.014 |
| | | | RMSE | | 0.010 | | | RMSE | | 0.014 |
| Yield (kappa-30), % | F | 0.94 | South | 46.7 | 0.845 | F | 0.34 | A | 46.55 | 1.609 |
| | p | 0.369 | North | 45.9 | 1.416 | p | 0.584 | B | 46.05 | 0.624 |
| | | | All | 46.3 | 1.161 | | | All | 46.30 | 1.161 |
| | | | RMSE | | 1.166 | | | RMSE | | 1.221 |
| Reinforcement coefficient (l/w) | F | 0.98 | South | 11.45 | 0.308 | F | 6.96 | A | 10.97 | 0.344 |
| | p | 0.36 | North | 11.12 | 0.579 | p | 0.039 | B | 11.60 | 0.336 |
| | | | All | 11.28 | 0.463 | | | All | 11.28 | 0.463 |
| | | | RMSE | | 0.464 | | | RMSE | | 0.340 |

**Table 6.** Results from bleaching experiments, pulps from four selected stands.

| | | Stand 5944 | 5770 | 5954 | 5916 |
|---|---|---|---|---|---|
| Cooking | Kappa number | 30.3 | 30.4 | 32.7 | 30.5 |
| | Cooking yield, % [a)] | 46.5 | 45.6 | 45.6 | 46.8 |
| O-stage | NaOH charge, % | 1.9 | 1.9 | 1.9 | 1.9 |
| | Kappa number | 17.7 | 17.4 | 19.1 | 17.2 |
| | Kappa reduction, % | 41.6 | 42.8 | 41.6 | 43.6 |
| | Viscosity, ml $g^{-1}$ | 1042 | 1048 | 1017 | 1041 |
| Bleached pulp | Brightness, % | 89.4 | 89.7 | 89.2 | 89.7 |
| | Kappa number | 0.7 | 0.7 | 0.8 | 0.5 |
| | Viscosity, ml $g^{-1}$ | 947 | 952 | 954 | 962 |
| | Bleaching yield (incl. $O_2$ stage) | 94.3 | 94.1 | 93.1 | 93.8 |
| | Pulp yield, % on wood | 43.9 | 42.9 | 42.4 | 43.8 |
| | Tot. $ClO_2$ cons. % act. Cl | 6.16 | 6.13 | 6.57 | 5.98 |
| | Act. Cl cons./$O_2$ kappa | 0.348 | 0.352 | 0.344 | 0.348 |

[a)] Cooking yield = screened yield + 0.7 · screenings

**Table 7.** Papermaking properties of the bleached pulps after beating in a PFI mill, interpolated to tensile indices 50 and 70 Nm g$^{-1}$.

| Stand | Beating revs | CSF | SR | WRV | Tensile index | Tensile stiffness index | Modulus of elasticity | Zero-span tensile index (wet) | Zero-span tensile index (dry) | Tear index | Fracture toughness index | Bulk | Air resistance Gurley | Scott Bond | Scattering coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ml | | g g$^{-1}$ | Nm g$^{-1}$ | kNm g$^{-1}$ | Mpa | Nm g$^{-1}$ | | mNm$^2$ g$^{-1}$ | Jm g$^{-1}$ | cm$^3$ g$^{-1}$ | s | J m$^{-2}$ | m$^2$ kg$^{-1}$ |
| 5944 | 209 | 642 | 15.5 | 1.77 | 50.0 | 5.99 | 4155 | 120 | 138 | 19.3 | 23 | 1.45 | 3.5 | 250 | 27.7 |
| | 745 | 608 | 17.0 | 1.92 | 70.0 | 6.79 | 4997 | 124 | 147 | 13.9 | 23 | 1.36 | 6.2 | 345 | 23.9 |
| 5770 | 433 | 665 | 14.7 | 1.72 | 50.0 | 6.13 | 4099 | 127 | 143 | 21.0 | 24 | 1.50 | 1.6 | 218 | 25.1 |
| | 1066 | 644 | 16.2 | 1.79 | 70.0 | 6.89 | 4844 | 130 | 149 | 16.0 | 25 | 1.42 | 2.6 | 307 | 21.6 |
| 5954 | 442 | 630 | 15.4 | 1.78 | 50.0 | 5.77 | 3957 | 130 | 141 | 18.5 | 21 | 1.46 | 2.1 | 234 | 26.1 |
| | 1513 | 559 | 18.3 | 1.89 | 70.0 | 6.64 | 4856 | 135 | 151 | 14.3 | 21 | 1.37 | 4.7 | 343 | 22.1 |
| 5916 | 485 | 640 | 16.0 | 1.76 | 50.0 | 6.02 | 4086 | 115 | 143 | 18.0 | 21 | 1.47 | 2.0 | 234 | 25.1 |
| | 1524 | 571 | 19.1 | 1.87 | 70.0 | 6.89 | 4998 | 129 | 154 | 13.3 | 22 | 1.38 | 4.2 | 340 | 21.2 |

the thinning removals from the stands revealed only a 5-unit variation in the kappa number of unbleached pulp. Although considerable variation in wood basic density (385–443 kg m$^{-3}$) and kraft pulp yield (total yield 44.2–47.8 % at kappa number 30) were observed, the variation was not explained by geographic position or site productivity (Table 5).

The differences in fiber length (1.86–2.19 mm) and coarseness (0.160–0.201 mg m$^{-1}$) (Table 4) indicated variation in the papermaking properties of the pulps. Both fiber length and coarseness were, on average, greater in the material obtained from the southern sites (Table 5). Notably, the wood density or fiber properties did not correlate with the proportion of pre-drainage wood.

Bleaching of the four pulps (ODEDED) did not show differences in the consumption of bleaching chemicals nor in bleaching yield based on stand origin (Table 6). The bleaching response was essentially only dependent on the kappa number of unbleached pulp. The papermaking properties of the four bleached pulps after beating in a PFI mill are listed in Table 7.

The processing value of the thinning removals varied among the stands. Variation in the most important factor affecting pulp production costs, wood consumption, ranged from 5.81 to 7.03 m$^3$ per metric tonne of 90% bleached pulp (Table 8). The difference, over 1 solid m$^3$ with bark, corresponded to almost 50 EUR per tonne of pulp applying the current pine pulpwood prices at the mill in Finland. In addition to stand type, the geographical location of the stand had an effect on its properties. The most unfavorable stands in terms of the pulp properties were situated in northern Finland (Fig. 1).

### 3.2 Tree-Level Material

The total variance of wood density consisted of 11% of variation among stands, 22% of variation among trees, and 67% of variation within trees (i.e. variation among sample discs within individual trees). For fiber length, coarseness and yield, the contribution of variation among trees ranged from 17% to 24%, and that of within-tree variation from 73% to 83%.

Wood density was higher on both of the VT site

**Table 8.** Wood consumption (solid m$^3$ with bark per metric tonne air-dry (90% d.s) bleached pulp) for the samples representing the various stands. Calculated with yields in bleaching proportional to unbleached kappa number.

| Stand | Basic density, kg m$^{-3}$ | Bark content, % | Yield of unbleached pulp[a)], % | Yield in bleaching[b)], % | Wood consumption, m$^3$ t$^{-1}$ pulp |
|---|---|---|---|---|---|
| 5932 | 387 | 20.0 | 44.2 | 93.5 | 7.03 |
| 5944 | 385 | 18.7 | 46.5 | 94.3 | 6.56 |
| 5945 | 396 | 17.5 | 47.4 | 93.5 | 6.21 |
| 5958 | 424 | 16.8 | 46.1 | 94.0 | 5.89 |
| 5770 | 437 | 18.6 | 45.6 | 94.1 | 5.89 |
| 5954 | 443 | 17.5 | 45.6 | 93.1 | 5.81 |
| 5916 | 400 | 17.8 | 46.8 | 93.8 | 6.24 |
| 7164 | 421 | 19.3 | 47.7 | 93.5 | 5.94 |

a) Unbleached yield = screened yield + 0.7 · screenings
b) Including oxygen delignification

types than on MT2 (Table 9). Somewhat surprisingly, wood density on the DsT site type did not differ from that on MT2, and fertilization had a positive effect on density. Wood density decreased with increasing average tree-ring width, and from the stump upwards. The model covered 55% of the total variance of wood density. The variance not accounted for by the fixed part of the model derived from variation within and among trees, each contributing about 50% (Table 9).

Fiber length was most clearly affected by the height position (i.e. variation based on height above ground of sample discs taken from the stems of individual trees), increasing from the stump upwards and being at its greatest at 2–4 m (Table 10). Further, fiber length increased with increasing tree DBH, and slightly with increasing age (number of tree-rings in disc). The model covered 49% of the total variance. Two thirds of the remaining variance in fiber length was derived from variation among trees (Table 10).

Coarseness and cooking yields were poorly explained by the variables measured. Coarseness increased slightly with increasing age (number of tree-rings) of the sample disc and with increasing wood density, and it was lower on VT2 than on the other site types. Variation within and among trees contributed almost equally to the remaining variance of coarseness. Yield (kappa 30) increased from the stump upwards to the 4-m level, and decreased slightly with age (number of tree-rings) of the disc. Variation within trees

**Table 9.** Significant (0.050 level) model parameters and variance components for wood basic density (kg m$^{-3}$, sample disc averages including pre- and post-drainage wood). Standard errors are shown in brackets. Observations from 285 sample discs from 80 Scots pine trees from eight drained peatland forest sites.

| Fixed part | | | Random part | | |
|---|---|---|---|---|---|
| Effect | Parameter | (s.e.) | Effect | Parameter | (s.e.) |
| Constant | 422.6 | (17.6) | | | |
| Stand-level variables | | | Tree | 678.2 | (141.7) |
| VT1[a)] | 45.4 | (12.6) | Disc | 690.2 | (68.1) |
| VT2[a)] | 27.2 | (9.0) | | | |
| One fertilization[b)] | 16.5 | (7.9) | | | |
| Two fertilizations[b)] | 39.5 | (12.4) | | | |
| Disc-level variables | | | | | |
| Age[c)] | 0.275 | (0.142) | | | |
| Average ring width | –13.0 | (7.0) | | | |
| 2-m height[d)] | –31.8 | (5.2) | | | |
| 4-m height[d)] | –46.8 | (6.7) | | | |
| 6-m height[d)] | –51.1 | (8.4) | | | |
| 8-m height[d)] | –60.0 | (10.6) | | | |
| 10-m height[d)] | –60.0 | (14.4) | | | |

a) Dummy variable, basic level MT2 site type
b) Dummy variable, basic level no fertilization
c) Number of annual rings in the disc
d) Dummy variable, basic level stump (felling cut)

**Table 10.** Significant (0.050 level) model parameters and variance components for fiber length (mm, length-weighted averages). Standard errors are shown in brackets. Observations from 124 sample discs from 33 Scots pine trees from six drained peatland forest sites.

| Fixed part | | | Random part | | |
|---|---|---|---|---|---|
| Effect | Parameter | (s.e.) | Effect | Parameter | (s.e.) |
| Constant | 1.422 | (0.160) | | | |
| Tree-level variables | | | Tree | 0.030 | (0.008) |
| DBH | 0.024 | (0.012) | Disc | 0.015 | (0.002) |
| Disc-level variables | | | | | |
| Age[a)] | 0.002 | (0.001) | | | |
| 2-m height[b)] | 0.564 | (0.037) | | | |
| 4-m height[b)] | 0.578 | (0.051) | | | |
| 6-m height[b)] | 0.489 | (0.063) | | | |
| 8-m height[b)] | 0.408 | (0.078) | | | |
| 10-m height[b)] | 0.427 | (0.117) | | | |

a) Number of annual rings in the disc
b) Dummy variable, basic level stump (felling cut)

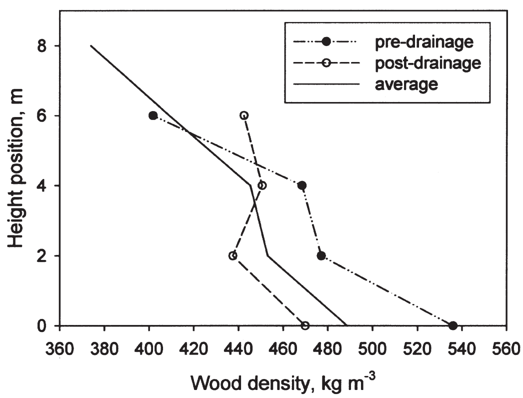


**Fig. 2.** Basic density of wood formed before and after drainage in site 5958. Values are means of all sample trees, weighted with sample disc areas. 'Average' denotes density measured for the whole sample discs without partitioning into pre- and post-drainage wood.

contributed about two thirds of the remaining variance, the remaining third coming from variation among trees.

Wood formed before drainage was, on average, denser than post-drainage wood (Fig. 2). Pre-drainage wood had slightly shorter fibers, some units higher kappa-values, and produced slightly lower yields than post-drainage wood.

# 4 Discussion

## 4.1 Pulping Properties

The properties of the thinning removals from the best stands were almost comparable with pine pulpwood from current commercial cuttings on mineral soil sites. However, the processing value of thinning removals varied considerably by stand and geographically. Poor production economy and low fiber length were often associated with the same stands. Low kraft pulp yields and wood basic density, which mean high wood consumption in pulp production, and relatively short fiber length were typical especially for the stands from northern Finland. Corresponding geographical variation in the properties of pine pulpwood is previously well known (e.g. Hakkila 1998). The correlation between fiber and pulp sheet properties proved to be more vague than was expected, and the pulp properties could not be predicted as well as was expected using only basic fiber analyses such as fiber length and coarseness.

The properties of the bleached pulps proved to be similar to those obtained from first-thinnings pine grown on mineral soil sites. Compared with those produced from commercial pine pulpwood, they showed good beatability (development of tensile strength), light scattering ability, and bonding ability (Scott Bond). They also formed sheet with high density and air resistance values, but low tear strength and fiber strength (Zero-span). Kraft pulp properties such as sheet density, Scott Bond or air resistance usually have an opposite correlation with fiber length and tear index (Fig. 3).

The papermaking properties also varied by stand. The pulp with the greatest fiber length gave an acceptable tear index (T = 16.0 mNm$^2$ g$^{-1}$ at tensile index 70 Nm g$^{-1}$). The other three pulps were, however, unacceptable in terms of their strength for good quality softwood kraft pulp (T = 13–14 mNm$^2$ g$^{-1}$). It may be noted, however, that site 7164 (which was not included in the bleaching) would most likely have produced the best strength level based on fiber length.

The results obtained confirmed earlier observations (Korpilahti et al. 1998) on property variation between peatland stands. The variation observed was, however, smaller than was expected considering the principle of selecting the stands aiming at determining total variation as well as possible. The fiber length and tear index levels observed were somewhat higher than those of the earlier peatland stands studied. None of our stands gave pulps with equally low strength level than the worst of the earlier stands (extreme stands in Fig. 3, tear index about 12 mNm$^2$ g$^{-1}$ at tensile index 70 Nm g$^{-1}$).

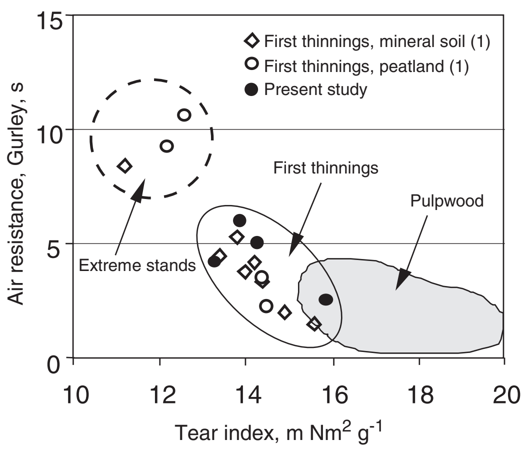


**Fig. 3.** Air resistance vs. tear index of bleached kraft pulps beaten to tensile index 70 Nm g$^{-1}$ in a PFI mill. The pulps were made from Scots pine wood samples representing cutting removals from various stands. Reference data (1) from Korpilahti et al. (1998).

## 4.2 Property Variations

Property variations between pre- and post-drainage wood were smaller than were expected, and the proportion of pre-drainage wood did not contribute significantly to the variation of any of the fiber properties studied. Mostly the within-tree variation followed that regularly observed when moving radially from tree pith towards bark, and from the stump upwards (e.g. Atmer and Thörnqvist 1982, Rissanen and Sirviö 2000). Excluding the high density caused by slow growth rates, the properties of pre-drainage wood were typical for juvenile wood in general. Thus, pre-drainage wood should not pose specific problems for processing. Further, its higher density should compensate for the smaller yield from pre-drainage wood. In any case, the proportion of pre-drainage wood was on average only 3% of the volume of the thinning removal (without bark) (Table 1). The relatively high material consumption observed is thus not likely due to pre-drainage wood, but to other properties such as the relatively high bark content. The mean bark content in our sample trees was 18% of volume, which is higher than the average of 12% reported for pine pulpwood from the same geographic regions in general (Lindblad and Verkasalo 2001), and 15% for first-thinnings wood obtained from mineral soil sites (P. Hakkila, unpublished data).

As the proportion of dense pre-drainage wood was generally low, the basic densities of pulpwood obtained from our sites were well within the range generally observed for pine pulpwood (Rissanen and Sirviö 2000), and depended on the height position and radial growth rate (ring width), which is in agreement with the literature (Hakkila 1966, 1968). In contrast, it was unexpected that fertilization would have a positive effect on wood density, and that material originating from DsT sites would not differ from that obtained from more productive sites in regard to wood density. These results should not, however, be over-emphasized: our material was not large enough for dealing with site type-fertilization-climate interactions.

When the variation in different fiber and pulp properties was broken down into the different hierarchical levels in the modeling analysis, it became evident that in all cases most of it was derived from the tree level. If there was significant variation among stands to begin with, as with wood density, it could be accounted for by simple stand-level variables, such as site type. The remaining, 'unexplained', variation in the models was derived either from within trees or among trees. The significant proportions of variation among trees indicate that there is potential to direct the quality properties of stands and/or cutting removals by means of silvicultural treatments. This still requires further research, however, as we must learn to link the quality properties of trees to their external characteristics.

### 4.3 Conclusions

On average, the fiber and pulp properties of wood material obtained from first thinnings on peatland sites do not differ markedly from those of corresponding material currently used, that largely originates from mineral soil sites. We might phrase this in the form that pulpwood from first thinnings on peatlands is no worse than pulpwood from first thinnings in general. Variation of pre- and post-drainage wood does not seem to pose any specific problems for pulp production. Consequently, peatland pulpwood may be mixed with pulpwood from other sources.

The most suitable end-use for wood from first-thinnings stands on peatland, as well as for wood from corresponding mineral soil stands, is obviously not in making pulps required to possess high reinforcement ability as are typically used in mechanical printing papers (SC, LWC). These pulps would probably be better suited for uses requiring high bonding, e.g. in the top ply of multi-ply board grades or in some specialty grades.

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*Total of 21 references*

**Appendix 1.** Testing methods for the papermaking properties of the pulps.

| Property | SCAN | ISO |
|---|---|---|
| Freeness, CSF | SCAN-C 21:65, ml | ISO 5267-2:1980 |
| SR number | SCAN-C 19:65 | ISO 5267-1:1979 |
| WRV | SCAN-C 62:00 | |
| Preparation of laboratory sheets | SCAN-CM 26:99 | ISO 5269-1:1979 |
| Density | SCAN-P 7:96 | ISO 534:1988 |
| Tensile index | SCAN-P 38:80 | ISO 1924-2:1994 |
| Elongation | SCAN-P 38:80 | ISO 1924-2:1994 |
| Modulus of elasticity | SCAN-P 38:80 | ISO 1924-2:1994 |
| Tensile stiffness index | SCAN-P 38:80 | ISO 1924-2:1994 |
| Zero-span tensile index, rewetted (Pulmac) | | ISO/DIS 15361 |
| Zero-span tensile index, dry (Pulmac) | | ISO/DIS 15361 |
| Tear index | SCAN-P11:73 | ISO 1974:1990 |
| Fracture toughness index | SCAN-P 77:95, mod | |
| Nominal tensile index | SCAN-P 77.95, mod | |
| Air resistance, Gurley | SCAN-P 19:78 | |
| ISO-brightness | SCAN-P 3:93 | ISO 2470 |
| Opacity | SCAN-P 8:93 | ISO 2471 |
| Light scattering coefficient | SCAN-P 8:93 | ISO 9416 |
| Light absorption coefficient | SCAN-P 8:93 | ISO 9416 |
| Scott Bond, Huygen internal bond tester | mod. Tappi T 833 om-96 | |